CLIMATE IMPACTS, IMPLICATIONS AND ADAPTION OPTIONS FOR THE URANIUM SUPPLY CHAIN IN AUSTRALIA

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Dedicated to my mother, *Cristina Loza*, in gratitude for her infinite love…

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Abstract

The level of emissions of greenhouse gases (mainly CO_2) has increased dramatically in the last few decades. This is owing to the growing use of fossil fuels and the fast-economic growth of developing countries. These elevated levels of greenhouse gases may have contributed to recent changes in the climate that is affecting our society, industries, and environment. The way society and industries have been facing these climate conditions may no longer be effective in the future, making it crucial to identify adaptation options.

The energy sector represents the most pollutant activity worldwide; in 2010 it contributed 35% of total Greenhouse Gases (GHGs). In this sector, electricity generation presents the fastest growth in the most recent years, thus the search for reliable energy sources is a worldwide concern. Uranium has been argued as a potential solution because it is a lesser pollutant compared with other sources e.g. lifecycle emissions of nuclear power are 29 CO_2e/GWh compared to 888 CO_2e/GWh for coal. In light of these facts, a significant increase in demand for uranium is expected in the future. This potential increase in uranium demand would be beneficial to Australia since it holds 31% of the total worldwide uranium resources.

Australia currently has three operating uranium mines: Ranger Mine, Olympic Dam and Four Mile. This research focuses on Ranger and Olympic Dam since they have provided more than 80% of the Australian exports in the period 2013 to 2016 - approximately 12% of worldwide demand. Due to this high supply, there is a need to study, at depth, any potential threat to this market including climate change and extreme weather events.

In order to obtain better understanding, knowledge, and information about how the Australian uranium industry (and its supply chain) has previously been impacted by climate change and how they may be impacted in the future has been conducted. This research has included:

- A literature review of climate change concepts (climate scenarios, exposure, sensitivity, adaptive capacity, supply chain, and uranium industry), and vulnerability assessment across different areas/fields to perform an assessment of the mining industry.
- Analysis of annual and sustainability reports (for the period 2006-2016) to identify past impacts of climate change in the uranium industry in both mines under study.
- Design of the research strategy (survey) to perform a vulnerability assessment.
- Identifying uranium supply chain participants
- Identifying adaptation needs and options
- Ranking the adaptation options.

In the first stage of this research, several climate impacts were identified at the Ranger Mine, which led (on several occasions during the study period) to the disruption of mining and processing operations, flooding of the operational pit, flooding of the tailings storage facilities and blocked access to the high-grade ore. These events were linked to documented financial impacts such as decrease in production of 20% in 2006 compared to the previous year, 28% in 2010, and in 2011, a shortfall in production of 30% compared to planned production. All these disruptions caused a decrease in revenue of approximately AU$64 million in 2006 and AU$196 million in 2010. In addition to this, during 2011 the company was forced to purchase 2126 tonnes of uranium in the spot market at an estimated cost of AU$253.2 million to meet contract commitments, which led to zero profit margins at these operations.

Furthermore, capital expenditure increased by 206% in, 2007 , 180% in 2008, 122% in 2010, 216% in 2011 and 166% in 2012. This was mainly due to costs associated with the impacts of climate events that included flooding and cyclones (e.g. in 2012 was commissioned a brine concentrator to increase the water management capacity especially in the wet season). The total economic losses (in the study period) which includes loss of production, mineral purchases, and capital expenditure due to climate events was estimated at A$934.5 million.

Climate impacts at the Ranger Mine also implied additional capital and operating costs associated with the removal of temporary excess water from the pit, raising the height of the tailings storage facility three times and installation of a new water treatment facility. The total cost of the previous adaptation measures during the study period was estimated to be AS$ 594.8 million.

To study climate impacts in depth, a climate vulnerability assessment (characterisation of exposure, sensitivity, and adaptive capacity) of the Australian uranium supply chain (composed of Mining, Downstream, and External stakeholders groups) was performed. The vulnerability assessment showed that both operations supply chains have the capacity to respond to current climate risks. However, the capacity to anticipate future climate risks, including the knowledge of vulnerability assessments or risk reduction planning appears to be very limited. Further, this assessment revealed the distinct aspects of sensitivity (direct and indirect) to climate change in both supply chains with a special focus on the impacts on mining companies. It was shown that vulnerabilities are location-specific e.g. Ranger Mine, which is located in a tropical climate has excess-water sensitivities compared to Olympic Dam located in an arid climate who has water scarcity issues. The most vulnerable group to future climate impacts was identified as the Mining group in both chains. Interesting, they were also identified as having the greatest capacity to adapt. At both locations, the least prepared group is the Downstream group suggesting that they may require the most assistance to reduce their vulnerability.

The results of the vulnerability assessment allowed the identification of adaptation needs and options to meet those needs. Adaptation options are considered an investment; however, their costs and benefits are difficult to quantify. As a result of this, they were assessed using a Multi-Criteria Analysis (MCA) approach. The results of this analysis show that the adaptation needs and satisfactory options are specific for each groups of stakeholders and scenario considered. Further, it was found that the greatest potential for improvement is associated with internal and external communication and that by doing this, will lead to better climate change adaptation capacity across the supply chains of both mines. The analysis also revealed the need to improve the identification of climate risks in the Risk Management Plan (RMP) of each mine. Internal failures such as lack of understanding of the principles of risk assessment in the RMP and poor staff communication (in the risk management context) were also revealed.

This research is unique to the Australian Uranium Industry and is the first of its kind. This study was completed to support companies' decision-making processes associated with adaption to future climate change conditions. By no means, does it provide a definitive answer, and additional research opportunities have been identified.

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Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

Publications declaration

I hereby declare that this thesis contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

This thesis includes *1* original papers published in peer reviewed journals and 1 accepted and under review. The core theme of the thesis is climate change impacts and adaptation on uranium mining. The ideas, development and writing up of all the papers in the thesis were the principal responsibility of myself, the student, working within the Department of Civil Engineering under the supervision of Professor Bre-Anne Sainsbury, Dr. Jane Hodkinson and Dr. Barton Loechel from CSIRO.

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I have / have not renumbered sections of submitted or published papers in order to generate a consistent presentation within the thesis.

Student signature: [redacted] **Date:** 25 /07/2018

The undersigned hereby certify that the above declaration correctly reflects the nature and extent of the student's and co-authors' contributions to this work.

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1 Introduction

This chapter provides background information about the key concepts of climate change employed in this thesis that include Greenhouse Gases (GHGs), emission levels, and Representative Concentration Pathways (RCPs). In addition, information about the global and local uranium market and the Australia uranium industry are provided as background information.

1.1 Climate Change Concepts

The concept of the greenhouse effect may seem to be new but scientific understanding began to develop in the 19th century. The pioneers in the field include Joseph Fourier (1878) with his "Analytic theory of heat" (Fourier, 1878); John Tyndall (1859) who was able to demonstrate that water (H_2O) vapour and carbon dioxide (CO_2) absorb infrared radiation for the first time in his studies of radiant energy (Tyndall, 1859); and Svante Arrhenius (1896) who studied the responses of the Earth's surface to the changes in the level of concentrations of CO_2 and H_2O and identified the natural greenhouse effect (Arrhenus, 1896).

Climate refers to an average condition of meteorological characteristics in a specific region over a period of time - usually 30 years (Solomon *et al*, 2007). When average climate characteristics change by a significant level (and are maintained), then this is defined as "climate change" (Solomon *et al*, 2007). According to an assessment carried out by the United Nations Intergovernmental Panel on Climate Change (IPCC), there is currently a high probability that the world climate is changing. This alteration is caused by the increase in levels of greenhouse gases that include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs); sulphur hexafluoride (SF6) and chlorofluorocarbons (CFCs) (Solomon *et al*, 2007). The increase is largely attributed to the use of fossil fuels since the Industrial Revolution (Stocker *et al*, 2014). The consequences of climate change will affect our society, industries and natural environment (Houghton *et al,* 2001; Solomon *et al*, 2007; Stocker *et al*, 2014).

'Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level (Stocker *et al*, 2014)'.

The climate of our planet in geological history has been influenced by natural causes that have included meteors, volcanic eruptions, solar activity and continental movements. However, there are recent mechanisms, which are not natural. These mechanisms or anthropogenic causes are due to rising

levels of greenhouse gas (GHG) emissions, aerosols, deforestation and land erosion (Solomon *et al,* 2007). The higher deforestation contributes to increase CO_2 emissions, since trees and other types of vegetation remove CO_2 from the atmosphere by the photosynthesis process (Solomon *et al*, 2007).

According to data gathered at the Mauna Loa Observatory in Hawaii, the mean level of CO_2 emissions in the atmosphere has increased from 278 ppm in the pre-industrial period to 407.60 ppm in April 2017 (NOAA, 2017). See Figure 1.1.

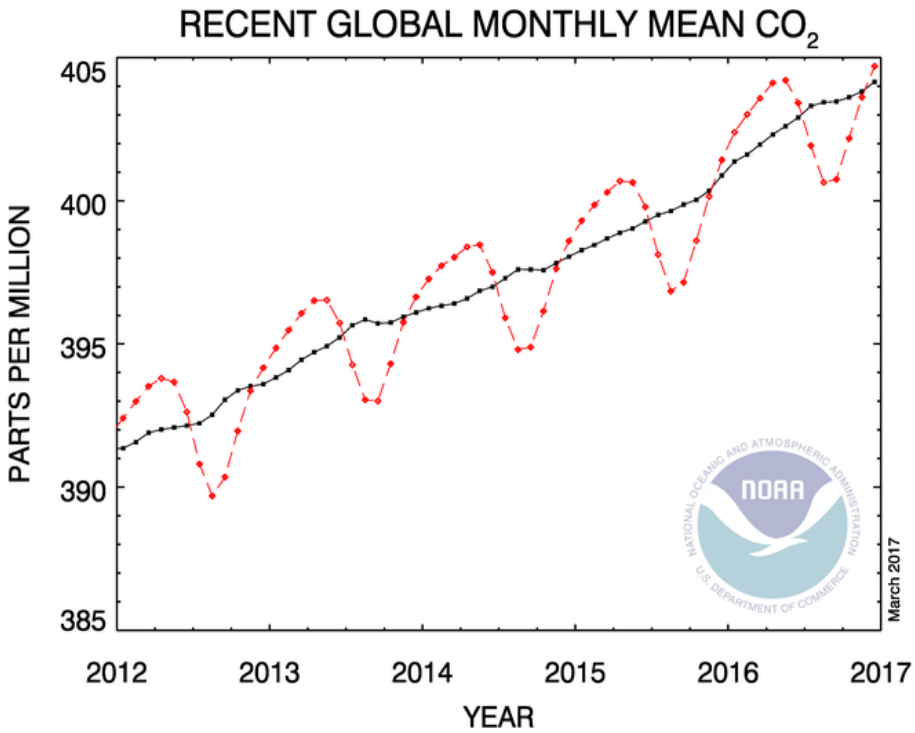

Figure 1.1: Emissions of carbon dioxide by months - red line - and by years – black line. (Source: NOAA, 2017).

As technology and knowledge have advanced, scientists and mathematicians have developed climate models to obtain climate projections. Climate models are based on the use of mathematical equations to simulate the interaction between the ocean and the atmosphere (NOAA, 2012). The Global Climate Observing System (GCOS) provides temperature data from oceans, atmosphere, the surface and space (WMO, 2014a). According to these direct observations, the average temperature at the Earth's surface is rising (NOAA, 2016).

The natural climate system is complex with many factors involved in its evolution. For this reason, it is not easy to obtain accurate projections. Climate models have been developed since the 1950s (McGuffie and Henderson-Sellers, 1999). Through the years the resolution of these models has increased, allowing better projections to be made. There are three different classes of models that

include : weather forecasting, seasonal forecasting and earth system models (WMO, 2014b). The main difference between a weather forecast model and an earth system model is the period for which the prediction is completed. Weather forecasting models are generally limited to 24 hrs to several days. Due to their longer time frame, earth system models are also able to include factors associated with the ocean, soil, carbon cycles and as well as sea ice and the atmosphere (Stocker *et al*, 2014). Climate models are completed based on simulations of interactions of the climate drivers that include various emission scenarios (Nakicenovic *et al*, 2000). An emission scenario has previously been defined by Nakicenovic *et al*. (2000) as follows:

"*A scenario is a plausible description of how the future might develop, based on a coherent and internally consistent set of assumptions ('scenario logic') about the key relationships and driving forces (e.g. rate of technology change or prices)*. "

In 2001, the IPCC published a series of emissions scenarios (SRES) for climate projections (Nakicenovic *et al*, 2000; Stocker *et al,* 2014). The future scenarios do not consider catastrophes or wars (Nakicenovic *et al*, 2000) and are classified in four categories: A1, A2, B1 and B2 (Nakicenovic *et al*, 2000). The classification was completed based on hypothetical characteristics of a future society (Nakicenovic *et al*, 2000). In 2014 the IPCC published the latest version of the emission scenarios called Representative Concentration Pathways (RCPs). These four scenarios represent the most likely trajectories of the emissions in the future and are presented in Figure 1.2.

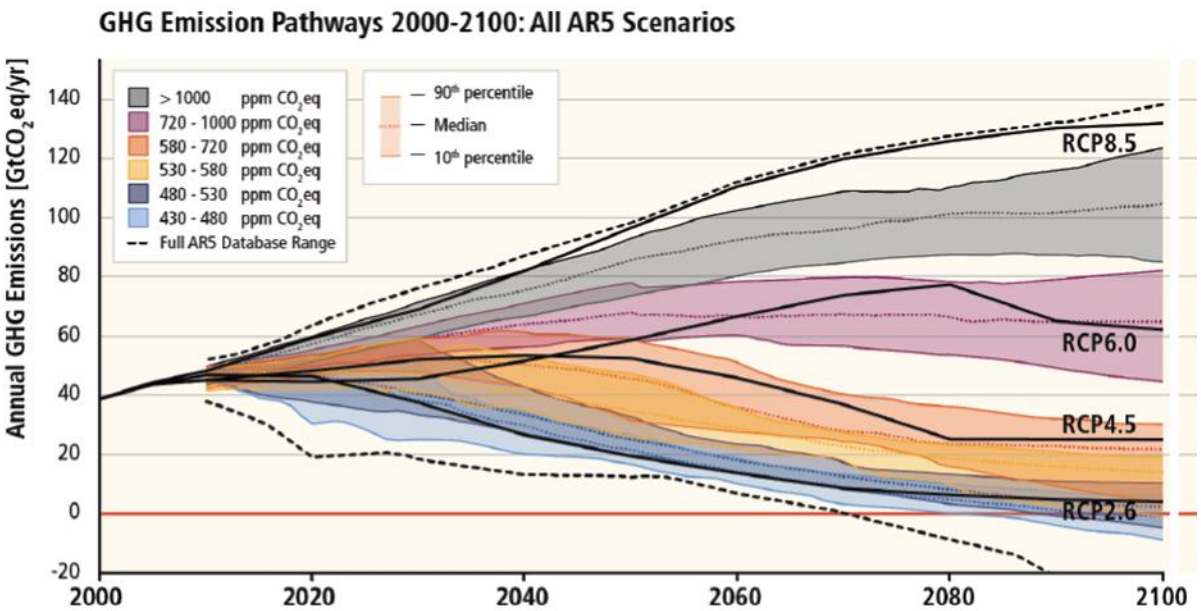

Figure 1.2: Likely paths of the emissions of $C0_2$ in the future (Stocker *et al*, 2014)

RCP 8.5 represents a continuing rise of emissions without any mitigation measures taken by society. This leads to a case in which emissions could reach up to 1370 ppm of CO_2 by 2100. Under RCP 6.0 some mitigation measures lead to a stabilization of CO_2 at 850 ppm after 2100. RCP 4.5 presents a stabilization of CO_2 at 650 ppm. The best future scenario is presented by RCP 2.6 where $C0_2$ emissions peak at 490 ppm at 2100 before they decline (Stocker *et al*, 2014).

The increase of the average surface temperature of the Earth $\geq 2^0$C (equivalent to the pre-industrial period) is considered the best-case scenario (Canziani *et al*, 2007). An increase above 2^0C would not allow human and environmental systems to adapt with large-scale irreversible damages occurring (Canziani *et al*, 2007). The threshold for CO_2 emissions to stay below a 2^0C rise in temperature is 450ppm (Canziani *et al*, 2007). Any change in our climate requires adaptation measures to be implemented through long-term planning. It is clear, that the only way to minimise temperature impacts is to reduce emissions of GHGs. This is the greatest challenge for society today to provide a similar or better environment for future generations while still maintaining population growth and energy consumption.

1.2 The Role of Uranium as an Alternate Energy Source

The level of emissions of greenhouse gases (mainly CO_2) has increased dramatically since the industrial revolution. This is owing to several factors such as deforestation, the growing use of fossil fuels (coal, oil, and natural gas) and the increasing demand for electricity by the fast-economic growth of developing countries. In this context, uranium has been argued as a potential solution because it is a lesser pollutant compared with other sources e.g. lifecycle emissions of nuclear power are 29 CO_2e/GWh compared to 888 CO_2e/GWh for coal.

1.2.1 Uranium

Uranium is a common element that is found naturally in the environment around us. It can be found in soil, water, plants, and even in our body - but in low concentrations (USADOE, 2001). Uranium in high concentrations can be found in the natural mineral Uranite. Uranium is unique because of its natural instability. It is changing continually in a process of natural radioactive decay. Through this decay process, it releases energy (USADOE, 2001). Uranium is also fissile, which means its nucleus can be divided in smaller parts when bombarded by neutrons. This property of uranium makes it suitable as fuel in nuclear reactors (USADOE, 2001); but also requires strict safety and environmental controls.

1.2.2 Global Uranium Market

The commercial market use of Uranium is composed of 445 nuclear reactors worldwide requiring roughly 75,000 tonnes of uranium oxide (U_3O_8) per year, of which 63,000 tonnes are generated from mines. These reactors have the combined capacity to generate 390 GWe (WNA, 2016) - or approximately 5.8% of the global energy demand in 2015 (IEA, 2017).

The demand for Uranium is projected to increase in the future (WNA, 2016; NEA and IAEA, 2016), due to the increased demand for electricity (UDP, 2009; Hall and Coleman, 2013; NEA and IAEA, 2016), especially in the fast- growing economies such as China and India. Growth in global demand for Uranium has been dampened since the Fukushima Daiichi incident in 2011 (Figure 2.3). The accident contributed to an increase in construction costs for nuclear power plants to account for additional safety measures, leading to higher costs of initial investment (IEA, 2011; Hayashsi and Hughes, 2013). In addition, the lack of a worldwide agreement on where to store the radioactive waste compounds start-up risks. This weaker demand has also led to a drop in the price in the last 6 years (IEA, 2011; Hayashsi and Hughes, 2013).

However, a slight increase of the global demand has been noticed, for example, in 2016 was 83,400 tonnes, 1.1 % higher than 2015 (AG, 2017). The new start-up of planned reactors in China, India and Russia will support this increase of demand; however, this increase will be offset by the closure of old reactors in Germany, Japan and Korea (AG, 2017). Figure 1.3 shows the historical trend of uranium demand worldwide and the projections for the coming years.

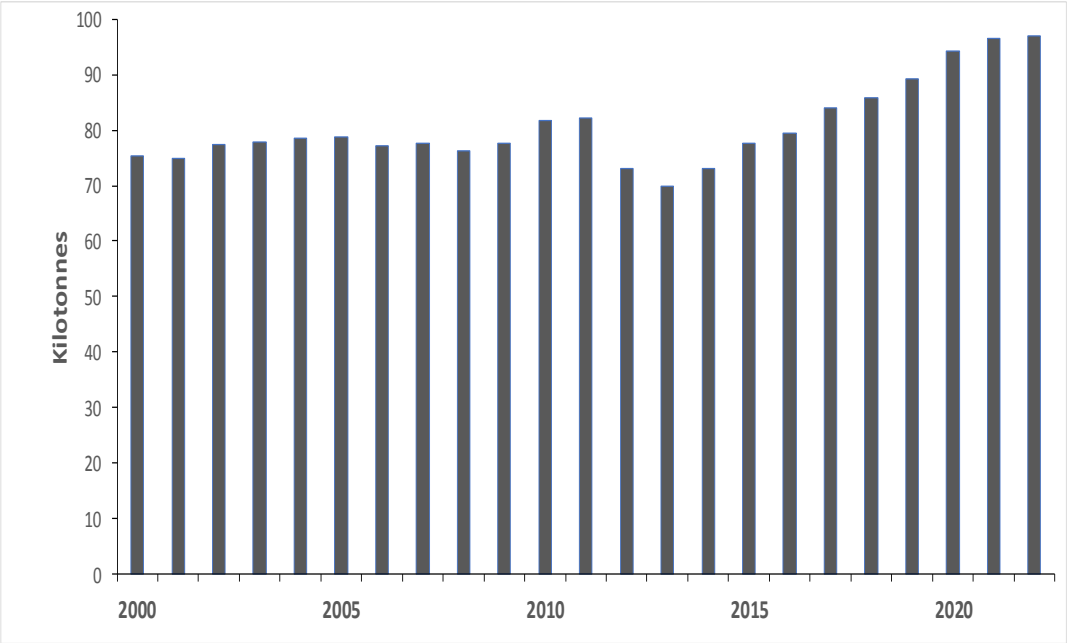

Figure 1.3: Historical trend of global demand of uranium and projections by 2020 (Based on: AG, 2017)

1.2.3 Uranium Price

The price of uranium had a small spike in June of 2015 due to China's nuclear power demand, but this small growth was limited (supplied by existing inventories) and it was not enough to reactivate the exploration activity or production in Australia (AG, 2015). An increase in the price is expected by US$27.15 to US$28.85 per pound in 201, and 2019 respectively, due to the re-start and new power plant operations in China and India (AG, 2017). For 2022, the spot price is expected to reach US$ 48 (AG, 2017). Future projections are presented in Figure 1.4.

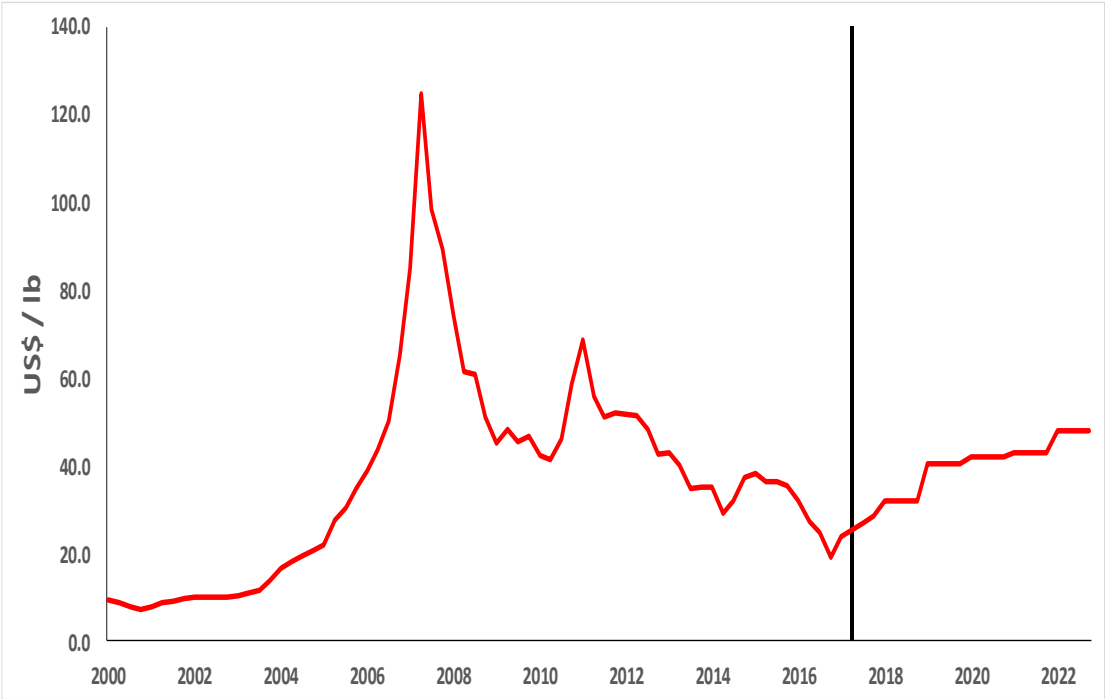

Figure 1.4: Historical trend of spot price of uranium (Based on: AG, 2017)

1.3 Australia's Position in the Global Uranium Market

The contribution of the mining industry to the Australian economy (GDP) has historically been important but has decreased from 11% in 2013 to 10% in 2014 and 8.7% in 2015 (ABS, 2015a). In 2016 it was approximately 6.9%. However, it represents 46% of the total value of Australian merchandise exports (ABS, 2016). Uranium represents a small portion of the mining industry comprising 0.8% of the total value of exports; however, it represents 16.5% of the total energy exported from Australia in 2014- 2015 (AG, 2016).

In 2016, the global production of Uranium from mines was 72,600 tonnes of U_30_8 – the equivalent to approximately 85% of the world demand (AG, 2017). The remaining demand was provided by secondary sources that include stocks of uranium from discarded nuclear weapons. By 2017, the production is projected to increase by 1.9%.

According to the Australian Government (2017), Australia was the second largest producer of uranium in 2005. Since then it has lost this position and is now the fourth producer worldwide (AG, 2017). Australia still has the largest deposit of uranium recoverable at a cost less than US$130 /kg which represents 31% of worldwide resources, followed by Niger with 10%, Canada 9%, and Kazakhstan 9% (AG, 2015; MCA, 2016). The variation of Australia's position in the global market is shown in Figure 1.5.

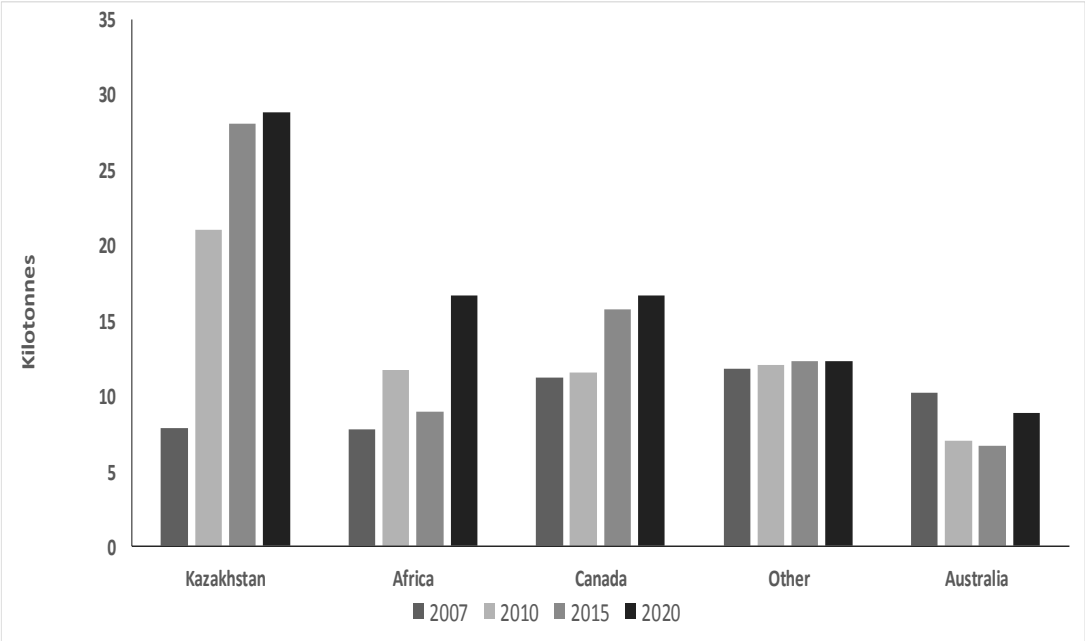

Figure 1.5: Global production of uranium by countries and Australia's position (Based on: AG, 2017).

1.3.1 Uranium Exploration Expenditure in Australia

Exploration activity can be related to the price of the commodity, thus when the price of the commodity increases the exploration spend usually increases too. After a sustained growth from the middle of the last decade, total expenditure in uranium exploration in Australia has been constantly decreasing since FY 2010-11 (ABS, 2015b). For FY 2014-15, the total amount was $40.6 million, which was 75% less than FY 2010-11 (AG, 2015). Figure 1.6 shows the expenditure trend in the period 2005-2016.

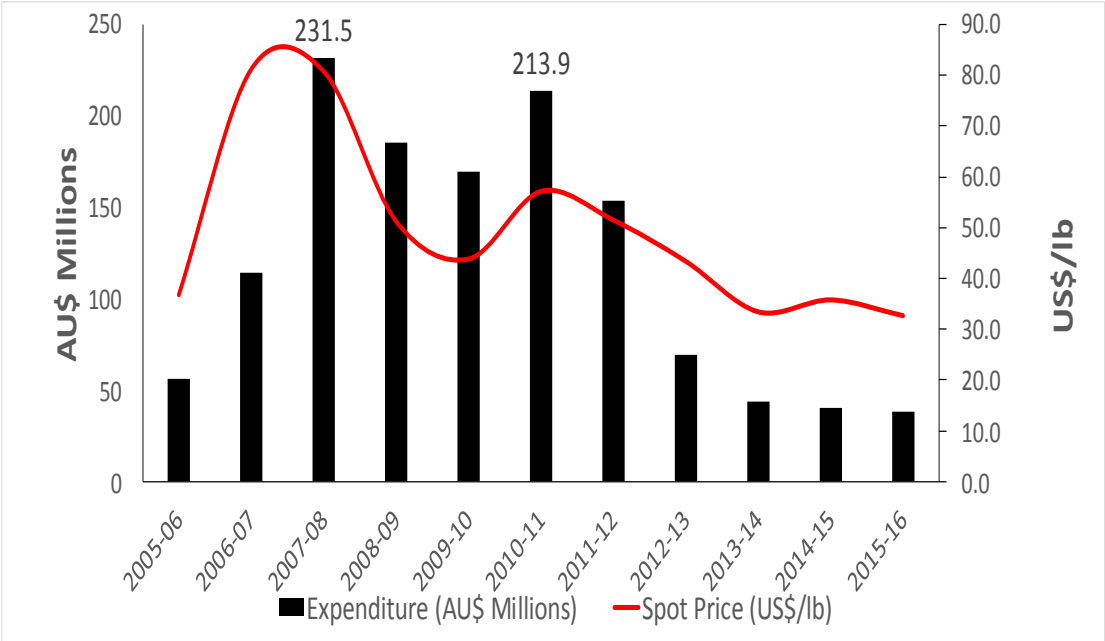

Figure 1.6: Total Expenditure in Uranium Exploration by Fiscal Year. (ABS, 2015b)

The bulk of uranium mining exploration expenditure is located in Western Australia, with a growing participation in the total of exploration undertaken in the country (albeit from a decreasing total amount). It constitutes approximately two thirds of total exploration expenditure, with an increasing share in 2015 (AG, 2015). Exploration in South Australia is decreasing, going from 25% in 2010, to only 5% in 2015 (AG, 2015). In the Northern Territory, the proportion has remained stable. Queensland has seen an increase in the past, (AG, 2015) however, expenditures decreased significantly during 2015, due to changes in policies and regulation (Table 1.1).

Table 1.1: Breakdown of expenditure of exploration in Australia

Location	2010-11	2011-12	2012-13	2013-14	2014-15
Western Australia	47.10%	51.00%	50.50%	51.50%	65.00%
South Australia	25.10%	21.50%	14.80%	3.20%	5.70%
Northern Territory	19.60%	18.90%	14.40%	19.60%	19.70%
Queensland	1.90%	3.70%	5.60%	14.60%	8.40%
Total (A$ million)	213.9	153.6	69.3	43.9	40.6

Source: ABS (2015b)

It is expected new uranium projects will be completed in Australia such as the re-open of Honeymoon mine located in South Australia and Mulga Rock in Western Australia (AG, 2017). In the meantime, the increased demand opportunity will need to be met by existing operations. Australia has many uranium deposits and Olympic Dam is the largest (Figure 1.7)

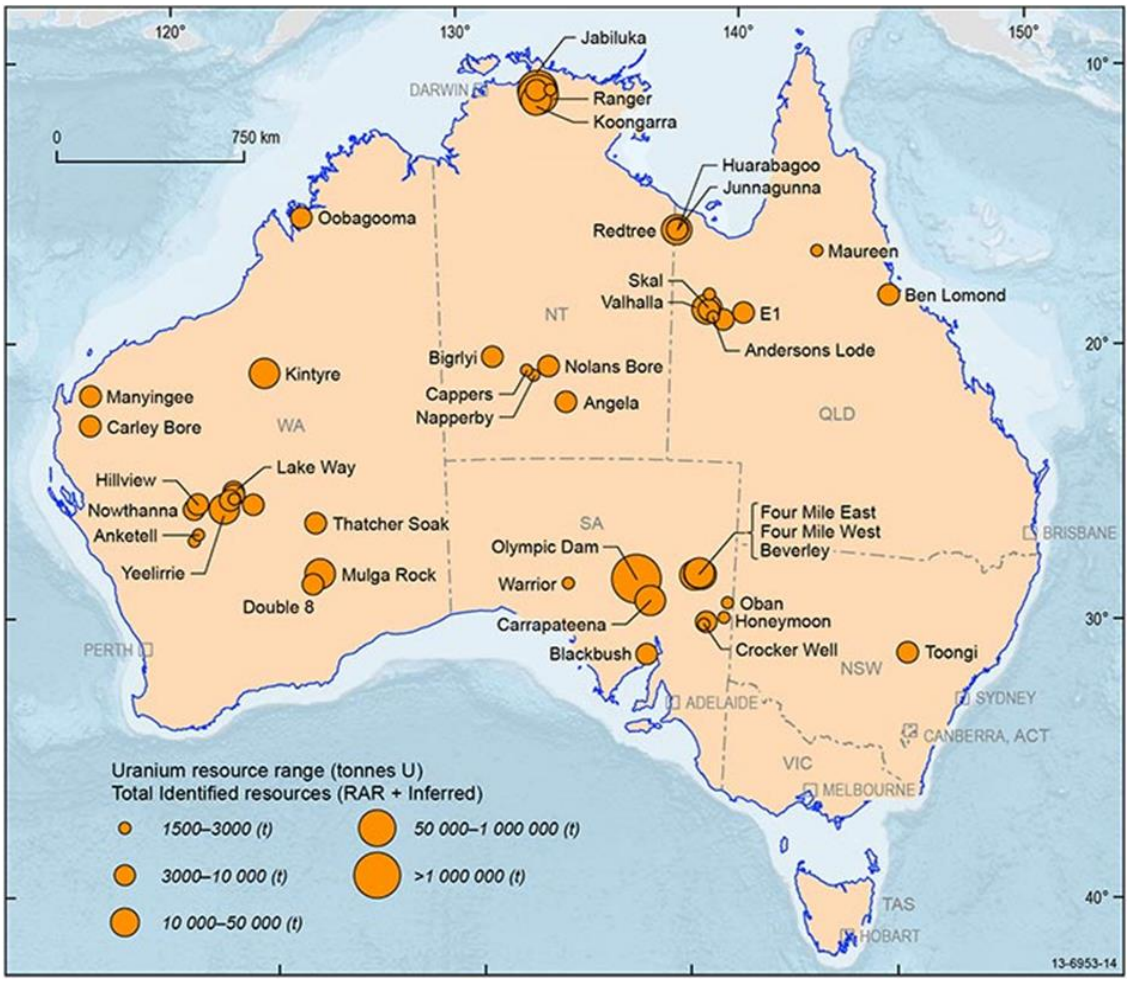

Figure 1.7: Deposits of Uranium with significant resources in Australia (Geoscience Australia, 2012)

1.3.2 Uranium Production in Australia

Australia has five uranium mines: Ranger, Olympic Dam, Beverly, Four Miles and Honeymoon. Of these, the operations of Honeymoon were suspended (owing to the low prices compared to the cost of production) in November 2013 and Beverly entered care and maintenance during April 2014. These mines contain 31% of the known uranium resources in the world and they supply 12% of uranium demand worldwide (MCA, 2016).

Table 1.2 shows the historical uranium production by mines in Australia.

Table 1.2: Historical production (tonnes) of uranium mines in Australia

	Production	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15
Ranger	tonnes	5256	5273	5678	4262	2677	3284	4313	1113	2044
Olympic Dam	tonnes	3474	4115	3974	2258	4012	3853	4064	3988	3144
Beverley	tonnes	847	707	626	630	347	413	453	188	0
Four Mile	tonnes								186	922
Honeymoon	tonnes						151	124	37	0
Total		9577	10095	10278	7150	7036	7701	8954	5512	6110

Source: WNA (2017)

1.3.3 Australian Uranium Exports

In the fiscal year 2015-2016 Australia exported 7,837 tonnes of U_3O_8, which represents an increase by almost 50% compared with the previous fiscal year 2014-2015. A small decrease on exports by 7,141 tonnes is projected for this calendar year (2016-17) (AG, 2017). The recent drop in spot prices, and the expectation of moderate price increases for the short term means the export earnings for the fiscal year ending in 2017 are expected to be lower than those in the previous year compared to 2016 (AG, 2017). Table 1.3 shows the historical trend in production and exports value since FY 2015-16 and a forecast for the coming years.

Table 1.3: Historical and future projections of productions and exports

	unit	2015-16	2016-17	2017-18	2018-19	2019-20	2020-21	2021-2022
Production	tonnes	7,665	7,141	7,850	8,450	8,550	9,200	9,800
Export value	tonnes	7,837	7,141	7,850	8,450	8,550	9,200	9,800
nominal value	A$m	959	907	995	1,064	1,105	1,186	1,252
real value	A$m	976	907	974	1,018	1,031	1,080	1,112
Average nominal price	A$kg	122.4	127.0	126.8	126.0	129.2	128.9	127.8
real d	A$kg	128.6	127.0	124.1	120.4	120.6	117.3	113.4

Source: Australian Government (2017).

1.3.4 Uranium Opportunities for Australia

The global demand of uranium for 2017 is projected to increase by 6% and is projected to keep increasing at rate of 2.7% p.a. from 2017 to 2022 (WNA, 2016; AG, 2017). This means total demand may reach 97 000 tonnes of U_30_8 by 2022 (WNA, 2016; AG, 2017). This increase is projected because there are 66 reactors under construction, 160 planned and 300 proposed (WNA, 2015). Current mines and future projects worldwide will be able to provide just a portion of this projected demand (Hall and Coleman, 2013). In 2015, the mining industry provided approximately 90% of the total demand (WNA, 2016b). The balance has been covered by stockpiles of uranium remaining from secondary sources (civil and utilities) mainly from Europe, USA and Asia (WNA, 2016b).

Despite the persistence of factors that negatively affect demand (costs of uranium extraction and enrichment, fuel designs, security issues, performance of the nuclear power plants, fuel cycle facilities and others), the consensus from industry experts is that demand will increase in the future (NEA and IAEA, 2016). This projection is based on the fact that demand is determined by the performance of the installed nuclear power plants (NPPs) and an expanding sector of global activity (NEA and IAEA, 2016). The world average energy availability factor increased to 80% during the 2000-2010 period. This led to an increase in uranium requirements. The Fukushima Daiichi incident in 2011 triggered a decline of the availability factor to 78.7% in 2011 and 73.9% on average for the period 2012-2014 (NEA and IAEA, 2016). Considering the factors mentioned above, installed capacity is forecast to increase between 418 GWe (low scenario) and 683 GWe (high scenario). This is significant compared to an installed capacity of 377 GWe in 2015 (NEA and IAEA, 2016).

1.3.5 Australian Uranium Demand Projections

Australian production of uranium decreased by 6.8% in FY 2016-17 due to operational disruptions at the Ranger Mine and Olympic Dam. A ramp-up of production is expected during FY 2017-18 (AG, 2017). This increase is supported by China and the new reactors currently under construction (AG, 2017).

Although, the medium-term scenario for Australian producers may be difficult, because of the low price of the commodity and the expiry of the current sales contracts, growth is expected (AG, 2017). This upward trend projection can be seen in Figure 1.8.

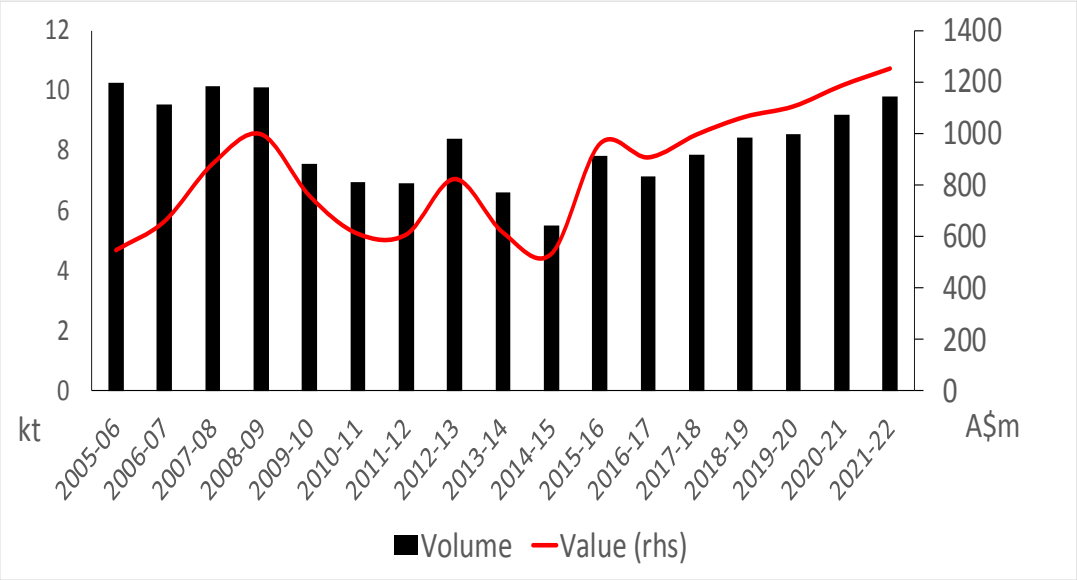

Figure 1.8: Historic exports value of uranium and projected trend up to 2019-2020 (AG, 2017)

The next section will present the research methodology, including research definition and the purpose of this research, research questions, aims, and objectives. Further, a specification of the research stages is included. The specific methodology for each stage is included in the proper chapter e.g. Chapter 6 includes the methodology for the vulnerability assessment performed in that chapter.

2 Research Methodology

This chapter provides a description of how this research was defined, the two domains of study (climate change and uranium mining), the articulation of the research questions; the aims and objectives are detailed. Further, the complete methodology employed in this research is detailed.

2.1 Research definition

The research topic was selected based on observation, natural curiosity, personal interest and providing a practical solution to a current problem. The research was (in part) inspired specifically by the dynamic climate in Melbourne – Australia. From personal observations about the environment around me, I became interested in topics that included: What is happening with the climate? Is it just here or at a global level?

Natural curiosity was a motivator to look for an explanation about what was happening with the climate. This established the first area of interest for this research that included "climate change".

I have a personal interest in the mining industry, especially in uranium mining. This personal interest was the second motivator to define my research topic. I had questions such as: Is mining important for Australia? Alternatively, Is Uranium mining important worldwide and for Australia? The initial answers for these questions helped to define the research that considers the specific topic of "Climate change related to uranium mining".

2.2 Two domains of research

This research provides a link between two study domains: climate change and the uranium supply chain, this is explained as follows. Each of the mines (Ranger and Olympic Dam) have been considered as the leading partner/coordinator in each of their supply chains (Mining group), more details in Chapter 7. Both mines have the property to contribute to reduce the carbon dioxide footprint of the whole supply chain, one of this option is by reducing their electricity consumption in their facilities which is obtained by carbon-based fuels (e.g. diesel and gas). Table 2.1 shows the breakdown of the electricity uses at Olympic Dam mine in the processing of 9Mtpa to produce 4,500 TPA of uranium oxide.

Table 2.1: Electricity consumption in the process to produce uranium oxide.

Underground mine		Concentrator		Hydrometallurgical plant	
		Input	9 Mtpa ore	Input	8.6Mt/a tailings uranium
Electricity consumption	170 Gwh/a	Electricity consumption	287 Gwh/a	Electricity consumption	43 Gwh/a
Ore extracted	9 Mtpa	Output	8.6Mt/a tailings uranium	Output	4,500 tpa uranium oxide
			0.4Mt/a copper concentrate		

Source: BHP Billiton (2009)

Furthermore, Olympic Dam uses other carbon-based fuels in its production such as diesel, kerosene, petrol, fuel oil, LPG , and coke for its operations (BHP, 2009b). Details are provided in Table 2.2.

Table 2.2: Carbon based-fuels used at Olympic Dam

Energy source	Usage
Diesel (L)	25,131,541
LPG (t)	16,950
Kerosene (L)	6,564,780
Petrol (L)	263,940
Fuel oil (t)	5,175
Coke(t)	9,940

Source: BHP Billiton (2009)

It is clear that reducing the use of carbon-based fuels that emissions can be reduced. BHP Billion has adopted different strategies to reduce its emissions (during the project design and equipment selection) such as energy efficiency, increasing productivity, adoption of low emission technologies, and creation of reduction projects such as Reducing Emissions from Deforestation and Forest Degradation (REDD+) (BHP Billiton, 2009)

Meanwhile, Ranger Mine is processing stockpiles since the pit 3 was completely mined out in 2012. The processing of lower ore grades has been associated to higher electricity consumption (Mudd,

2008). ERA has been processing (by Heap Leaching) a low-grade ore (0.10 per cent) in recent years (2015, 2016 and 2017) (ERA, 2016; ERA, 2017), however, Its GHGs emissions have increased, albeit marginally from 114 (kt CO_2) to 126 kt $C0_2$ and it is expected they will stay constant until 2020 (ERA, 2013). This increase is mainly due to the brine concentrator operation (commissioned in 2013). ERA is committed to reduce its emissions as much as possible, including the use of Life Cycle Analysis (LCA) in its production and the search for energy efficiency opportunities (ERA, 2009b; ERA, 2013f).

2.3 Research questions

To articulate specific research questions, it was necessary to look for a link between the two main domains of this research (climate change and uranium mining) as was described previously. A review of public domain literature concluded that the consequences of climate change would affect our society, industries and our natural environment (Houghton *et al*, 2001; Solomon *et al*, 2007a; Stocker, 2014). A preliminary review of corporate websites confirmed that extreme weather events have already impacted the mining industry and its associated communities in Australia (ERA, 2007a; ERA 2012). In addition, government releases of statistical data confirm the importance of the energy sector to our GDP and more specifically uranium to our export industry (AG, 2016). Given the importance of uranium as a potential solution to generate lower emission electricity (IEA, 2012) the idea to research the impact of climate change on our uranium mining industry was strengthened. The concept of supply chain emerged to be included in the research topic based on experts' suggestions in the field. This link can be summarised through the main research question for this research: "How has the uranium supply chain been (and might be) impacted by climate change in Australia?"

This research question generated a set of other research questions such as: How is the uranium supply chain structured in Australia? How can the impacts of climate change be assessed across the uranium supply chain? What are the adaptation needs and options of adaptation across the supply chain? Is it feasible to implement such adaptation options? Have adaptation options been assessed across the supply chain? Table 2.3 summarises the research questions and the area of science where they can be classified.

Table 2.3: Summary of research questions and the area where they can be classified

Research area	Research questions
Multidisciplinary	Has the uranium mining industry been impacted by climate events in the past?
Economy and Business	How is the uranium supply chain structured?
Multidisciplinary	How has the uranium supply chain been (and might be) impacted by climate change in Australia?
Vulnerability Assessment (Multidisciplinary)	How can the impacts of climate change across the uranium supply chain be assessed? Has a vulnerability assessment been conducted before?
Adaptation Adaptive Capacity (Multidisciplinary)	What are the adaptation needs and options across the supply chain? Is it possible to implement them?
Climate science (Multidisciplinary)	Have adaptation options previously been assessed across the supply chain?

From the articulation of the research questions, five main stages of this research were defined. They are summarised in Table 2.4

Table 2.4: Stages of the Research

Research questions	Research stage
Has the uranium mining industry been impacted by climate events in the past?	Analysis of reports (annual and sustainability) and vulnerability assessment of the uranium mining industry
How is the uranium supply chain structured in Australia?	Supply chain member identification
How has the uranium supply chain been (and might be) impacted by climate change in Australia?	Perform a vulnerability assessment
What are the adaptation needs and options across the supply chain? Is it possible to implement them?	Identification of adaptation needs and options across the supply chain
Have adaptation options previously been assessed across the supply chain?	Assessment of adaptation options proposed across the supply chain

The stages of this research are complementary and sequential.

2.4 Research objectives

The focus of this research included investigating the present climate vulnerability in the uranium industry and its supply chain. This included climate risks they have experienced in the past, the direct and indirect impacts that have occurred and an assessment of the present adaptive capacity.

A future scenario (with greater climate risks) was considered to assess the potential future vulnerability. This was used to investigate the variation of impacts and factors that can increase the vulnerability, resources needed to operate and the adaptive capacity of a future time.

The adaptation capacity of the uranium supply chain in Australia was also considered. Adaptation options were identified through a vulnerability assessment and an assessment of the suitability of the adaptation options was performed

The research focus is summarized by the following question:

"How has the Australian uranium industry and its supply chain been impacted by climate change in the past and how will it be impacted in the future?"

This question has been considered through a sub-set of questions that are summarised below.

- How is the Australian uranium supply chain structured?
- Has the Australian uranium industry/supply chain been impacted by climate events in the past and what will be the likely climate-impacts in the future?
- Has a vulnerability assessment of the industry and its supply chain been (or need to be) conducted?
- Have adaptation needs and options been (or need to be) identified across the Australian uranium supply chain?
- Have adaptation options been (or need to be) assessed across the Australian uranium supply chain?

This research provides a link between two mains domains, which are climate change, and uranium mining with its supply chain.

To obtain an answer for each of these questions a thorough literature review was required that spanned several disciplines. Table 2.5 provides a summary of the research aims / objectives.

Table 2.5: Summary of the research aims together with the research questions

Research questions	**Research Aims / Objectives**
Has the uranium mining industry been impacted by climate events in the past?	To explore if the uranium mining industry has been affected by climate events through a literature review and industry survey
How is the uranium supply chain structured in Australia?	Establish who are the participants in the uranium supply chain in Australia
How has the uranium supply chain been (and might be) impacted by climate change in Australia?	To identify the impacts across the supply chain and to estimate if it would be affected by climate change in the future. This was completed via analysis of annual and sustainability reports and an industry survey.
What are the adaptation needs and options across the supply chain? Is it possible to implement them?	To determine what are the adaptation needs and propose adaptation options across the supply chain
Have the adaptation options been assessed across the supply chain?	To identify what options should be implemented and in which part of the supply chain.

2.5 Outline of Chapters

Table 2.6 provides a summary of the nine Chapters presented in this thesis.

Table 2.6. Thesis chapters

	Description
Chapter 1	
Introduction	Background information about global and national uranium market.
Chapter 2	
Research Methodology	Includes a link between the two domains of research, research aims, objectives, and philosophy. The research methodology and strategy are established. Ethical considerations have been documented.
Chapter 3	
Establishment of Research Framework	Clarification of research terminology associated with the mining industry, supply chain framework and vulnerability assessment and adaption options assessment.
Chapter 4	
Australian Uranium Industry	Current conditions of the key infrastructure of the two uranium mines were established.
Chapter 5	
Establishment of the Uranium Supply Chain Participants	Some traditional supply chain stakeholders were identified, this served as basis to the identification of the other supply chain participants (18 groups were identified in the vulnerability assessment)
Chapter 6	
Vulnerability assessment	Historical literature review of the impacts of climate change and presentation of the survey distributed to mining operations. The results of the vulnerability assessment highlighted the need to study at depth the climate impacts across the entire supply chain,
Chapter 7	
Consideration of the Vulnerability Assessment of the Australian Supply Chain to Climate Change	The survey results for the supply chain participants and external stakeholders is presented. This included the adaptive capacity assessment.
Chapter 8	
Assessment of adaptation options	Adaptation needs were identified based on the vulnerability assessment and adaptation options were proposed and prioritised using Multi Criteria Analysis (MCA).
Chapter 9	
Conclusion/s	General conclusions are identified along with requirements for additional research.

2.6 Research Philosophy

The research philosophy refers to a set of beliefs and assumptions required to develop a research plan (Saunders *et al*, 2016). Saunders *et al* (2016) state that assumptions include epistemological (related to human knowledge of what is acceptable or valid), oncological (they are about the nature of realities it refers to how you see and study your research problem), and axiological (your own values in the research, or more specifically to the ethics in the research). These assumptions influence the interpretation of the research questions and the methods chosen to interpret the results of the research (Crotty, 1998).

Koro-Ljungberg and Douglas (2008) state four categories of research philosophy for studies in engineering, which include: post positivism, interpretivist, critical/emancipatory, postmodern/post structural. A summary is provided below.

- Post positivism: The main objective is to test hypothesis and establish relationships among previously known variables (Creswell, 2002). Findings or new appreciations or conclusions are not accepted during the data collection and the analysis. The sample selection is random, and the participants are selected based on the importance of knowledge provided for the research (Koro-Ljungberg and Douglas, 2008). The researcher has an independent role and does not influence the results (Koro-Ljungberg and Douglas, 2008). This perspective is characterised by a monological generalizability that refers to the application of the results (Freeman *et al*, 2007). They can be applied to anywhere, anytime, and anyone (Freeman *et al*, 2007; Koro-Ljungberg and Douglas, 2008).
- Situational perspective (includes interpretivist, critical/emancipatory, and postmodern/post structural perspective after Koro-Ljungberg and Douglas, 2008). This perspective has a common goal that is to understand one situation/phenomena through descriptions, critiques or adding information. It is accepted to obtain another appreciation or conclusions in the data collection phase. In contrast with the post positivism, participant selection is “purposeful” (Koro-Ljungberg and Douglas, 2008). The researcher’s role is more active in the data collection phase. Concerning the generalizability of the research; it is considered to be representational or generalizability only. This means that the results of the research can be generalized to other participants but only through the same context.

Table 2.7. provides a summary of the philosophies of research in engineering.

Table 2.7: Research philosophies for a research (based on: Koro-Ljungberg and Douglas, 2008)

		Situational Perspective			
Theoretical perspective	Positivism/Post positivism	Interpretivist	Critical emancipatory	Postmodern/ Post-structural	Pragmatism
View of the reality (Oncological)	Single reality/find relationships between known variables	Multiple subjective realities to describe a situation or phenomena	Multiple subjective and political realities in socio-political context to produce a critique	Multiple fragmented realities in historical context	Reality is practical based on experiences and practices
Methods (Epistemology)	Methods and variables are defined previously	Methods and approaches are defined during the research	Methods and approaches are defined to capture inequities	Methods and approaches are developed during the research.	Methods are developed according to the needs of the research
Researcher's role (Axiology)	Independent of the data collection or result	Participant and researcher are partners	Participant and researcher are activists	Various changing roles	Reflexive role. Research is supported by the beliefs and doubts of the researcher
Results of the research	General or context free	Focalised	Critical to policy changes	Reconceptualised descriptions of a phenomena	Practicality-focalised

Source: Saunders *et al* (2016).

There is a fifth philosophy included by Saunders *et al* (2016) which is Pragmatism, which is also described in the previous Table. This philosophy refers to the improvement of practical knowledge in specific contexts. A researcher with this philosophy begins the research with the problem defined, and the research is targeted to solve the problem and contribute to solutions. The role of the researcher is reflexive, and the research is supported by his/her beliefs, values and doubts. The results of this philosophy are targeted to the practical solution of the research problem, so it is focused. For each of the research aims/objectives, each stage required a different philosophy.

A summary of each section is provided below.

- **Identification of uranium mining supply chain members**

  This stage had a mix of the two philosophies (Interpretivist and Pragmatism) since the information was categorised from a practical perspective (based on experience, information, and practices). The methods for reviewing company reports were developed during the research and adapted according to needs.

  The role of the researcher was participant and reflexive. I.e. The researcher's knowledge, information or beliefs supported research development at this stage. The results of this stage were practical and focalised on the uranium mining industry and the supply chain in Australia.

- **Vulnerability assessment**

  This stage also had a mix of the two philosophies (Interpretivist and Pragmatism). Data at this stage was interpreted based on social/cultural aspects and by the participants based on their practical experiences and/or knowledge. The methods (surveys) in this stage were defined during the research and constructed to ensure data was obtained from a practical perspective.

  The researcher's role was participant and reflexive since the vulnerability assessment was based on the reflections or knowledge acquired in the literature review.

  The results of this stage were focused on the uranium mining industry and its supply chain in Australia.

- **Identification of adaptation strategies**

  The research philosophy focused on Pragmatism at this stage, since the reality was based on the practical experiences of the participants. The methods (based on survey results) at this stage were defined during the research and the role of the researcher was reflexive since I was looking for a practical result in a specific context.

- **Evaluation of adaptation strategies**

  This stage focused on a Positivism/Post positivism perspective since analysis of the adaptation strategies was based on previously defined tools. The researcher did not have influence over the results. Since the results were focused on the uranium supply chain in Australia, they are not generalizable to other industries; however, the methodology employed can be used in other contexts.

In conclusion, this study had mostly a Pragmatism philosophy of research with methods developed during the research to provide a practical purpose. The researcher had an active role in most of the study. The study did not include the development of a theory due to the purpose and practical nature of the study.

2.7 Descriptive Research Design

According to traditional criteria, research in engineering can be classified in two mains groups that are descriptive research and experimental research (Olds *et al*, 2005). Descriptive research uses commonly qualitative, quantitative or a mixed methodology in the development of the study; experimental research employs mainly a quantitative methodology (Olds *et al*, 2005).

Descriptive research is commonly used to study one topic that has not been studied previously or where there is a limited range of studies (Borrego, 2009). Descriptive research employs statistical concepts such as medians or standard deviations to study or describe one topic. Descriptive studies do not establish any relationship between groups of data or indicators (Borrego, 2009). Data is mainly gathered from surveys, interviews and other ways of text data collection (Olds *et al*, 2005).

Based on the limited existing data and literature associated with the current research this research can be classified as exploratory and practical research because it will seek to answer the research questions from a practical perspective. This is in contrast to basic research that intends to develop new knowledge through theories (Graveter and Forzano, 2015).

2.8 Methodological Selection

The most common methodological approaches in research are quantitative, qualitative and mixed methods (Saunders *et al*, 2016).

A **quantitative methodology** has a hypothesis that guides how the data will be collected through laboratory experiments (Creswell, 2013). These data are analysed with statistical tools and concepts. The experiment's results allow us to draw conclusions and inferences (Borrego, 2009).

A **qualitative methodology** employs text data as well as analysis to answer research questions (Old *et al*, 2005). The data set can be collected by surveys, focus groups or interviews, observation, conversational analysis, meta-analysis and, ethnographic studies (Borrego *et al* ,2009; Olds *et al*, 2005).

A **mixed methodology** has been classified as a "third methodological movement" by Tashakkori, and Teddlie, 2003. Its legitimacy is subject to debate. Authors such as Howe (1998) see an "incompatibility

of thesis" in this method. Johnson and Onwuegbuzie (2004) claim that "qualitative and quantitative cannot be mixed" reinforcing the paradigm between the two methodologies. Holistically, a mixed research methodology uses a combination of quantitative and qualitative data and integrates them during an analysis phase (Creswell *et al*, 2003; Creswell and Clark, 2007; Borrego *et al* 2009). Creswell (2013) defined a mix method of research as follows:

"A mixed method of research involves the collection or analysis of both qualitative and quantitative data in a single study and involves the integration of data at one or more stages in the process of research".

The mixed methodology of research has been employed in this study. E.g., a quantitative method has been used to analyse company reports (annual and sustainability) and part of the responses obtained from the survey. Survey responses also contain text data, thus requiring the use of a qualitative method. The identification of industry participants and supply chain members has employed mainly qualitative data.

In the mixed methodology of research, Creswell *et al* (2003) identified four subcategories that include triangulation, embedded, explanatory, exploratory and quantitating. These subcategories are based on the timing of collection and the integration of both data - quantitative and qualitative (Morse, 2003). They are briefly described below and summarised in Table 2.6.

Triangulation

Triangulation corresponds to the joint collection of quantitative and qualitative data, for the purpose of offsetting the weaknesses in each of them (Saunders *et al*, 2016). Data for both methods can be collected at the same time or concurrently. The integration phase is performed in the analysis or interpretation of both methods and is addressed to respond the research question.

Embedded

This data collection can be concurrent or sequential - one kind of data serving as a complement to the other (Borrego *et al* 2009). Creswell and Clark (2007) state that research can be called embedded if the second data source does not make any sense without the first set of data.

Explanatory

In this case, data collection is sequential - quantitative data is collected first. This phase is usually lengthy and completed before the qualitative data collection. Usually, the analysis of quantitative data is used to feed the quantitative phase (Borrego *et al*, 2009; Creswell and Clark, 2007).

Exploratory

Data collection is sequential - qualitative data is collected first and has priority. However, the results are provided in quantitative form. The first qualitative phase is used to prepare the second quantitative phase. This model, design or strategy is often used to create a standard instrument in a new area (Borrego *et al* 2009).

Quantifying data

This refers to the transformation of qualitative data into quantitative data for statistical analysis. More specifically the term "quantizing" means to assign codes to the qualitative data for the analysis. It is a technique used to merge both kinds of data (Tashakkori and Teddlie, 2003).

Table 2.8: Categories, timing, weights and mixing process in research methods (adapted from Borrego *et al*, 2009).

Category	Timing	Weights assigned Quantitative Qualitative	Mixing phase
Triangulation	Concurrent	Equal	Interpretation or analysis
Embedded	Concurrent-sequential	Unequal	One phase is embedded in the other
Explanatory	Sequential; quantitative > qualitative	Quantitative has priority	Quantitative informs qualitative
Exploratory	Sequential; quantitative > qualitative	Quantitative has priority Qualitative	Qualitative informs quantitative
Quantitizing	Sequential; quantitative > qualitative	Qualitative has priority	Conversion of qualitative into quantitative

The classification of the stages of this research according to the nature of the data collected has been described below:

Industry participants and supply chain member's identification:

Data collection in this stage was text (qualitative). The relative priority was sequential with respect to the next stage.

Vulnerability assessment:

Data collection in this stage was both text (qualitative) and quantitative. The analysis completed was quantitative in nature. The relative priority in this stage was concurrent or sequential. This stage had sequential relative priority respect to the adaption needs stage.

Identification of adaptation needs:

Data derived from the previous stage and analysis were both qualitative with a relative concurrent priority. This stage had sequential priority respect to the next stage; assessment of adaption options.

Assessment of adaptation options:

Data derived from the previous stage is qualitative, but its analysis is quantitative. A concurrent data collection with equal relative priority was performed at this stage. Both kind of data were integrated in the analysis.

Table 2.9 shows the methodological choice for the stages of the research.

Table 2.9: Methodological choice (kind of data, timing, priority, and integration) for each stage of this research

Project phase	Kind of data	Timing data collection	Relative priority	Total priority	Integration phase	Subcategory
Has been the uranium mining industry impacted by climate events?	Qualitative and Quantitative	Sequential	Qualitative prior to Quantitative	Concurrent	Interpretation of data and analysis	Exploratory
Vulnerability Assessment both cases (industry and supply chain)	Qualitative and Quantitative	Sequential	Qualitative prior to Quantitative	Sequential to the previous stage	Interpretation of data and analysis	Explanatory
Identification of adaptation needs	Qualitative	Concurrent	Equal	Sequential to the previous stage	Data analysis	Triangulation
Assessment of adaptation options	Qualitative and Quantitative	Concurrent	Equal	Sequential to the previous stage	Data analysis	Exploratory

2.8.1 Data Collection

While all the data collected in this survey could be codified in numerical values, two distinctive differences between the responses have been characterised. Quantitative data can be of two categories: categorical and numerical (Brown and Saunders, 2007). Categorical data is data whose numerical value does not represent the measurement of a quantity, but rather the belonging to a set (Descriptive) or the position in a rank order (Rank) (Brown and Saunders, 2008). If the number of sets

can be no higher than 2, then categorical data is defined as Descriptive (Dichotomous); if the possible sets are more than 2 then the definition is Descriptive (Nominal) (Brown and Saunders, 2008). If the sets can be ranked, then the variable is called Ranked (Ordinal).

In contrast with categorical data, for numerical data, numbers represent a measure of an attribute or characteristic (Brown and Saunders, 2008). This characteristic makes numerical data more precise than categorical data since it is possible to assign a position in a value scale and uses a broader number of statistical methods to analyse them, as opposed to categorical data (Saunders *et al*, 2016).

Numerical data can be divided into two categories, depending on the nature of the relationship between two data values. If the relative difference between two data values can be estimated, then the data is defined as a Numerical Ratio. If the relative difference between two data value cannot be estimated, then it is defined as Numerical Interval. A second description corresponds to the units of measurement of the data. If the data can theoretically assume any value within a given interval, then the data is of a Continuous Nature. On the other hand, if it can only take some values (like integers) only, then the data is defined as Discrete.

According to these definitions, several data types were collected in the current research survey. For example:

Question 1 which asked the kind of company the respondent works for. The answer was a set of Dichotomous variables, since the respondent had to state whether they belonged (or not) to each organisation.

When participants were asked to specify their role in the company, or the geographical location of the company (by state), the answers were mutually exclusive, so the data corresponded to a Descriptive Categorical type.

When participants were asked to rate the risk exposure of their companies, or the impact of climate events from Low to High on a scale of 1 to 10, these responses correspond to a Ranked (Ordinal) data.

With regards to numerical data, examples of interval data obtained in this study are: years of experience, frequency of climate events, or years living in the area. In all these cases, the responses were given or established in discrete intervals.

2.8.2 Analysis of Data

The data was collected through an online survey. SurveyMonkey integrated the data collected through basic statistical concepts (percentage, average rating, and average ranking). To provide further analysis, the data was processed using the IBM SPSS statistics software, coding the categorical and numerical data as explained below:

Coding Categorical data: Dichotomous data was coded as 1 if respondent selected (ticked) the option, and 0 otherwise. This was very useful for analysing the proportion of respondents who selected any particular option, by adding a sequence of 0s and 1s, and dividing by the total number of respondents.

Nominal data was coded by assigning numbers to every category (i.e. country of residence). These variables were used in most instances to divide the sample in units of analysis, to inspect the behaviour of other variables.

Ranked (Ordinal) data was directly recoded form the participant´s respondents. These ranks were averaged, to compare the results within groups and categories.

Coding numerical data: For interval data, some variables (like years of experience or living in the area) were recoded to categories, by dividing the total range of answers in several segments. For example, years of experience was converted into three categories: 1 to 10 years; 11 to 20 and 21 or higher.

2.9 Research Strategies

Research strategies include experiment; surveys; interviews; archival and documentary research; ethnography; action; grounded theory; narrative inquiry; and case study (Saunders *et al*, 2016). The research strategies used in this study to link between the research philosophy, data collection, and the analysis (Denzin and Lyncoln, 2005) are summarised below.

- **Archival and documentary research**: This strategy refers to information obtained from various sources such as the internet; libraries; government and other organisations or sources. Documents obtained in this way are considered secondary data sources (Saunders *et al*, 2016). This strategy was employed in the first stage of this research where the uranium industry stakeholders were identified. Information was obtained from websites, companies' reports, government reports, and previous research related to uranium mining.
- **Case study**: This strategy refers to studying similar scenarios in context that can help to develop research ideas in the exploratory phase or develop research strategies in a posterior phase of the research (Saunders *et al* 2016). This research strategy was used to explore what

has been done in the uranium mining field related with climate change and vulnerability assessment e.g. Canadian mining study to understand the vulnerabilities to climate change of the industry (Pearce *et al*, 2009, Pearce *et al*, 2011).

- **Surveys**: Commonly used in descriptive and exploratory studies (Saunders *et al*, 2016). Surveys are used to gather data that cannot be observed (Olds *et al* 2005). To create a useful survey can be a difficult, time consuming task (Olds *et al* 2005). However, the main inconvenience with this data collection tool is the quality of the information that respondents provide (Olds *et al* 2005). The quality of the data depends on the honesty, knowledge and accurately of each individual. Validation of a survey can be completed by an expert in the field (Olds *et al* 2005). Data collected from a survey is considered a primary data source. Due to the lack of data associated with this research topic, a survey was used as the main research strategy for the evaluation of the vulnerability in both cases (uranium industry and the supply chain).

2.10 Time Horizon

In this study, the research question posed is "How has the uranium supply chain been affected/ and will be affected by climate change?"

The answer to the research question (and to the other research questions) involved the longitudinal concept of time because it mentions how was (in the past) and how will be (in the future). Longitudinal refers to a series of snapshots in time associated with what is being studied (Saunders *et al*, 2016) and allows the study of changes and development through series of data sets (Saunders *et al* 2016). The survey has been able to indicate changes which overtime might save time and costs (Jensen and Laurie, 2016).

2.11 Ethical Considerations

There are ethical issues when research involves data collected from organisations or individuals (Saunders *et al*, 2016). Ethics in this context primarily refers to the researcher's conduct in relation to the rights of participants of the research (Saunders *et al*, 2016).

This research employed a survey and the following ethical considerations were made:

- Voluntary participation
- Avoid harm
- Privacy and confidentiality of responders
- Responsibility in the data analysis and publication of findings

- Provide enough information about the research to the participants
- Consent of participation

These considerations were resolved through the provision of an explanatory statement, consent form and permission letter.

- **Explanatory Statement:** Provided a full explanation about the research that included: why we were conducting a survey, who was invited to participate, confidentiality and privacy of the participants, the responsibility of data analysis and results, publication of findings and, future data storage.
- **Consent form:** Explicit form in which the participants provide their consent to participate in the survey.
- **Permission letter:** Provides access to the researcher within an organisation to recruit participants for the survey.

All the guidelines mentioned above (and others) are considered in the Ethics approval **(CF15/3814 – 2015001668)** from Monash university, thus this research will need to fulfil the requirements of the Monash University Ethics Guidelines.

Further, ethical issues also included data analysis and storage. It was compulsory to assure confidentially and anonymity to the participants in this stage (Saunders *et al*, 2016). In this research, the set of data was limited to the research student, and supervisors. Survey responses were anonymous and will remain confidential. Only the analysis of aggregate responses was published which makes it impossible to single out responses from an individual.

2.12 Reliability and Validity of the research

Reliability and validity are criteria used to evaluate the quality of research. According to Saunders *et al* (2016), reliability is related to the consistency and replication of the research. This can be both internal and external.

Internal reliability refers to the consistency of the research. This can be achieved with more than one researcher in the study, with both collaborating to conduct the surveys and analysis (Saunders *et al,* 2016). The research team herein was composed of three experienced researchers and the Ph.D. Candidate.

External reliability refers to the techniques employed in the data collection and the analysis. Are they new? Have they been used in other research to ensure consistent findings? To obtain reliable results the selection of the survey participants was based on the Delphi subject definition provided by Hsu

and Sandford (2009) (after Pill, 1971; Oh 1974). These authors suggest that a participant in a study should have a background and experience related to the target issue, so they would be able to make a worthy contribution to the study. Additionally, Delbecq *et al* (1975) suggested the following characteristics of a valuable respondent: top manager, in a decision-making position or professional staff member within their teams. All these characteristics were sought in the participant selections for the survey.

Reliability of the survey results was also ensured through the consideration of the issues summarised below.

- **Error made by participants**: Includes any action or factor that can diminish the worth of the participation of a respondent, e.g. a request to complete a survey right before going home. This kind of error was minimized through providing appropriate time (months) to request the completion of the survey.
- **Partiality of participants:** Includes any action or factor that can lead to false responses. This factor was reduced by ensuring the full anonymity of respondents and their responses.
- **Mistakes of the researcher:** Includes any action or factor that can influence the interpretation of the results. The results of this research were interpreted impartially, nothing was suggested, nor were conclusions drawn prior to completing the research. The data was also reviewed independently by four researchers to provide conclusions.
- **Partially of the Researcher:** Includes influence or the opinion of the researcher. For example, guiding the survey to obtain a response that fits the researcher's point of view. In this case the survey was delivered by email (and answered at the convenience of the respondent) so there was not any chance to influence the responses.

Validity refers to the suitability of the measures employed, and the exactness and generalization of the results obtained (Saunders *et al*, 2016). Three criteria are considered with respect to measurement, internal and external validity. They are considered below in relation to this research.

- **Measurement validity**: Refers to the suitability of the measures employed to assess what is being studied. In this case, a panel of three experts in the field participated to assess the appropriateness of the questions in the survey (content validity).
- **Internal validity**: Is established when a *causal relationship* between two variables can be found to obtain a result. Validity can be proven if "*a set of questions can be shown statistically to be associated with an analytical factor or outcome"* (Saunders *et al*, 2016). Evidence of these correlations can be found in several instances of this study. For example, when we divided responses by groups, each group responses were on average significantly different from that

of the rest of the sample (p values < 0.05). This indicated that the variable used to classify the respondents in groups was correlated to their responses.

- **External validity**: Is related to the generalization of results in terms of replicating the research in other contexts or areas. The approach of this research can be generalised to other groups (other industry in another country) in the same context (climate change) by changing the appropriate items.

Several additional factors that can affect the validity of research (described by Saunders *et al*, 2016) were also considered and are described below.

- **Past or recent events:** Any reason or event that can change the perception of the participants. E.g. a major storm event during participation in the survey. This factor is beyond the control of the survey.
- **Future consequences:** The perception of the participants can be altered if they believe their participation in the research may have future consequences associated with their jobs. This factor was minimized through anonymous responses and completing an aggregated data analysis.
- **Instrumentation:** Changes in the techniques or tools between stages of research can lead to a complicated process during results comparison. There were no changes of instrumentation in this research.
- **Withdrawal:** When a research participant changes job it can impact the study. In this case, this factor is not relevant, since every likely participant was working in the area at the moment of invitation to complete the survey.
- **Unexpected changes:** Various reasons out of the study scope can change the perception of the participants. For example, training provided by the company. This factor is not relevant, because of the relatively brief period required to complete the survey.

More details about the survey preparation and design can be found at Chapter 5, sections 5.2 and 5.3.

3 Establishment of Research Framework

The research framework has been developed based on a review of exiting literature that is presented in Appendix I. A summary is provided below.

3.1 Value Chain versus Supply chain

Finding a suitable definition, boundary and scope between the two concepts of value chain and supply chain for this project has been challenging. Sometimes the two terms are confused because the chains of activities often overlap each other. In many cases, they are complementary and interact with the same goal, which is to produce goods or services (Feller *et al*, 2006). It is not always clear where one finishes and the other one starts (Velthoen, 2013).

'Supply chain' and 'value chain' can be considered an extension of the company because they are part of the business (Feller *et al*, 2006). Supply chain is commonly associated just with the logistics and transportation of a product between one place to another (Mudulli and Barve, 2011). Recently it has been associated with supply chain management that includes other aspects such as social and environmental issues (Mentzer *et al*, 2001).

The concept and analysis of the value chain comes from Porter (1998). Porter suggests that, instead of looking at the firm as a static figure it should be looked as:

"*A collection of discrete activities a firm performs in designing, producing, marketing, delivering, and supporting its product*".

A value chain analysis looks at these activities, in terms of their behaviour, the costs they generate, and the way these can be diminished or the potential for differentiation from competitors. In this analysis of the value chain, the company is seen as a system composed of subsystems. Porter argues that a company can be divided into subsystems with inputs and outputs in each step of the subsystem. Furthermore, Porter (1988) classifies the activities in a company into a primary and a secondary group of activities. Porter, states that all activities in a company are interrelated and thus the way one of these activities perform will affect the others. By optimizing the performance of each subsystem, the optimization of the company is achieved (Porter, 1998).

Nowadays, it is common that a company's value chain crosses the boundaries of the company and even the country, owing to globalization (Sturgeon, 2001). This concept is evolving, and this could be the reason that the definitions are not yet clear (Feller *et al*, 2006).

Some authors (Noemi, 2012; Christopher, 2016) considered that the direction/objective of the supply chain is from the source to the client. In contrast, the direction/objective of the value chain is from the customer to the source -in terms of demand (Feller *et al*, 2006). Feller *et al* (2006) differ from Mentzer *et al* (2001) in the use of terms downstream and upstream. Feller *et al* (2006) use the term "upstream" referring the group of suppliers and producer process and downstream referring the creation of value for the client-which they also define as value chain. However, Mentzer *et al* (2001) define upstream referring to suppliers and downstream referring to distribution. Nonetheless, they coincide in the direction of both chains. See Figure 3.1.

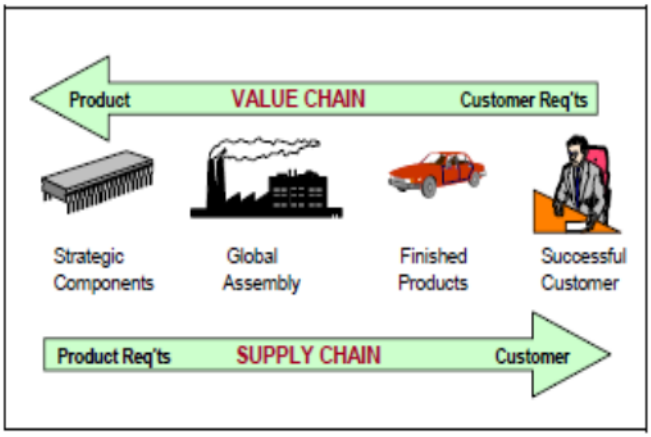

Figure 3.1: Different focus of supply chain and value chain (Feller *et al*, 2006)

The main difference between value chain and supply chain is the fact that in the value chain there is value added for the product or service in each step. When supply chain is considered there is no value added or physical modification to the product (Velthoen, 2013). Furthermore, the supply chain can be seen as the way to access to the value chain.

Since this research is not focused on the uranium production stages (where there is a value added from the raw material to the final product U_3O_8) but is centred on the chain of activities without physical change of the product, this research will be focused on the supply chain only.

3.2 Supply chain definition

Prior to the 1980s, companies used to work separately from their suppliers, which were not considered as important or key partners by the company. The idea of an integrated supply chain (suppliers) was born first in the U.S textile and grocery industry (Lummus and Vokurka, 1999). Owing to the high competitive textile market, the industry ordered an analysis of its supply chain (from raw material to final consumer). The study showed that most of the production time was actually consumed in

"waiting time" in warehouses or in transit, which resulted in economic losses for the industry (Lummus and Vokurka, 1999). As a result of this study a Quick Response (QR) strategy was created which consisted in the adoption of a partnership way of work between retailers and suppliers with the purpose of responding efficiently to consumer needs by sharing information (Lummus and Vokurka, 1999). Since the results of this study the focus of the supply chain changed from the suppliers to the customer. In the 90s, the supply chain was defined by the APIS Dictionary as follows:

"*the processes from the initial raw materials to the ultimate consumption of the finished product linking across supplier-user companies; and the functions within and outside a company that enable the value chain to make products and provide services to the customer*" (Cox *et al*, 1995)

Since then, several definitions for the supply chain have been coined in research and in practice (Cox *et al*, 1999; Mentzer *et al,* 2001; Sherer, 2005; Stock and Boyer, 2009; Mudulli and Barve, 2011; Lu, 2011; Noémi, 2012; Christopher, 2016, and others**)**. Table 3.1 provides a summary of some definitions of the supply chain present in the literature.

Table 3.1: Concepts and definitions of supply chain in the present literature.

Authors	Concept/ Definition
La Londe and Masters (1994)	"the set of firms which pass these materials forward can be referred to as a supply chain"
Cox *et al* (1995)	"the processes from the initial raw materials to the ultimate consumption of the finished product linking across supplier-user companies; and the functions within and outside a company that enable the value chain to make products and provide services to the customer"
Aitken (1998)	"A network of connected and interdependent organisations mutually and co-operatively working together to control, manage and improve the flow of materials and information from suppliers to end users"
Cox (1999)	"The operational supply chain refers to the series of primary and support supply chains that have to be constructed to provide the inputs and outputs that deliver products and services to the customers of any company."
Mentzer *et al* (2001)	"…a set of three or more entities- organizations or individuals- directly involved in the upstream and downstream flows of products, services, finance and/or information from a source to a costumer…"

Authors	Concept/ Definition
Sherer (2005)	"Supply chain is a term now commonly used internationally – encompasses every effort involved in producing and delivering a final product or service, from the supplier's supplier to the customer's customer."
Stock and Boyer (2009)	"it is a network of relationships within a firm and between interdependent organizations and business units consisting of material suppliers, purchasing, production facilities, logistics, marketing, and related systems that facilitate the forward and reverse flow of materials, services, finances and information from the original producer to final customer with the benefits of adding value, maximizing profitability through efficiencies, and achieving customer satisfaction."
Mudulli and Barve (2011)	… a green supply chain as all phases of the product's life cycle, from the extraction to raw materials through the design, production, and distribution phases, to the use of the product by customers and its disposal at the end of the product's life
Lu (2011)	"A group of inter-connected participating companies that add value to a stream of transformed inputs from their source of origin to the end products or services that are demanded by the designed end consumers."
Noémi (2012)	"supply chain as the processes of cooperating companies that are aimed at creating value based on the existence and development of trust."
Walker *et al* (2007)	They conceptualised the supply chain as upstream participants (clients and end user), downstream participants (suppliers, contractors, and consultants), and a coordinator partner (company).
Christopher (2016)	The supply chain is the network of organisations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate consumer

Finding the proper definition of a supply chain for this study was a challenge due to the myriad definitions found in the literature: *there are as many definitions as many of those who care to write about it* (Lu, 2011). A lack of consensus exits about the supply chain definition, however, the majority of the authors agreed that concept has originated from a strategic and operational perspective (Cox, 1999). Furthermore, researchers seem to agree that the integration of stakeholders and proper management can provide a competitive advantage (Sherer, 2005; Walker *et al*, 2007; Stock and Boyer, 2009).

Different factors have been considered by authors to provide a definition of supply chain such as the flows within a supply chain, the orientation of the chain, the structure of the chain, and the scope or domain (groups participants) of the chain.

The definition of flows within the supply chain has been one of the trend in this field, previous to 80s the flow of materials or products was the main flow considered to define supply chain since then up to four flows have been defined (Mentzer *et al,* 2001; Lu, 2011). Lu (2011) defines four types of flows in the supply chain: material flow (manufacturing chain from raw material to the end product); information flow (e.g. demand information, market forecasts, production schedules, etc) this flow can have both direction upstream and downstream; finance flow (customer is the source of this flow); and commercial flow.

Some authors based their definitions on the linear flow of materials and communications between suppliers of a firm (La Londe and Masters, 1994; Cox, 1999; Aitken, 1998; and Mentzer *et al*, 2001). However, nowadays the linearly of flows within supply chains is not always true, especially in the complex production of technological products (Sherer, 2005).

Numerous authors include the orientation of the supply chain in their definitions. Since the 1990s, most companies changed their supply chains orientation to focus on the customer because they estimated that the only way to achieve competitive success is by turning customer necessity into a virtue and giving the highest level of quality to the customer, as well as being flexible to satisfy the customer demand (Cox, 1999). It is well recognised the importance of the customer's needs however an important exception has been highlighted: there are some companies such as Microsoft or CISCO having the property to dominate the customer's needs which allows them to forego the search for the customer's delight (Cox, 1999).

However, in academia some authors pose the direction of the chain from the supplier to the customer (Aitken, 1998; Mentzer *et al*, 2001; Christopher, 2016) while others do it from the customer to the suppliers (Sherer, 2005, Walker *et al*, 2007). This differentiation of direction or orientation of the supply chain is based on the importance for the author(s) of the type of flow considered in the definition. For example, Sherer (2005) agreed that communication (by sharing information) is seen as a competitive advantage. However, she emphasised that communication flow is concurrent and not sequential, and it is shared by many nodes of the chain at the same time. In the past, communication resources limited sharing information sequentially; but today, technology allows the concurrent sharing of information, improving the efficiency of a supply chain (Sherer, 2005). Sherer (2005) sees the customer as an active participant and the demand driver and not the passive actor who just expects to receive the final product.

Meanwhile, Aitken (1998) and Mentzer *et al* (2001), defined supply chain based on the flow of products and information and from the source to the customer. Furthermore, Mentzer *et al* (2001) differentiated between three types of supply chains which are: direct supply chain, extended supply chain, and the ultimate supply chain. They argued that a company can be part of more than one supply chain and it can be located on the upstream or downstream of different chains.

Another trend of research is focused on the structure of the supply chain. For example, Stock and Boyer (2009), Noemi (2012), Lu (2011), and Christopher (2016) conceptualise the supply chain as a network (rather than a chain) with several nodes (business units). It can be formed by more than one company, with different ownership, connected thru the process of adding value to the flow of materials (Lu, 2011). The connection between nodes conforms the nature of the relationship (Noemi, 2012). It is argued that trust and commitment are fundamental pillars of a strong relationship between supply chain participants, and it is what creates a real competitive advantage (Handfield and Bechtel, 2002; Kwon and Suh, 2004; Noemi, 2012;).

On the other hand, is the scope or domain of the chain. Initially (in the 1970's or 1980's), the domain of supply chains was limited to connect the organization's inputs to its outputs (e.g. customer, company, and suppliers) and usually involved just transportation and storage. Nowadays supply chains have extended their domains to meet various challenges such as lowering costs, ensuring timely deliveries, reducing adverse environmental impacts and waste disposal to satisfy regulators, customers, and environmental advocacy societies (Mudulli and Barve, 2011). These requirements are the basis for the term "green supply chain", which includes the disposal phase of the product, underscoring the increasingly complex nature of a supply chain. This broader concept of supply chain involves more groups belonging to the chain.

Another relevant actor in the supply chain is the customer and its position in the chain. Since the early 1990's researchers have highlighted the importance of the customer as a demand driver (La Londe and Masters ,1994; and Cox ,1999, Mentzer *et al*, 2001; Sherer, 2005; Stock and Boyer, 2009; Lu, 2011; Noemi, 2012; Walker *et al*, 2007; Christopher, 2016). However, a lack of consensus exists regarding the position of the customer in the chain. Some authors place the customer in the upstream group of the chain (Sherer, 2005; Walker *et al*, 2007). Other authors place the customer in the Downstream group (Aitken, 1998; Mentzer *et al*, 2001; Christopher, 2016). There is another group of researchers that argue the customer doesn't belong to the supply chain such as Lu (2011)**.** The author recognised that the only reason for the existence of the supply chain is to serve the end customer and it is the source of financial reward, but he argues the customer is the recipient of the supply which is provided

by the supply chain, so it actually doesn't belong to the supply chain, this argument contrast to Sherer *et al* (2005) which it was detailed above.

A more recently trend is name a “focus company” or “coordinator partner” within the supply chain which is the “manufacturer company” and it is placed in the centre of the chain (Bessant *et al*, 2003; Walker *et al*, 2007; Lu, 2011). It is also recognised by all trends of research the more increasing complexity of the chain because of more participants groups (supplier’s suppliers or customers of customers and external stakeholders) are added.

Researchers focused on cluster of industries such as construction and mining classified the groups participants of the supply chain such as upstream (end users and customers), downstream (suppliers, contractors, and consultants) and a coordinator partner (walker *et al*, 2007) . In the construction industry, the information flow is not distributed equally (Bessant *et al*, 2003; Walker *et al*, 2007) even when is well known that the effective management of this flow can create a competitive advantage for the firms (Spekman *et al*, 2002; Maqsood *et al*, 2007; Lu, 2011; Noemi, 2012; Cristopher, 2016). Downstream participants (suppliers, contractors, and consultants) of the supply chain are often poorly treated with deficient schedules of communication (sharing knowledge) or consideration (Latham, 1994; Walker *et al*, 2007; Maqsood *et al*, 2007.

Walker *et al* (2007) also incorporate the external stakeholders to the supply chain domain even though they do not explicitly belong to the supply chain. This group of external stakeholders is composed of the general community, independent individuals or groups, and invisible stakeholders (e.g. family network). We adopted the Walker *et al* (2007) concept of supply chain and the participants (upstream, downstream, and a coordinator partner) together with the direction (from the sink to the customer) of the supply chain based on the flow of communication. Furthermore, the classification of external stakeholders provided by Walker *et al* (2007) is also used to identify the uranium supply chain participants in Australia. More details in chapter 7.

3.3 Establishment of the Mining Supply Chain

There are several studies associated with supply strategies e.g. supply management, supply integration or supply scope - all are areas other than mining e.g. food, wine, informatics and logistics (Mentzer *et al*, 2001; Gibson, 2000; Gibson *et al*, 2005; Kleindorfer and Saad, 2005; Flint and Golicic 2009; Lu, 2011; Plaganyi *et al*, 2014). In the case of supply chain in mining, there are just a few studies in Australia and worldwide (Azapagic, 2004; Loechel *et al*, 2013a; Benn *et al*, 2013). In general, the

regional supply chain in mining is composed of three main elements: government and regulatory institutions, support systems and input/outputs (Loechel *et al*, 2013a). In their research, Loechel *et al* (2013a) provide a breakdown of these three elements, which are presented in Table 3.2.

Table 3.2: Elements of the supply chain in mining

Government and Regulatory Institutions	**Support Systems**	**Inputs/Outputs**
Federal government and regulations	Social infrastructure	Water
State government with services and regulations	Transport infrastructure around the mine site	Energy (electricity, fuels and gas)
Local government and regulations	Supply infrastructure	Telecommunications
Regional planning organizations	Transport infrastructure to customers	Materials
Industry associations	Waste management	Equipment
		Mining services
		Labour skill
		Finance and insurance
		Mine production
		Processing
		Customer
		Mine rehabilitation
		Surrounding environment and communities

Source: Loechel *et al* (2013a)

Key elements in this chain of activities include: mining companies, federal and local Government agencies, communities, surrounding environment, water, energy and transport (Loechel *et al*, 2013a; Hodgkinson *et al,* 2010). According to the previous studies, these key elements are most at risk by climate change and extreme weather events and should be the focus of analysis and adaptation strategies to avoid or minimise the effect across the supply chain (Loechel *et al*, 2013a; Hodgkinson *et al*, 2010).

3.4 Adaptation and Adaptive Capacity

The concept of climate adaptation has been developed to face the changes in the climate system. Adaptation is a series of process to develop characteristics of adjustment in ecological, economic systems and the social environment in response to climate change in order to survive (Smit and Wandel, 2006; Canziani *et al*, 2007). In other words, adaptation is a preventive action that may involve a cost or sacrifice, in order to obtain future benefits (or create opportunities from a negative event).

Numerous authors (Dowing and Patwardhan, 2004; Ford and Smit, 2004; Smit and Wandel, 2006; Canziani *et al*, 2007, Gaillard, 2010; Cardona *et al*, 2012; Stocker *et al*, 2014) support the claim that climate vulnerability and adaptation are related in two ways : vulnerability is the lack of capacity, and they are opposite (increasing the adaptive capacity reduces the vulnerability). Thus, increasing the adaptation strategies of human systems and facilitating the natural conditions of ecological systems to adapt to the changing climate conditions would reduce the vulnerability. The definition of adaptation provided by the IPCC is below:

"Adaptation is the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects"(IPCC ,2007 ;IPCC, 2014).

On the other hand, the characteristics or abilities that "organisms" have developed to survive to any disturbance e.g. climate change is termed adaptive capacity (Smit and Wandel, 2006; Engle, 2011). There are distinct categories of adaptive capacity such as the capacity for prevention, the capacity of response, and capacity for recovering (Lavell *et al*, 2012; Cardona *et al*, 2012), they are discussed in Chapter 8. The definition of adaptive capacity provided by the IPCC is presented below:

"The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences" (IPCC, 2007; IPCC, 2014).

There are other factors (drivers and barriers) present in the adaptation process such as international agreements, government legislation, policy formulation, evaluation of adaptation strategies, the adaptive capacity and the kind of technology used in the case of companies (Canziani *et al*, 2007; Cardona *et al*, 2012).

In this thesis we employed the only definition of adaptive capacity referring to mining present in the literature which was provided by Pearce *et al* (2009), the authors defined adaptive capacity as " *the ability of individual mines and sector as a whole to address climate chang*e".

3.5 Adaptation in mining

There is a limited body of research related with adaptation to climate change and the mining industry. Canada was the precursor for the topic (Ford *et al*, 2009; Pearce *et al*, 2009, Pearce *et al*, 2011) although the greatest and most up to date body of knowledge now lies within Australia (Hodgkinson *et al*, 2010; Hodgkinson *et al,* 2013; Loechel *et al*, 2013ab; Mason *et al*, 2013; Mason and Giurco,2013; Hodgkinson *et al*, 2014). In general, these studies have focused on obtaining the perception of climate change by the industry, identifying climate risks that affect the industry, identifying direct and indirect impacts, and identifying some adaptation measures proposed by the participants in their studies. These authors have used workshops, interviews, and surveys to gather data from participants in the mining industry.

The most common tool used by researchers to complete a vulnerability assessment of climate change in the mining industry is a survey (Loechel *et al*, 2013ab; Pearce *et al*, 2009; Mason and Giurco, 2013; Mason *et al* 2013). A survey has been used to explore what is being done in the mining industry to cope with future climate change. It especially useful if it is answered by practitioners it becomes a guide to know the main vulnerabilities at a mine (Pearce *et al* 2009).

3.5.1 Mining and adaptation planning

Mining and processing are the two main parts of the mine site that have been affected by climate hazards such as droughts, flooding, storms, and heat waves (Mason and Giurco, 2013; Mason *et al*, 2013, Loechel *et al*, 2013a). More specifically the water management systems (e.g. tailing storage facilities, evaporation ponds), the access to the operational pit (temporarily closed or halted), the physical infrastructure and equipment have been affected by flooding in mines located in a tropical climate (e.g. Ranger Mine, Ensham mine). These impacts and others have increased economic risks like loss of revenue and decreases in production. On the other hand, droughts can affect the water supply for mining operations, especially in arid climate e.g. Olympic Dam (Torrisi and Trota, 2013). Some types of risks associated with droughts in mining industry are the loss of production, loss of reputation because of unfulfilled of commitments, and inability to adapt to reduce water supply (equipment and infrastructure) (Mason and Giurco, 2013). Higher temperatures and heat waves have been associated to heat stress (both human and machinery), injuries, reduced productivity, increased energy consumption and increased costs of maintenance (Mason and Giurco, 2013).

It has been argued that the only way to reduce the impacts of climate hazards and the associated risks is by adaptation planning (AECOM, 2010; Mimura *et al*, 2014). Several barriers that limited the

adaptation planning have been found in the mining industry. One of them is the lack of knowledge in topics such as: risk management processes, vulnerability assessment, and climate science (e.g. understanding of climate projection under different RCPs) (Ford *et al*, 2011; Loechel *et al*, 2013ab, Hodgkinson *et al*, 2014; Grabowski and Clark, 2016; Pizarro *et al*, 2017). Even though adaptation measures are specific for different types of impacts, Mason *et al* (2013) have suggested some adaptation options can be applicable in general at mining and mineral processing such as modifying the current risk identification to incorporate climate events, the use of climate models based on local or regional data and climate projections, implementation of measures based on the risk identification, the constant review of data and monitoring of measures to assure they are proper and effective. To implement adaptation measures it is necessary to possess information about current exposure, sensitivity, associated risks, and adaptive capacity. This information can be obtained using two different approaches: one, a climate vulnerability assessment (IPCC 2001-2007) or a climate risk assessment (IPCC 2014). The latter concept has coined in an attempt to merge the two major streams in climate science: climate adaptation and disaster risk management (Jurgilevich *et al*, 2017). In the former approach, vulnerability is determined by the exposure, sensitivity, and the adaptive capacity of a system. All of them are considered dynamic, projectable and adaptable (Jurgilevich *et al*, 2017). On the other hand, climate risk assessment is composed of: hazard identification, exposure and vulnerability (sensitivity and adaptive capacity). All of them are also considered dynamic, projectable and adaptable (Jurgilevich *et al*, 2017). The vulnerability assessment method was employed in this study, due to the lack of quantitative data in the mining climate adaptation field, the limited information about the implementation and performance of adaptation measures, and the limited literature. More details about the vulnerability assessment approach that was followed can be found in Chapters 6 and 7.

3.6 Climate adaptation in Canadian mining

Canadian Researchers have been pioneers in the subject of adaptation to climate change in the mining industry, most likely because they have been affected (perhaps earlier) by climate change impacts such as warmer conditions, in contrast to other countries (Pearce *et al,* 2009; Pearce *et al*, 2011; Ford *et al*, 2009). More specifically, Pearce *et al* (2009) used two surveys to explore the current and future vulnerability. These authors obtained nine key results extracted from the survey's results to mining industry practitioners in Canada in 2008. For this study, questions in the survey were targeted to obtain an answers in the following topics: sensitivity of the industry to climate change, perception of negativity of climate change, actions to cope with climate change, common barriers to adapt to climate change, likely impacts of climate change over the company, perception about climate projections,

what is being done by companies to face the new climate, barriers of adaptation (cost and uncertainties) , the mining industry is taking mitigation actions to reduce GHGs emissions.

A sample of 42 representatives of mining practitioners responded the survey that contained 24 questions. Some of the findings for this research included that 75% of those surveyed agreed that the sensitivity of the industry to climate change was significant. 35% considered that the companies were being negatively affected by climate change. 45% said their companies are taking actions to cope with climate change. 43% considered the cost a barrier to adaptation and 45% estimated the uncertainties about future climate projections as a cause for not taking adaptation strategies into account (Pachauri and Reisinger, 2007). The rest of questions were answered as follows: 50% estimated that climate change will affect the operations in their companies, 48% thought climate change will affect their business in a negative way, 30% said that their companies are taking actions to face climate change and 58% argued their companies are reducing their emissions of GHGs (Canadian Mining Journal, 2005).

In summary, the research carried out by Pearce *et al* (2009) has shown that the majority of company representatives surveyed were aware of climate change issues and that climate change can damage or delay operations, but they were still reluctant to invest in adaptation strategies because of the uncertainties of climate projection and the cost of the investment, especially when the benefits of this investment can be observed in the long term rather than in the short term.

The authors of the Canadian study also state that there a gap in the literature associated with the mining industry and how they would face climate change. The Canadian literature shows there is an increasing need to incorporate adaptation strategies in the daily business development of mining companies (Pearce *et al*, 2009; Ford *et al*, 2009). There is also a need to incorporate the sustainability principles in the operation of mines (Pearce *et al*, 2009). Incorporating sustainability into the mining industry and other associated industries will ensure they will be viable in the future (Auld and MacIver, 2006).

To develop adaptation strategies, it is crucial that a commitment from the authorities, regulators, scientists, companies and other stakeholders be present (Pearce *et al*, 2009; Pearce *et al*, 2016). Pearce *et al* (2009) pointed out in their research that the infrastructure in Canadian mines has been designed for a stable climate, for this reason, the impacts of extreme weather events has been negative. However, climate change is not a great concern for the mining stakeholders since it is ranked lower than other issues such as market scenario conditions or fulfilling regulatory requirements (Pearce *et al*, 2009). According to the authors had not been adequate planning for future climate change (at the

time the research was undertaken), and consequently, there were vulnerabilities owing to the scarcity of planning (Pearce *et al*, 2009).

However, this research is an important contribution to the limited literature on mining climate adaptation and vulnerability assessment in the mining field. On the other hand, this study has two main limitations: 1) the participatory framework and 2) the small sample size.

1) Pearce *et al* (2009), is based on a Community Based Adaptation (CBA) that relies on the Community-Based Participatory Research (CBPR) framework, which present some limitations and potential negative impacts (Ford *et al*, 2016). This framework was created because of the need to convert climate science into practical adaptation to climate change, which includes the community's priorities, needs, knowledge and capacities (Ford *et al*, 2016). The CBPR framework has been argued as a buzzword research modality to sell projects and to fulfil the requirements of Governments, Environmental, Social Licence to operate, etc. (Ford et al, 2016). Problems arise when the participatory framework is not true, this can lead to altered findings or outcomes (Ford *et al*, 2016) together with inappropriate adaptation measures or maladaptation practices, for the previous reason, CBPR has been negatively criticised. However, from the findings of Ford *et al* (2016) it is argued that this CBPR is adequate just in some cases, mainly when the community has previous research experience, project nature, priorities, interests and engagement. Specific benefits from CBA are practical information can be obtained, future focus, evaluation, and community adaptation (which the priority in this framework). On the other hand, specific limitations are community resistance to participate in the process (e.g. workshops, interviews), the adaptation focus vs other issues, conflictive findings between scientific knowledge and traditional local/indigenous knowledge, high expectations of CBA analysis and the perceptible/observable outcomes specially in the short-term (Ford *et al*, 2016).
2) The small sample size in this study did not allow a proper statistical analysis in some cases, in others the high number of blank responses or "not sure" makes the interpretation of the results difficult. In addition, a significant increase in the tendency to respond "not sure" was detected between the responses provided to the face-to-face survey (first stage of this study) and phone interviews during the second stage of the research.

3.7 Vulnerability Concept

There are different definitions of vulnerability which depending on the context, the framework, and the discipline's point of view used to define the causes of vulnerability. In climate science, it generally

refers to the capacity of a system to cope with an adverse environment. Initially, the IPCC (2001-2007) defined vulnerability as follows:

"*Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity*" (Parry *et al*, 2007).

The previous definition incorporates external physical causes (e.g. exposure) as part of vulnerability. The exposure was considered dynamic, projectable and adaptable in the short term, but it has been a difficult task perform projections in the long term, mainly for the different driver-factors (e.g. population grow or land use) of the exposure (Jurgilevich *et al*, 2017). The other two drivers of vulnerability were emphasised by the sensitivity and the adaptive capacity, the three drivers are shown in Eq. (3.1).

$$Vulnerability = f(exposure, sensitivity, adaptive\ capacity) \quad (3.1)$$

Therefore, the climate vulnerability of a system is determined by the degree or dimension of exposure, sensitivity and adaptive capacity (Metgzer, 2005; Fussel and Klein, 2006).These components of vulnerability have been defined by the literature (Downing and Patwardhan, 2002; Metzger, 2005; Fussel and Klein, 2006; Smit and Wandel, 2006; Pearce *et al*. 2009; Ford *et al*, 2009; Pearce *et al,* 2011; Glick *et al*, 2011) as follows:

- **Exposure**: Measure of the magnitude and extent of exposure of a system to climate risk derived from climate change. Dependant on the geographic location.
- **Sensitivity**: Refers to the degree to which a system may be affected negatively or beneficially, direct or indirectly by climate variations.
- **Adaptive capacity**: Refers to the capacity or degree of adjustment of a system to the climate variations in order to moderate potential damages or take advantage of this new condition.

This definition and domain of vulnerability have been widely used (Duerden, 2004; Fussel, 2006; Fussel and Klein, 2006, Smit and Wandel, 2006; Canziani *et al*, 2007; Berrand Ford, 2008; Smit *et al*, 2008; Pearce *et al*, 2009; Hodgkinson *et al*, 2010; and others) in the climate vulnerability context.

However, in the last IPCC (2014) a new definition of vulnerability was coined with the social drivers (sensitivity and adaptive capacity) explicitly emphasised and the external physical causes (e.g. exposure) were considered independent of the vulnerability (Hewitt, 2007; O'Brien *et al*, 2007, Jurgilevich *et al*, 2017). The modified definition of vulnerability presented by the IPCC (2014) is :

"*Vulnerability* is *the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt*"

Furthermore, vulnerability was considered a component of a new concept defined by Lavell *et al* (2014) :"climate risk". The interaction of a climate hazard, the exposure of the system, and its vulnerability are the drivers of climate risk, this is shown in Eq.(3.2) and Eq.(3.3) shows the new domain proposed of vulnerability.

$$Climate\ risk = f(Climate\ Hazard, Exposure, Vulnerability) \quad (3.2)$$

$$Vulnerability = f(Sensitivity, Adaptive\ Capacity) \quad (3.3)$$

In this approach, the vulnerability domain is limited to the sensitivity and the adaptive capacity. Vulnerability is seen as an outcome of the physical, economic and social conditions which establish the level of predisposition of a community in the case of facing a phenomenon either natural or anthropogenic (Cardona, 2003, Cardona *et al*, 2012).

The following Table 3.3**Error! Reference source not found.** shows a brief summary of both trends of vulnerability definitions present in literature.

Table 3.3: Summary of relevant definitions of vulnerability

	Definitions		
Author	**Vulnerability as a pre-existing condition**		**Vulnerability as outcome**
Smit and Wandel (2006)	"…vulnerability of any system (at any scale) is reflective of (or a function of) the exposure and sensitivity of that system to hazardous conditions and the ability or capacity or resilience of the system to cope, adapt or recover from the effects of those conditions…"	Cannon (1997)	"…vulnerability is a characteristic of individuals and groups of people who inhabit a given natural, social and economic space, within which they are differentiated according to their position in the society into more or less vulnerable groups"
Fussel (2006)	"vulnerability of a system's attribute(s) of concern to a hazard (in temporal reference)"	Weichselgartner (2001)	"vulnerability is conceived as both a biophysical hazard as well as a social response within a specific geographic domain"
Adger (2006)	"vulnerability is the state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt"	Cardona (2003)	"…vulnerability might be defined as an internal risk factor of the subject or system that is exposed to hazards and corresponds to its intrinsic predisposition to be affected."

Canziani *et al* (2007)	"…the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change. Vulnerability is a function of the character, magnitude and rate of climate change and the variation to which a social or ecological system is exposed, its sensitivity and its adaptive capacity…"	Gallopín (2006)	"vulnerability is the propensity of a system to suffer significant transformations as a consequence of its interaction with external or internal processes or events ("perturbations")
Pearce *et al* (2009)	"...vulnerability is a function of exposure-sensitivity to climate conditions and the adaptive capacity to deal with those risks"	O'Brien *et al* (2007)	"A present inability to cope with external pressures or changes, such as changing climate conditions. Contextual vulnerability is a characteristic of social and ecological systems generated by multiple factors and processes"

Source: Own recompilation from authors

Climate risk concept is the result of merge the vulnerability concepts employed by the two main streams in this area: Climate Adaptation and Risk Reduction (DRR) (Fussel and Klein, 2006; Jurgilevich *et al*, 2017) . Might be the main different between these two conceptualizations of vulnerability is that the vulnerability is seen as "an internal outcome" of the interaction of its drivers (IPCC, 2014) rather than a pre-determinate condition (IPCC 2001-2007).

In this thesis we adapted the concept and definition of vulnerability employed by, Smit and Wandel (2006), and Pearce *et al* (2009). In the mining sector, vulnerability might be determined by economic resources employed to face climate change, company approach to climate adaptation, political and government regulations, mine category (underground or open pit) and the climate condition at the geographical location of the mine. We believe the exposure in mining is a driver of vulnerability because a mine is located in a specific place and it cannot be moved to another location, otherwise the mine wouldn't exist anymore.

3.8 Vulnerability Assessment

The vulnerability definition selected is characterised by the exposure, sensitivity and adaptive capacity of a system to disturbances, thus the vulnerability assessment represents an attempt to measure / characterise or assess these components. There is a vast literature about methods to assess the climate vulnerability, an example of these studies are Ford and Smit (2004); Ford *et al* (2008) ; Pearce *et al* (2009), and Ford *et al*, (2009). Further, there are two trends of approaches of vulnerability assessment: Top-Down and Bottom-up, they are presented in Figure 3.2.

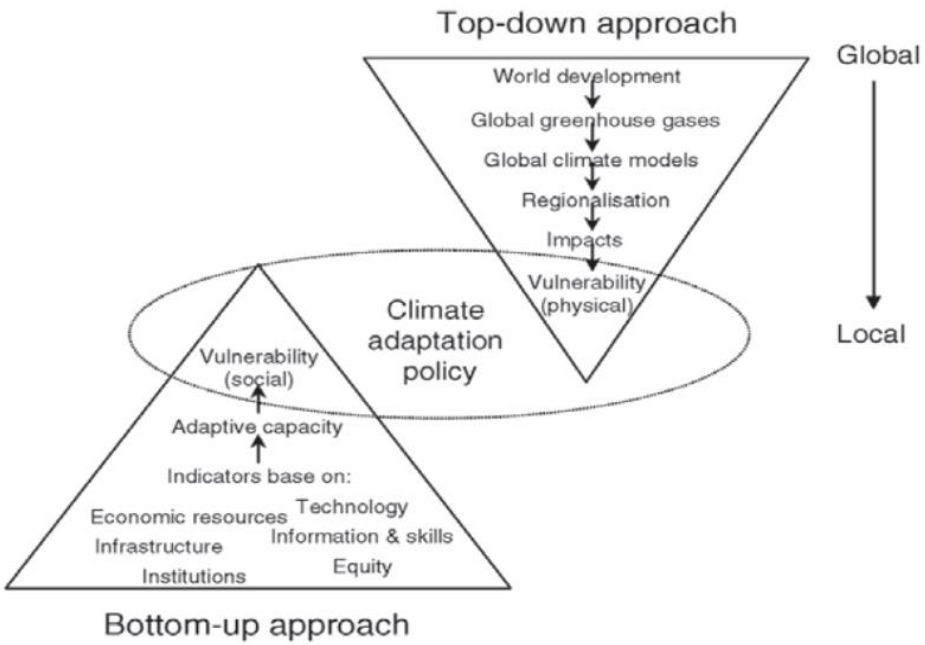

Figure 3.2: Two approaches to vulnerability assessment in climate change (Dessai and Hulme, 2004)

A "Top-Down" approach uses the probabilities of global emissions of GHGs, global climate models and downscaling approaches to feed biophysical models to predict impacts of climate change and vulnerability (Schneider, 1997; 2000; 2001) . This technique was the initial approach to assess vulnerability and it was termed the first generation of adaptation research (Burton *et al*, 2002; Van Aalst *et al*, 2008). However, it has been argued by other authors (Dessai and Hulme, 2004; UNDP, 2005) the need to research all *possible outcomes* of climate change not just a few variables (Van Aalst *et al*, 2008).

In the process to explore more local pathways to climate adaptation the Bottom-up approach arose. This approach includes the local economic and social conditions with a focus on the past and present to obtain future predictions of vulnerability and identify adaptation options. The predictive biophysical tools are replaced by the vision (or opinion) of the stakeholders and/or scenario analysis to identify

adaptation options of a system. (Dessai and Hulme, 2004; Van Aalst *et al*, 2008; Rowan, 2011; Preston, 2012). These two approaches (Top-Down and Bottom-up) address the climate adaptation from different points of view but with a common goal : vulnerability assessment to identify adaptation options as the Figure 3.2 shows.

Despite the vast literature employing the Bottom-up approach (Ford and Smit, 2004; Ford *et al*, 2008; Fussel, 2007; Ford *et al*, 2009; Rowan et al, 2011; Agrawala, 2010; Loechel *et al*, 2013ab, Mason and Giurco, 2013; Hodgkinson *et al*, 2014) as was pointed out in the section 3.6 this approach has been recently criticised by authors (Forsyth , 2013; Dodman and Mitlin , 2013; Sherman and Ford , 2014; Ford *et al*, 2017). They have emphasized that the participatory technique is not the most successful approach to assess the vulnerability and propose local adaptation options as few years ago was indicated.

Therefore, is currently no consensus about the methods or approaches to assess vulnerability, which makes it difficult for the comparison of results in different fields and/or locations (Preston, 2012; Preston, 2013). The selection of an approach for a vulnerability assessment depends on purpose, availability of data, framework, time, resources and knowledge in the field (Nelitz *et al*, 2013). Here, the vulnerability assessment of the uranium mining was performed to develop knowledge related to climate change to identify adaptation needs, adaptation options, and can be used to focus long-term planning , thus we selected the Bottom- up approach.

In the search of literature focus on the vulnerability assessment of mining we found the study undertaken by Pearce *et al* (2009), the authors extended the scope of a "Bottom-up" approach to the mining industry to include economic, political and climate factors at different scales. In this study, exposure and sensitivity were defined as *"the propensity of mining operations to be negatively affected when exposed to climate conditions*" and adaptive capacity as we pointed in the section 3.4 . The framework used by Pearce *et al* (2009) was composed of 'two-time' stages - a past and future analysis of exposure-sensitivities and adaptive capacity. The historical results were used as input in the analysis of future scenarios. The data collection was based on the opinion of mining stakeholders through surveys and interviews. The scheme of the conceptual framework for this analysis is shown in Figure 3.3.

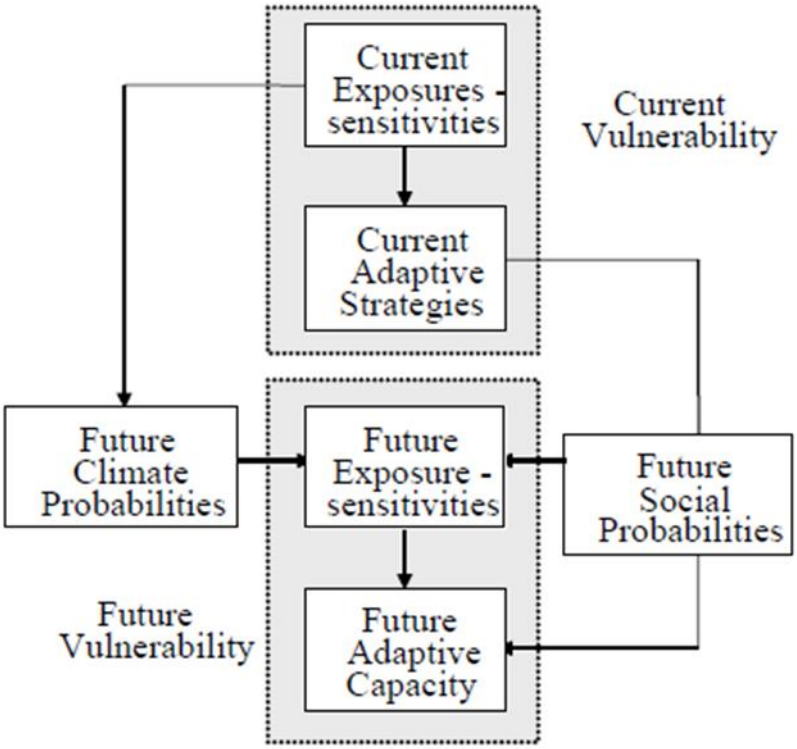

Figure 3.3: Conceptual framework for vulnerability assessment in mining (Pearce *et al*, 2009)

3.9 Current Vulnerability Assessment

A current vulnerability analysis is performed in the present and considers past events. It evaluates how current climate conditions affect operations at a specific location. The analysis is based on the identification of current exposure-sensitivities and current adaptive capacity.

3.9.1 Exposure-Sensitivity

Pearce *et al* (2009) began their study with the identification of the current climate conditions that included precipitation, temperatures as well as extreme weather events. The identification of the climate risk(s) e.g. event frequency, timing, and affected locations are an important part of the assessment. The result of this assessment provides guidance for managers in short term planning roles (Pearce *et al* 2009).

3.9.2 Adaptive Capacity

Adaptive capacity of the mine is assessed through the evaluation of the current Risk Management Plan (RMP) before, during and after climate risks occur. The effectiveness of the current RMP is evaluated

with the identification of weaknesses and strengths. This generates knowledge about the items that make the current risk management plan effective or not (Pearce *et al*, 2009).

3.10 Future Vulnerability Assessment

The results of the current exposure-sensitivity and adaptive capacity are used as a starting point for the analysis of the future vulnerability. The results of this stage can help to prepare for long-term planning (Pearce *et al*, 2009).

3.10.1 Future Exposure-Sensitivity

The evaluation of future exposure sensitivity includes the identification of how climate change will impact the sensitivities that already exist for the current climate conditions (Pearce *et al*, 2009). In this stage, it is important to identify future climate variations such as frequency, seasonality or intensity and magnitude.

3.10.2 Future Adaptive Capacity

Future adaptive capacity refers to the effectiveness of the current risk management plan for dealing with future climate risks. This includes an evaluation of ability to deal with hypothetical scenarios associated with climate change.

The next subsections present an overview of the techniques present in the literature to assess the adaptation options in order to gather information and knowledge to assess the adaptation options proposed to the uranium supply chain in the Chapter 8.

3.11 Adaptation Options Assessment

Uncertainties can be present in global climate projections, regional climate projections, future society, statistical downscaling, impact modelling and adaptation process (Riskchange, 2015; Refsgaard *et al*, 2013) as outlined in Figure 3.4. These uncertainties make climate adaption decisions difficult and complex (Refsgaard *et al*, 2013); especially since the uncertainties have a cascade or accumulative effect (Refsgaard *et al*, 2013; Hallegatte *et al*, 2011b; Pachauri *et al*, 2014).

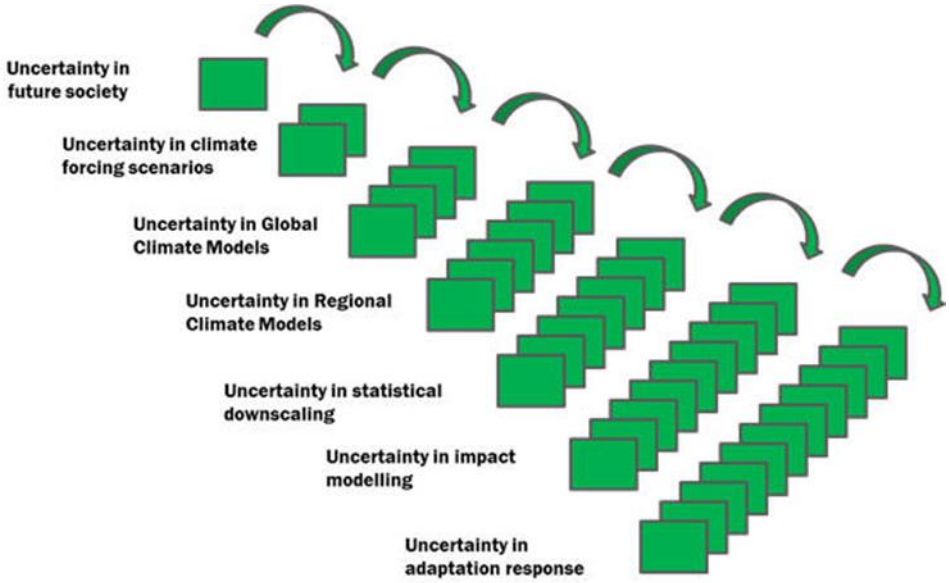

Figure 3.4: Uncertainties in climate change (Riskchange, 2015)

Uncertainties are also present in the adaptation process that include limited knowledge about climate change and cost of implementation (Pearce *et al*, 2009). In many cases, adaptation options are considered an investment to minimise future damages of climate change (Wright, 2003). In this context, adaptation options can be assessed by economic approaches. There are three economic techniques to evaluate the adaptation options cost-benefit analysis, cost-effective analysis and multi-criteria analysis.

The next subsections present an overview of the economic techniques of Cost-Benefit Analysis (CBA), Cost Effectiveness Analysis (CEA), and Multi-Criteria Analysis (MCA), which are most frequently used in the literature to assess the feasibility of alternative adaptation options and their ranking, in order to apply such methods to gather information and knowledge to assess the adaptation options proposed to the uranium supply chain in the Chapter 8.

3.11.1 Cost - Benefit Analysis (CBA)

A cost-benefit analysis technique is based on a comparison between costs and benefits associated with an investment over time (Noleppa, 2013). This technique provides support to decision makers when there are different adaptation options presented. Costs and benefits must be expressed in monetary terms for this method to work (Noleppa, 2013). The study undertaken by Damigos (2011) is a good example of the CBA approach of the impact of climate change, for the special case of the Greek mining industry. A brief description of the study is presented in the next subsection.

3.11.2 Cost and benefits analysis in the Greek mining industry

Damigos (2011) used the "top down" approach and the A1B climate scenario to estimate the future projections in the period 2021-2050 of likely impacts of climate change in the mining industry. These impacts were classified as direct and indirect (Damigos, 2011). Direct impacts of extreme weather events corresponded to: damage to mining infrastructure, the increased frequency of fires, the decrease of water resources, increase of dust emissions, lower quantity of hours worked due to production stoppages and the cost of applying better measures to protect from the environment (Damigos, 2011). Indirect impacts on the other hand are associated with mitigation measures to reduce the emissions of greenhouse gases and include the increase in the cost of energy, the reduction of employment in mining and increasing costs in operations due to climate mitigation strategies (Damigos, 2011). Unfortunately, the full quantification of the direct and indirect impacts was not possible because of the absence of records and data (Damigos, 2011). In the following section, a detailed estimation of direct and indirect impacts is provided.

1) Estimation of direct impacts

Damigos (2011) quantifies the direct impacts as follows; for the estimation of the damage of infrastructure, an arbitrary value of US$19M was provided, for the case of just one extreme weather event during the period 2021-2050. The impact of fires on mining was not quantified due to the lack of information in this regard. In the case of water scarcity, the analysis to obtain the estimation was carried out based on the additional price paid to the water supply company due to the reduction in water resource availability. According to the climate projections for the relevant period considered, Damigos (2011) assumes a reduction of 8% in water availability, with an elasticity of demand of 0.2, which implies an increase of 40% in the price of water. Furthermore, Damigos (2011) considers an initial price for water of US$1.257/$m^3$, this price was taken from the national water company provider. Further, he used the total amount of water used by Greek Mining Enterprises Association in 2010, which is 17,000,000m^3. This in order to estimate the additional total cost as loss of consumer surplus. See Table 3.4. This calculation was based on Damigos (2011) but there is a small difference in the total annual cost. The author obtained total annual cost of 8.7 million (Damigos, 2011), this calculation was made to understand the methodology employed by the author.

Table 3.4: Calculation of total cost by increase in water price (Based on Damigos, 2011)

Price of elasticity demand	**0.2**
Decrease in water availability	8%
Increase in water price	40%
Initial price of water(per m^3)	US$1,257
Increase in water price due to Less availability	US$0.503
Final price of water	US$1.760
Volume used of water after the Increase of price (m^3)	17,000,000
Volume used of water before the increase of price	18,478,261
Additional cost of final intake	8,547,600
Value of decrease in intake	371,635
Total of annual cost	**8,919,235**

Figure 3.5 in the next page shows the loss of consumer surplus and the additional cost due to the expected increase in the price of water.

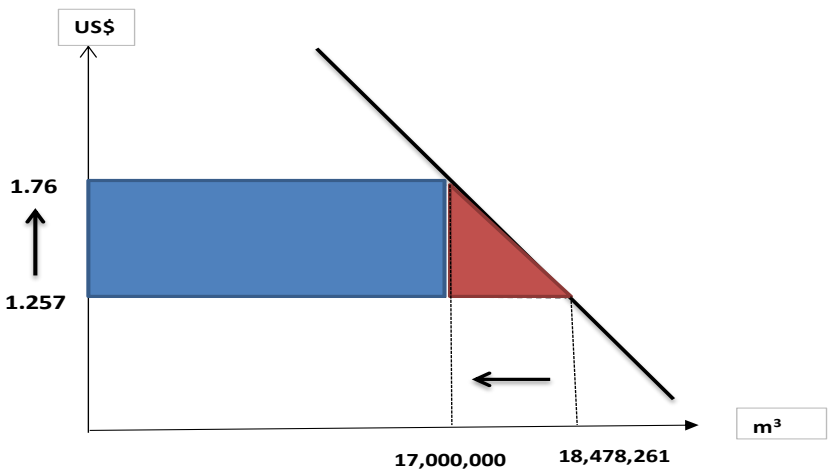

Figure 3.5: Additional cost of final water intake and less intake of water in 2021 (Based on Damigos, 2011)

A similar indirect calculation was used to estimate the cost in the increase of dust, resulting in a cost of US$4.6million/year. For better measures to protect the environment, it was assumed an increase of 50% taking as reference the cost in 2010. In addition, the decrease of labour hours was estimated

as 0.1% of the total production of all companies that were members of the Greek Mining Enterprises Association in 2010 that is US$2.3 million/year.

2) Estimation of indirect impacts

The estimation of the indirect impacts was based on two factors: the decrease of production of lignite because of the mitigation measures to reduce emissions and the increase of the price of electricity (Damigos, 2011). The amount of the increase in the price of electricity is due to the expected reduction of emissions of GHG that was estimated to be US$34.4 million/year. The total cost, including direct and indirect impacts calculated by Damigos (2011) is shown in Table 3.5.

Table 3.5: Quantifiable Direct and Indirect costs of Climate change for the Greek Mining sector

	Annual cost (US$ millions)
Increase in water cost	8.9
Increase in forest fires	0.0
Increase in dust emissions	4.6
Better measures of environmental Protection	6.0
Decrease of labour hours	2.3
Total direct impacts	21.8
Total Indirect impacts	34.4.
Total costs	56.2

The cost in damage to infrastructure (19 US$ million) was already assumed by Damigos (2011) for the period of 2021-2050. Apart from this cost, the total direct and indirect annual costs which are US$21.8 million and US$34.4 million respectively were brought to Present Value (PV) as of 2010. Table 3.6 shows the PV for the total annual impacts from 2021 to 2050, using a discount rate of 3%. The total amount obtained by Damigos (2011) is US$790 million.

Table 3.6: Present Value of direct and indirect impacts of climate change (Based on Damigos, 2011)

Annual direct impacts	**US$ Million**
PV annual direct impacts (US$21.8 million) from Table 3.5	293
PV destruction of infrastructure event	19
Total PV cost of direct impacts at 2010	**312**
PV of indirect impacts (US$34.4million) from Table 3.5 brought at 2010	**478**
Total PV	790

PV: Present Value

Therefore, Damigos (2011) estimates the total cost of direct and indirect impacts of climate change in the Greek mining industry for the period 2021-2050 to be US$790 million in 2010 prices.

There are a few elements considered in the analysis that are not clear. The amount of water used in 2010 is the same for 2021, the calculation should be for 2010 but the results represent better the year 2008. The author used information from different years to perform the calculation, which is confusing. Damigos (2011) assumed direct cost as adaptation costs and indirect costs as mitigation costs.

Even though there were limitations in the study, Damigos (2011) has shown that the option to consider adaptation strategies in the mining sector is highly recommended to decrease the cost of economic losses. Furthermore, Damigos (2011) has demonstrated that it is possible to do a quantification of the likely impacts of climate change for the mining industry in a particular country.

3.11.3 Cost-Effectiveness Analyses (CEA)

A Cost - Effective Analysis (CEA) is similar to a cost-benefit analysis and is used when it is not possible to properly quantify the costs and benefits in monetary terms. A CEA compares the relative costs and outcomes. The criteria for selection is the option with the lowest relative costs and most effective (relative) results. A limitation of this approach is that only options that have similar effectiveness can be compared, and this criterion itself can be difficult to estimate objectively. Examples of climate adaption employing this technique can be found in Hallagate *et al* (2011c); Chambwera and Stage (2010); Chadburn *et al* (2010).

3.11.4 Multicriteria Analysis (MCA)

This technique is used when the quantification of benefits as well as costs become more difficult. (Noleppa, 2013). In contrast to the previous techniques, an MCA is based on a qualitative analysis of several criteria that include feasibility, cost effectiveness, implementation and resources needed for the adaptation measures (Noleppa, 2013). This characteristic makes the MCA approach more prone to be subjective and may be unreliable because is based on the qualitative appreciation or estimation of experts. Examples of climate adaptation employing this technique can be found at Dixie and MacGray (2013), Preston *et al* (2013). More details about this approach and how it was employed in this research are shown in Chapter 8.

3.11.5 Selection of the technique

The decision of what technique to use in a particular case will depend mainly on the availability of data (Noleppa, 2013). More specifically, if costs and benefits of adaption options are measurable in monetary terms, CBA can be employed as per Damigos (2011). In the case of just quantification (costs and benefits) of adaptation is possible, CEA should be employed. And if both costs and benefits are difficult to quantify, then adaptation options might be able to be ranked using MCA criteria. Even though, the approach used by Damigos (2011) is very useful and interesting, this research is exploratory by nature, and the information about adaptation options employed by mining industry and its results are limited, thus in this research the MCA was used, which is detailed in Chapter 8.

4 Australian Uranium Industry

As outlined in Section 1.2.1 Australia has a notable number of uranium deposits (see Figure 1.7) but there are just six mines (Beverley, Beverley North, Four Mile, Honeymoon, Ranger Mine, and Olympic Dam). Of these six mines, just three are currently operating. This research will focus on the Ranger Mine and Olympic Dam since they have provided more than 80% of the Australian uranium exports in 2015 and 2016 (WNA, 2017). This chapter provides a background information of these two mines that include infrastructure (Tailings storage facilities, accommodation), water supply, power supply, roads access, Ports, and Airports. All these facilities have been affected by the extreme weather events or climate conditions.

4.1 Ranger Mine

The Ranger Mine is located in Kakadu National Park, a World Heritage Area located 230 km east of Darwin. The mine is owned and operated by Energy Resources Australia (ERA) that is owned 68.4% by Rio Tinto (ERA, 2013e). Ranger has two pits; Pit 1 was completely mined out in 1994 and Pit 3 was completed in 2012. Energy Resources of Australia has a licence to operate until 2021.

Ranger is currently processing ore from stockpiles that has increased from 4,177 tonnes to 10,383 tonnes since the cut off in grade has been reduced from 0.08% to 0.06 % (ERA, 2016). The ore reserves at Ranger at the end of 2016 are presented in Table 4.1.

Table 4.1: Ore reserves in Ranger at December 2016

Ore reserves	**Uranium Oxide (U_3O_8 tonnes)**
Ranger Ore Reserves as at 31 December 2015	6,756
Depletion by processing (primary and laterite ores)	-2,696
Stage design and block model improvements	216
Presentation of subgrade material for processing	178
Total of Ore Reserves as at 31 December 2016	8,081

Source: ERA (2017)

The main components of the mine include Pit 1, Pit 3, processing plant, mill, power station, administration and maintenance facilities, waste stockpiles, tailings storage dam, retention ponds, wetland filters, water treatment plant/s, Jabiru airport and access roads to the mine. Figure 4.3 shows the location of these facilities. Pit 1 is now being used to store tailings and Pit 3 will be used for the same purpose when Pit 1 reaches its limit.

The ore is passed through three stages of crunching and grinding circuit and then the sulphuric leaching process is used to extract uranium, a simplified scheme of this process is shown in Figure 4.1.

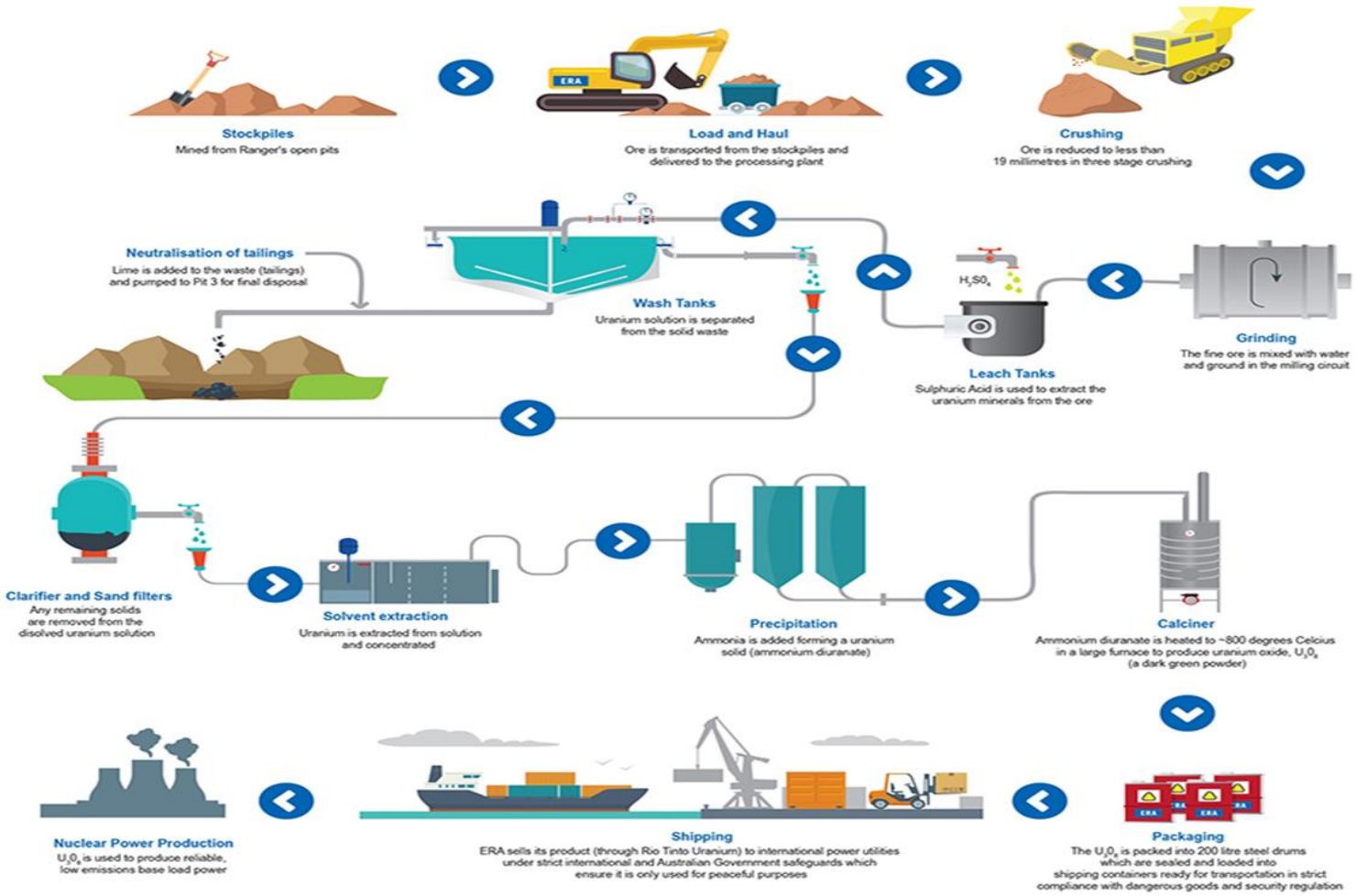

Figure 4.1: Production process of uranium employed by Energy Resources of Australia (ERA, 2017)

4.1.1 Key Infrastructure

The facilities of the Ranger Mine have previously been impacted by extreme weather events (Seidel and Crawford, 2013). The following sections provide an overview of the critical infrastructure that has been identified.

4.1.2 Tailings storage facility

The Tailings Dam and Pit 1 are used to contain the process water and tailings from the mineral processing. Natural evaporation is used to reduce the volume of process water in the dam (ERA, 2013b). This facility is reviewed and monitored each year by external engineers (ERA, 2013b). The location of the tailing storage facility is shown in Figure 4.2. In 2007, the level of water in this facility was extremely high and at risk of a spill, this because of heavy rainfall in the wet season. Due to these conditions, a “force majeure” situation was invoked by ERA and production was halted for 2 weeks (ERA, 2008b)

Figure 4.2: Location of Tailings storage facility, Pit 1 and Retention Pond (ERA, 2013b).

4.1.3 Workforce accommodation

The temporary and/or fly-in-and-out workforce employed by Ranger is accommodated in contractor camps located on the mine site (ERA, 2013b). Permanent-based workers are housed at Jabiru in a company house or in Darwin (ERA, 2013b). Jabiru has approximately 285 houses of which 216 are Ranger owned (Rio Tinto, 2011).

4.1.4 Water

There are five classes of water present at the Ranger Mine that include: stormwater, potable water, release water, pond water, process water and treatment water. Potable water comes from the Magela and Brockman bore fields. This water is used for human needs and intake (ERA, 2013b). There are four bores used for production operations. Additional bores are used for monitoring, evaluation and

exploration. The annual average of water used by Ranger in 2012-2013 was 182 ML. This represents a daily average of 498 kL/d (ERA, 2013b).

Stormwater, release water and pond water come directly from rainfall. This water is managed in diverse ways according to its location - both inside or outside the mining footprint. Process water is generally evaporated because it has been in contact with uranium (ERA, 2013b).

4.1.5 Power (Electricity)

Energy Resources of Australia (ERA) owns and operates the Power Station that provides electricity to the Ranger Mine and the Jabiru Township. The power station has five diesel generators of 5.1 MW and one diesel generator of 1.9MW (ERA, 2013c). The consumption of Jabiru town is roughly 15GW/h. In the wet season, the demand for electricity can double because of the humidity and warmer temperatures (Power and Water, 2014).

4.1.6 Mine access roads

The mine can be approached by land through three rural highways that include the Arnhem, Kakadu and Stuart Highways. The road most affected by climate conditions is Arnhem Highway that connects Jabiru with Kakadu National Park. This road is affected by interruptions and restrictions in the wet season, due to the flood plains of nearby rivers (ERA, 2013b; ERA, 2013d). Under these conditions, traffic is redirected to Stuart and Kakadu Highways (ERA, 2013d).

4.1.7 Jabiru airport

Jabiru airport is located 2.8 km northwest of the mine. It plays a key role for mine staff, tourism, local communities and emergency crews (ERA, 2013b). The airport operator is Energy Resources Australia. The Fixed Base Operator (FBO) is Kakadu air services. The airport counts with three charter operators: Jayrow Helicopters, Kakadu air and North Australian Helicopters (ERA, 2013b).

4.1.8 Darwin Port

The Port of Darwin is located 45 km from Ranger. It used to export uranium production mainly to Asia because of its strategic position (ACIL Tasman, 2009). The port has been closed by extreme weather events several times that has caused delays in shipping (ERA, 2007b). Owing to the continuous cyclone activity in the region, the port developed an emergency response plan in 2009 (Darwin Port Corporation, 2012).

1 Car Park
2 Security
3 Bulk Fuel
4 Shellsol
5 Sinter Carves Yard
6 Water Management Yard
7 Ammonia Handling
8 Emergency Dump Tank
9 Calciner & Product Packing
10 Solvent Extraction
11 Sand Filters
12 Administration
13 Product Warehouse
14 Engineering & Supply
15 Ranger 3 Deeps portal
16 Decline Laydown Area
17 Exploration Decline Office
18 Sub Station
19 Demineralisation Plant
20 Power Station
21 Plant Services
22 Grinding
23 Leaching & Clarification
24 Tailings Neutralisation & Process Water Head Tank
25 Corridor Road
26 Water Treatment Plant 1
27 Neutralisation
28 Acid Leach
29 Laterite Treatment Plant
30 Coarse Ore Stockpile
31 Fine Crushing
32 Secondary Crushing
33 Acid Plant (Decommissioned)
34 Acid Storage
35 Brine Concentrator
36 Water Treatment Plant 2
37 Radiometric Sorting
38 Primary Crushing
39 Pond Water
40 Mine Wash Down
41 Retention Pond 2
42 Retention Pond 3
43 Mines Office
44 Orica Explosive Storage
45 Trial Evaporation Channels
46 Pit 1
47 Georgetown Creek Mine Bore 'E'
48 Corridor Creek Land Application Area
49 Retention Pond 5
50 Corridor Creek Wetland Filter
51 Tailings Dam
52 Retention Pond 6
53 Trial Landform
54 Magazine
55 Retention Point 1 Land Application Area
56 Retention Pond 1
57 Retention Pond 1 Wetland Filter
58 Retention Point 1 Land Application Area Extension
59 Accommodation Camp
60 Workshop (Gagadju)
61 Jabiru East Land Application Area
62 Office of the Supervising Scientist
63 Telstra
64 Airport
65 Exploration Storage Yard
66 Jabiru East Potable Water Supply
67 Exploration Core Yard
68 Djalkmarra Land Application Area
69 Djalkmarra Land Application Area Extension
70 Pit 3
71 Levee
72 Magela Land Application Area
73 Borrow Pit
74 Pond
75 Exploration decline vent shaft

Figure 4.3: Locations of the facilities in Ranger Mine (ERA, 2013e)

4.2 Olympic Dam Mine

Olympic Dam is owned and operated by BHP Billiton. It is located in South Australia, approximately 560 km from Adelaide. The closest town is Roxby Downs that is 16 km from the mine site. Olympic Dam is a polymetallic underground mine and has deposits of silver, gold, copper and uranium. The deposit also contains reserves of barium, fluoride and rare elements. However, their extraction is not considered economically viable (BHP Billiton, 2009b). Table 4.2 shows the current resources and reserves at the Olympic Dam mine.

Table 4.2: Resources and reserves

	Measured Resource (Mt)	Copper (%)	Uranium Oxide (Kg/t)	Gold (g/t)	Silver (g/t)
Measured	1,330	0.96	0.29	0.4	2
Indicate resource	4,610	0.79	0.24	0.32	1
Inferred resource	4,120	0.71	0.25	0.24	1
Total resource	10,100	0.78	0.25	0.3	1

Source: BHP Billiton (2016).

The mine uses a sublevel open stope method. Waste rock (mullock) is used to refill the stopes after extraction (BHP Billiton, 2009b).

Copper and uranium ore are extracted from a depth of 860 metres. Ore-haulage is completed with an automatized train to feed the crushing, storage and hoisting facilities (BHP Billiton, 2009b). A schematic of the production process at Olympic Dam is presented in Figure 4.4.

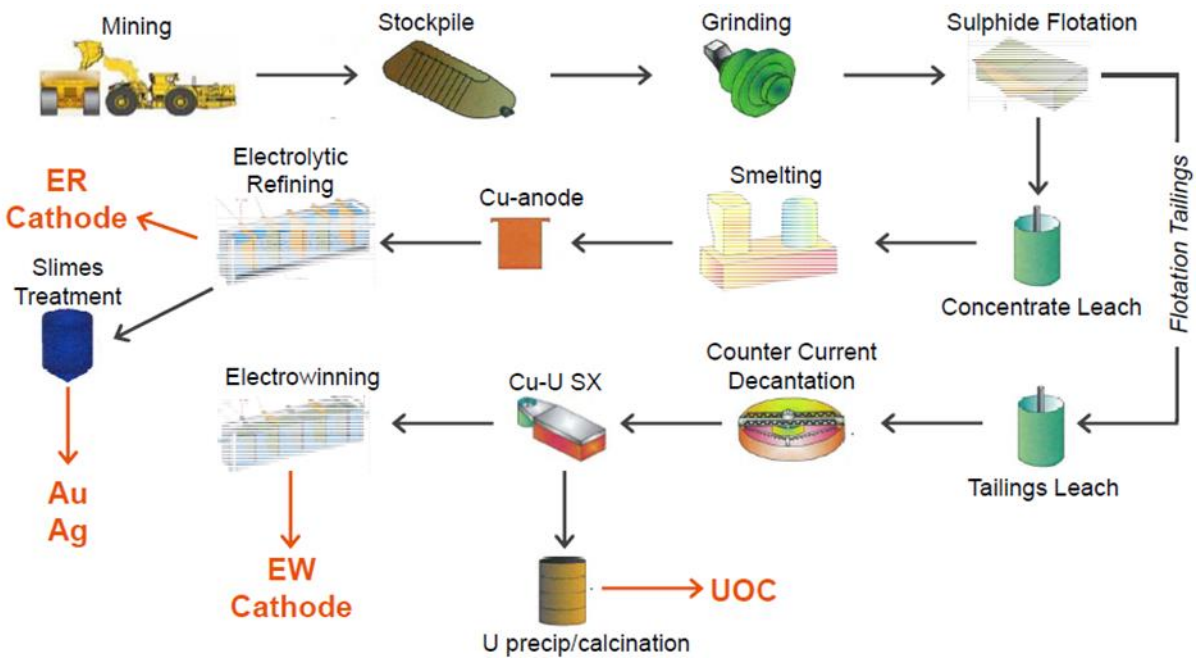

Figure 4.4: Simplified process of uranium extraction from mine to uranium oxide (BHP Billiton, 2015)

4.2.1 Key Infrastructure

Historically Olympic Dam and the closest town Roxby Downs have been affected by extreme weather events that include droughts, heat weaves, lightning and dust storms (BHP Billiton, 2009b). Occasionally, it has also been affected by heavy rainfall and storms e.g. storm of September 2016 (BOM, 2016).

4.2.2 Tailings storage facility

The Tailings Storage Facility (TSF) is composed of four cells used to store waste slurry. These cells cover 400 hectares (BHP Billiton, 2009b). Each year approximately 8 million tonnes of solid tailings are discharged in the tailing storage facilities (BHP Billiton, 2009b). These facilities are also used to discharge hazardous material from uranium processing, including radioactive material (BHP Billiton, 2009b). These facilities are open and exposed to climate conditions.

4.2.3 Workforce accommodation

The Olympic Dam village and Roxby Downs are the two remote communities that serve as the main locations housing the workers of Olympic Dam.

Olympic Dam village, also called the construction camp, is located 6 km south of the mine site. It was built to provide temporary accommodation for 1,365 people, it provides basic services for the workers (BHP Billiton, 2009b).

Roxby Downs is located 14 km south of the mine. It has a capacity to accommodate over 4500 people (BHP Billiton, 2009b). This township was built to service the mine and to accommodate the permanent staff, workers and contractors of Olympic Dam and their families. More than 60% of the Olympic Dam work force lives in the town (GSA, 2011).

4.2.4 Water

The main water source used by Olympic Dam comes from the Great Artesian Basin (GAB). The water contains a moderate level of salinity. There are two borefields used for mineral processing. Borefield A is located 120 km and the bore field B is 200 km from the mine (BHP Billiton, 2009b). The bore fields have some bores for production and others for monitoring. Approximately 6 million litres per day (ML/d) are extracted from Borefield A, while 26ML/d from Borefield B (BHP Billiton, 2009b). Every day about 37 ML are pumped. A small portion of this water (0.6 ML) is used by pastoral stations located along the route to the mine (BHP Billiton, 2009b). Olympic Dam has a desalination plant that treats 14ML of water every day. This water is used at the hydrometallurgical and refining process as to provide potable water for Olympic Dam village, Roxby Downs and Andamooka (BHP Billiton, 2009b).

4.2.5 Power

Electricity is transmitted by ElectraNet by a 275-kV transmission line from Davenport substation located in Port Augusta (Kinhill, 1997; BHP Billiton, 2009b). There is another transmission line of 132 kV from the National Electricity Grid that is mainly used as support or stand-by for emergencies (Kinhill, 1997; BHP Billiton, 2009b). In addition, the mine has two diesel alternators (2400kW) in the metallurgical plant and three diesel alternators at the Whenan shaft (800kW) that can be used in emergencies (BHP Billiton, 2009b).

4.2.6 Roads

The main access to the mine site is by road through the Stuart Highway, which passes within 103 km of the mine. From that point, it is necessary to take an outback track to Olympic Dam. Uranium oxide is transported in drums inside containers by trucks to Port Adelaide and then is transported by train to Port Darwin (BHP Billiton, 2009b) for export.

4.2.7 Air

The local airport at Olympic Dam is located 6 Km South of the mine site and 7 Km North of Roxby Downs. Alliance Airline is the flight operator; it employs an aircraft fleet consisting of Fokker F50 planes with a capacity of 56 seats (BHP Billiton, 2009b). The closest meteorological station to Olympic Dam mine is located in this airport. (BOM, 2011b).

4.2.8 Rail

Rail transport to the mine is limited from/to Adelaide because there is no rail line to Olympic Dam (BHP Billiton, 2009b). The railway has also been affected by the intense casual flooding in the area, which may lead to damages in the track formation and ballast, resulting in derailments, such as the one occurred in 2009 near Golden Ridge (AG, 2010). The last heavy storm of September 2016 caused damage to the railway infrastructure whose reparation cost is estimated at $1.2 million (Burns *et al*, 2017).

4.2.9 Port

A port storage facility is located in Port Adelaide. It consists of a copper handling and freight loading and unloading facilities. Chemicals are located in another facility 1.5km east of the Port (BHP Billiton, 2009b). This Port has been affected by extreme weather events especially flooding; the coastal areas of Adelaide have been classified as high vulnerable to climate impacts. Flooding has been classified as the highest cost ($32 million) natural disaster in South Australia (Burns *et al*, 2017).

5 Industry Survey

This chapter provides the information gathered from companies' reports about stakeholders then they were organised as supply chain participants in both uranium mines (more details in Chapter 6). Furthermore, details about the survey's preparation and how the research questions were related to the survey.

5.1 Establishment of the Uranium Supply Chain Participants

The selection of participants of the supply chain for each of the mines was based on the Delphi subject definition provided by Hsu & Sandford (2009) (Based on Pill, 1971; Oh 1974). This states that a participant in a Delphi study should have a background and experiences related to the target issue and are available to contribute their inputs to the study. In addition to this general profile, Delbecq *et al* (1975) suggest the following characteristics for a participant: top managers and decision makers and/or a professional staff member.

5.2 Ranger Mine

A description of the supply chain participants for the Ranger Mine is provided below. The sources of information to gather data about these groups included company's reports and websites.

5.2.1 Traditional owners

Traditional owners of the land are mainly indigenous communities who were settled in the territory before colonisation (Petheram *et al*, 2010). The traditional owners of the land around Ranger are described below.

Mirrar community: They are the traditional owners of the land where the mine is located (Banerjee, 2000). Their claim includes Jabiru and parts of Kakadu National Park. There are two Aboriginal Land Trusts and a free ownership created by the government that supports the Mirrar community as traditional owners of the land (ERA, 2013e).

The Gundjeihmi Aboriginal Corporation (GAC): The Northern Land Council at the request of the Mirrar community in order to receive the royalties paid by Ranger created this Corporation in 1995. This organization represents and helps the Mirrar community to protect their rights and interests (Petheram *et al*, 2010; GAC, 2017).

Northern Land Council (NLC): This organization was created under the 1976 Act of the Commonwealth Aboriginal Land Rights to represent the aboriginal people in their rights as owners (NLC, 2015). The main function of the NLC is to consult with the aboriginal people affected by mining operations, so they can express their view and concerns (NLC, 2015).

5.2.2 Regulatory bodies

The government agencies and local regulatory bodies have a mission to protect the environment and the inhabitants through regulations. Some of them are described below.

Department of Mines and Energy in the NT: Local government organization that has the responsibility to authorise the operations at the Ranger Mine. It also carries out audits and inspections at the mine site associated with health and safety (DME, 2015)

Commonwealth Department of Industry: This department belongs to the Australian Government and provides authorisation for ERA to extract and process uranium ore under specific conditions (ERA, 2013e). The authorization of exportation of uranium oxide is under the Regulation 9 of the Customs - Prohibited Exports-Regulations 1958 (ERA, 2013e). This department also approves the rehabilitation plan that is prepared in agreement between ERA and the Australian Government (ERA, 2013e).

Supervising Scientist Division (SSD): This division belongs to the Australian Government – Department of the Environment and was created in 1997 under the Act of 1978 (SSD, 2015). This division has the role to assess, supervise, audit, monitor and research the extraction and processing of uranium in the Alligator Rivers Region (SSD, 2015)

5.2.3 Committees

Alligator Rivers Region Technical Committee (ARRTC): This committee was created in 1993 under the Act of 1978 from the Commonwealth Environment Protection (Alligator River Region). The role of this committee is to assess the environmental research conducted in the region (ARRTC, 2015). The members of the committee are appointed by the Minister of Environment and include the Supervising Scientist and representatives of ERA, NLC, NT Mines and Energy Department and other stakeholders (ARRTC, 2015).

Alligator Rivers Region Advisory Committee (ARRAC): This committee was created under the Act 1978 as well as the ARRTC. The purpose of this body is to share information between stakeholders. This information is related to the effects of uranium mining in the region in order to make transparent to the public and other shareholder the mining operations (ARRAC, 2017).

Mine site technical committee: This committee provides support in the discussion and application of environmental management issues at mine sites (MTC, 2015). The members of this committee include representatives from The Department of Mines and Energy (DME), NLC, SSD, Mining Company involved and other relevant organisations (MTC, 2015). This committee can suggest changes in mining operations and rehabilitation (ERA, 2013a).

5.3 Olympic Dam

A description of the supply chain participants for the Olympic Dam Mine is provided below. Stakeholders are defined by BHP Billiton (2006) as follows: "Our key stakeholders are generally defined as people who are adversely or positively impacted by our operations, those who have an interest in what we do or who have an influence on what we do". According to this definition, BHP Billiton (2009) has classified their stakeholders below:

- Government: National, State (or Territory), and Local Government and representatives.
- Non-government organisations and services providers: Community groups, environmental groups, services providers and research groups.
- Industrial and business: Regional and local development and businesses organisations.
- Aboriginal groups: Traditional owners (Native title claimant groups).

  There are two aboriginal groups that claim ownership rights through the native title according to the Commonwealth Native Title Act of 1993 (Tolazzi, 2012). They include the Kolkatha and Barngarla communities (Tolazzi, 2012). The Kuyani community does not possess the native title claim but they affirm to have rights and interests in the area (BHP Billiton, 2009c).
- Landholders: Current pastoral leaseholders and freehold landowners.
- Relevant communities: Towns, cities, regions
- Employees and contractors: Staff, consultants and contractors.
- Public: National, State (or Territory), regional and local community.

5.4 Survey Preparation

A self-completed questionnaire (survey) was the basis for collecting data for this research. A copy of the survey distributed to participants can be found in Appendix II.

The survey was distributed to respondents through the internet. The questionnaire was designed considering the following factors:

- Company/organisation/community of the respondents.
- Seniority of the role of the respondents e.g. manager, engineer, operational work, etc.
- Knowledge or experience of respondents e.g. years or experience of working in a company or living in a community.
- Location of the respondents

The survey contained three classes of data that were collected: Factual or demographic, attitudes/opinions; and behaviours / events (Dillman *et al* 2014).

- **Factual or demographic variables**: are data easy to answer by the respondents and should be easy to disclose e.g. which best describes your role/position in the company/organisation/community? In which state is your company/organisation or community based/located? These data can be used to explore the difference in responses. In the design of this survey, there were five factual questions that established the respondents' credentials.
- **Attitudes and opinions variables**: In these questions the respondent must think before giving an answer to the question e.g. from your experience, what are the most influential climate conditions that most affect your company/organization/community?
- **Behaviours and events variables**: These questions are intended to collect information about what people/organisations did in the past regarding an event, or what they will do in the future e.g. Has your company/organisation/community performed a climate change vulnerability assessment?

The main concern regarding the design of this survey was to ensure that the data collected would provide specific answers to the research questions. To ensure the survey was designed correctly the following data table (Table 5.1) was prepared with requirements based on Saunders *et al* (2016).

Table 5.1: Data requirements for survey preparation

Main research question: How has the uranium supply chain in Australia been impacted/ and will be impacted by climate change?

Type of research: Mainly descriptive and exploratory

Investigative questions	Variable(s) required	How data is measured	Relation with key concepts in literature
Who are the uranium industry participants? (Factual and demographic)	Information about participants' sector in the supply chain e.g. Mining company, water, energy etc.; about role/position, years of experience/living, and demographic information about location	Direct information provided by respondents	Companies reports about stakeholders
What kind of climate risks have affected the uranium supply chain? (attitudes and opinion)	Kind of climate risk experienced, frequency, rate of the exposure of the system you belong	Opinion from respondents based on experience	Pearce *et al* (2009); Pearce et al (2011); Ford *et al* (2009); Loechel *et al* (2013 ab); Hodgkinson *et al* (2014)
How have climate risks affected stakeholders across the uranium supply chain? (attitudes and opinion)	Identification of impacts caused by climate risks in business performance and operationally e.g. loss revenue, quality production or processing plant, ore extraction, etc. Investigate about flow-through and flow-on impacts.	Opinion from respondents based on experience and knowledge	Pearce *et al* (2009); Loechel *et al* (2013ab)
How will climate risks affect members across the uranium supply chain in the future? (attitudes and opinion	Identification of the likely damages in business performance and in the operations.	Opinion from respondents based on experience and knowledge	Pearce *et al* (2009); Loechel *et al* (2013ab)
What has been done to cope with climate risks?	Rating of the response plan to cope with climate risks in terms of adequateness, clarity, responsibilities, procedures, and effectiveness. Identification of the existence of a vulnerability assessment plan.	Evaluation from respondents based on experience and knowledge	Loechel *et al* (2013ab), Pearce *et al* (2009), Pearce *et al* (2011)
How can the response to climate risks improve in the future?	Rating of the plan to cope with climate risks and improvements needed for the future climate change	Evaluation from respondents based on experience and knowledge	

5.5 Survey Design

The questions throughout the survey were designed to consider the wording, length and content of each question. There was a special focus on wording, to ensure clear questions were posed to ensure high quality responses. In some questions, it was not possible to keep the length less than 20 words as suggested (Sekeran and Bougie, 2013).

Questions were developed in such a way that content was easy to disclose and there was no requirement to disclose confidential information. The survey questions that focused on vulnerability assessment included mainly closed questions but also provided an open option. Open questions give the free option to answer the question (Fink, 2013) and closed questions limit the options of the answer to a list of alternatives (Vaus, 2016). Saunders *et al* (2016) provides a definition for open questions**.** These questions are common when the answer is unknown. They provide the opportunity to express unique ideas.

Saunders *et al* (2016) classify six types of closed questions that have been used in the current research to develop a 25 questions survey. They include:

- **List questions**: provide alternatives to the respondents. Respondents can choose one or more answers from the list including "do not apply" or "other". Of the survey developed, 13 out of the 25 questions are list questions with an open option which was "Other – Please Specify".
- **Category questions**: provide only one option for answers and are aimed at gathering data. The questions should be posed in logical order, mutually exclusive and be directly relevant to the respondents. For example: How often have climate risks affected your company?
- **Ranking questions:** order a list of options according to the importance for the respondents and may include "other" as an option. It is recommended not to include more than seven items to rank (Saunders *et al,* 2016). Of the survey developed, two out of the 25 questions were ranking questions.
- **Rating questions**: gather data from opinions or evaluations. The Likert-Style rating is often used, which grades from "Agree" to "Disagree" in descending order. Positive and negative statements are included to rate and the same categories if there are more than one statement (Dillman *et al*, 2014; Vaus, 2016).
- **Quantity questions**: define an amount and are aimed at gathering attribute/behaviour data (Saunders *et al,* 2016). Of the designed survey, two out of the 25 questions were quantity questions.

- **Matrix questions**: gather data of several related questions at the same time. Highly efficient, however, they can be difficult for respondents to understand (Dillman *et al,* 2014; Vaus, 2016). Of the survey developed, three out of the 25 questions are matrix questions.

In this survey, it was not conducted a pilot survey because of the time constraint. The survey was delivered via the internet to 250 stakeholders but just 21 responded it. In a second phase, the survey was delivered to additional 100 persons and we received five additional responses, for 26 responses. The data collection phase lasted from February to September 2016.

6 Vulnerability Assessment

The vulnerability assessment was published as a paper in a Q1 Journal (provided in Appendix IV). The reference is provided below.

Pizarro, J, Sainsbury, B, Hodgkinson, J, and Loechel, B, 2017. Australian uranium industry climate change vulnerability assessment. *Environmental Development*. http://www.sciencedirect.com/science/article/pii/S221146451630344X

A reformatted version is provided here in for completeness.

6.1 The Australian Uranium Industry

The mining industry's contribution to the Australian economy has historically been high: for example, in 2015 it represented 46% of the total value of Australian exports (ABS, 2016). As a source of energy, uranium is a small part of this trade comprising just 0.8% of the total value of exports; however, it represents 16.5% of the total energy exported from Australia in 2014-2015 (AG, 2016). Australia is the world's third largest producer, behind Kazakhstan and Canada (World Nuclear Association, 2016). Australia has 31% of the world's known uranium reserves, and supplies 12% of world uranium demand (MCA, 2016). At the present time, all of Australia's uranium output is exported to Asia, Europe and North America. Australia's volume of uranium exports is expected to increase by 9.9% during 2017-2018, in line with demand. This comes after a decrease of 6.8% in 2016-2017 (AG, 2016b). The expected nuclear energy demand has been recently impacted by:

- The devastating earthquake and tsunami in 2011 that resulted in the Fukushima Daiichi incident. This incident contributed to reducing uranium demand worldwide and increased the costs of construction of power plants due to increased safety requirements and higher discount rates for investments in nuclear energy (Hayashi and Hughes, 2013)
- Higher costs of initial investment, technical/knowledge expertise in nuclear plant operations and more stringent market and regulatory requirements with local governments and worldwide agreements (IEA, 2011)
- A lack of worldwide agreement regarding the long-term storage and treatment of nuclear waste (Bruckner *et al,* 2014)
- A trend of declining uranium spot prices in the last 6 years, with possible increases in future prices still dampened by the accumulation of inventories and abundant supply (AG, 2016).

Nevertheless, there are currently 66 reactors under construction, 160 planned and 300 in the proposal stages (WNA, 2016b). While Australia does not produce nuclear energy itself, the worldwide increase in nuclear power facilities offers a significant opportunity for the Australian uranium mining industry.

Uranium has been mined in Australia since 1954. During 2016, there were three Australian uranium mines operating: Energy Resources of Australia's (ERA) Ranger Mine located in the Northern Territory, BHP Billiton's Olympic Dam and Four Mile mines, located in South Australia (WNA, 2016a). Their locations are presented in Figure 6.1.

Figure 6.1: Current, former, and prospective uranium mines in Australia (Source: WNA, 2016a)

In 2015-2016, most of Australian uranium production (80.27%) was from the Ranger and Olympic Dam mines. Historically, these mining operations have been impacted differently by climatic conditions in both direct and indirect ways due to the nature of their operations (open pit and underground respectively).

At the Ranger Mine, production and safety have been directly influenced by extreme rainfall. Olympic Dam has been indirectly affected by energy interruptions during heat waves and scarcity of water during prolonged periods of drought (BHP Billiton, 2009b; BHP Billiton, 2012; Torrisi and Trotta, 2013; Toledano and Roorda, 2014). For example, during 2016, an unusually heavy storm impacted operation

at Olympic Dam mine that caused shutdown of the mine for 15 days due to energy supply issues (BHP Billiton, 2017).

Both mines have documented the monetary impact of extreme weather events to their operations in recent years (BHP Billiton, 2009b; BHP Billiton, 2012; Rio Tinto, 2012; ERA, 2013b; BHP Billiton, 2015) and they have considered climate change in their expansion plans (BHP Billiton, 2009a; ERA, 2013b).

6.2 Climate change adaptation in mining

Climate change scientists suggest that extreme weather events (primarily heat waves) would increase in frequency in South Australia and cyclones will increase in intensity in the Northern Territory by 2030 (Watterson *et al*, 2015; Moise *et al*, 2015; Reisinger *et al,* 2014). Loechel *et al* (2013a, b) have previously documented the disruption to the Australian mining industry caused by extreme weather events including drought, heat waves, and heavy rainfall. They also report that only a limited number of mining industry survey participants recorded that they were concerned about future climate change and the potential impact on their operations. At the time, mines were more concerned with developing mitigation measures to reduce their emissions (Loechel *et al* 2013b).

Three years on, in 2016, some mining companies have accepted climate change as being a significant risk to their operations (Rio Tinto, 2015; BHP Billiton, 2015). This suggests that proactive adaptation measures may be necessary to ensure business continuity in the light of climate change (Hodgkinson *et al,* 2010; BSR 2011) within mine operations plans. Without climate change adaption strategies in place, production may be adversely affected, impacting the world uranium supply chain. Therefore, there is a growing need to assess how climate conditions and climate risks have impacted the industry to date and how they may impact it in the future. For this purpose, a vulnerability assessment of the industry has been performed focusing on the current uranium operations at the Ranger and Olympic Dam mines.

Analysis of public domain company reports (full annual reports and sustainability reports) from both the Olympic Dam, and Ranger Mine was conducted to identify how they have been affected by climate risks and if they have taken any approach to deal with future climate risks.

6.3 The concept of vulnerability assessment

Vulnerability to climate change, as conceptualised by Ford and Smit (2004), Smit and Wandel, 2006; Ford *et al* (2009), Pearce *et al* (2009), and Pearce *et al* (2011) can be considered a function of

exposure/sensitivity and adaptive capacity. Pearce *et al* (2009) have defined components of vulnerability for the mining industry that have been applied in this study. They are provided below:

Exposure/sensitivity: the tendency of mining operations to be affected by climate conditions assessed by parameters including frequency, magnitude, location and impacts.

Adaptive capacity: the ability of the mining company to plan towards changing their operations to suit climate conditions. This involves the identification and characterisation of the current risk management plan's ability to cope with climate risks.

Nelitz *et al* (2013) have defined a vulnerability assessment as the process of measuring or characterising exposure, sensitivity and adaptive capacity of a system (natural or human) to any disturbance. Two approaches used to assess vulnerability include a top-down approach and a bottom-up approach (Nelitz *et al*, 2013). The top-down approach is focused on global climate models and their downscaling of projections that are used as inputs to project regional climate impacts and to evaluate the physical vulnerability (Nelitz *et al*, 2013). The bottom-up approach focuses on understanding the past and present vulnerability that is used to estimate future vulnerability and adaption options to reduce the future vulnerability (Nelitz *et al*, 2013). Both approaches have different emphasis or perspectives but are complementary (Dessai and Hulme, 2004).

In this study, the bottom-up approach has been applied based on the input of stakeholders to evaluate both social and physical vulnerabilities (Nelitz *et al*, 2013). Predictive biophysical models have been replaced by stakeholder feedback that has been collected via survey methods.

6.4 Historical impacts of climate and extreme weather events

This section describes the climate characteristics and historical record of the main climate events that have affected the region where each mine is located. It also reviews expected future climate conditions, based on downscaled projection provided by the Intergovernmental Panel on Climate Change and Reisinger *et al* (2014). These projections are based on the downscaling of Global Climate Model (GCM) simulations for each RCP scenario to the conditions of each area. A confidence language has been specified by IPCC (2007) for climate projections, that employs the follows qualifiers 'very high', 'high', 'medium', 'low' and 'very low' for confidence of projections.

6.4.1 Ranger Mine

Based on the division of Australia into Natural Resource Management (ANRM) regions, the Ranger Mine is located in the area described as the Monsoonal North West sub-cluster (Moise *et al*, 2015).

There are two well-defined seasons in this area that include a wet season, from October to April and a dry season, from May to September. The wet season has historically caused water management issues at the Ranger Mine (ERA, 2012). During 1910 to 2013, the temperature in this area has increased by 0.9^{o} C - 1.0^{o} C, in minimum and maximum respectively (Moise *et al*, 2015).

Since 2006, several extreme weather events (intense rainfall/flooding and cyclone activity) and their associated impacts have been documented at the Ranger Mine. They include:

- Halt of mining and processing for periods of one day to four and a half months during 2011 (ERA, 2011; ERA, 2012);
- Flooding of the operational pit in 2006, 2007, 2011, and 2012 (ERA, 2007a; ERA, 2008a; ERA, 2012; ERA, 2013);
- Flooding of the tailings facilities in 2007 and 2010 (ERA, 2008a; ERA, 2011);
- Blocked access to the high-grade ore in 2006, 2007a, 2010, 2011, and 2012 (ERA, 2007a; ERA, 2008a; ERA, 2011; ERA, 2012; ERA, 2013).

These events can be linked to documented financial and operational impacts that include:

1. Restriction of exploration activities (capacity to increase ore reserves) to the dry season only (ERA, 2013; ERA, 2014);
2. Decreased production (actual versus planned). Figure 6.2 presents historical production rates from 2005 to 2015 that clearly show the downwards trend in production over this time. In addition to the climate event impacts (detailed below) production at the Ranger Mine was also negatively impacted by lower milling rates in 2013 and the closure of the mine for 6 months in 2014 due to the accidental spill of slurry from a leach tank (ERA, 2014; ERA 2015).
   a) Production in 2006 decreased 20% to 4748 tonnes equating to AU$64 million loss in revenue (calculation based on average commodity price of AU $24.98 lb in 2006). This also resulted in the purchase of 316 tonnes of uranium oxide to fulfil contract commitments in 2007 (ERA, 2008a).
   b) In 2010, the interruption of mining operations caused a decrease in production of 28%, (1447 tonnes) resulting in a calculated loss of AU$196 million in revenue (ERA, 2011).
   c) Disruptions in 2011 led to 30% decrease in production and forced the company to purchase 2126 tonnes of uranium at an estimated cost of AU$253.2 million in the market to meet contract commitments (calculation based on the average spot price during 2011).

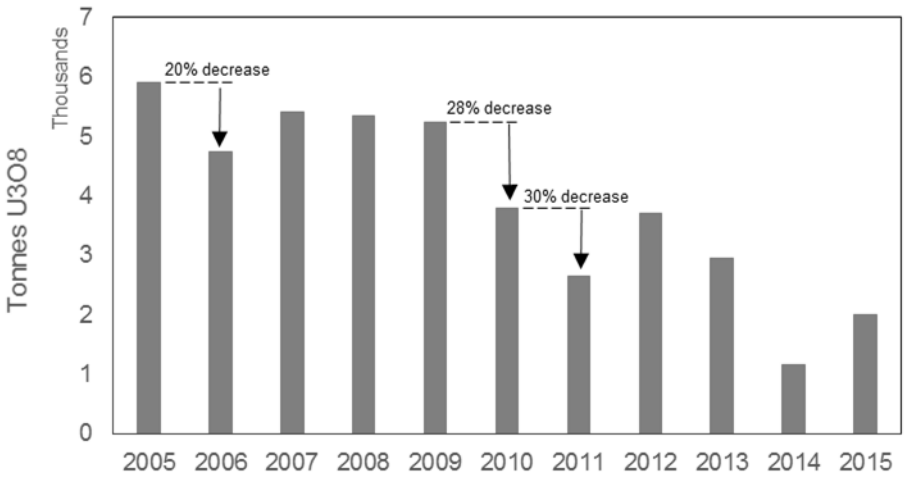

Figure 6.2: Production rates at the Ranger Mine 2005 – 2015 (ERA, 2008a; ERA, 2009; ERA, 2010; ERA, 2011; ERA, 2012; ERA, 2013; ERA, 2014; ERA 2015).

3. Damage to capital infrastructure. A review of annual reports provides costs associated with expenditure for each year (ERA, 2008a; ERA, 2009; ERA, 2011; ERA, 2012; ERA, 2013). The historical trend of capital expenditure at the Ranger Mine for the period 2006 to 2015 is provided in Figure 6.3. In each of the years, 2007, 2008, 2010, 2011 and 2012, the increase of capital expenditure can be attributed to costs associated with the impacts of extreme weather events that included flooding and cyclones. The 2012 costs can be directly attributed to the construction of a brine concentrator that is used to reduce the process water inventories, especially in wet season to avoid flooding or discharge of process water to the environment (ERA, 2013). The total cost of the brine concentrator was AU$220 million (ERA, 2011).

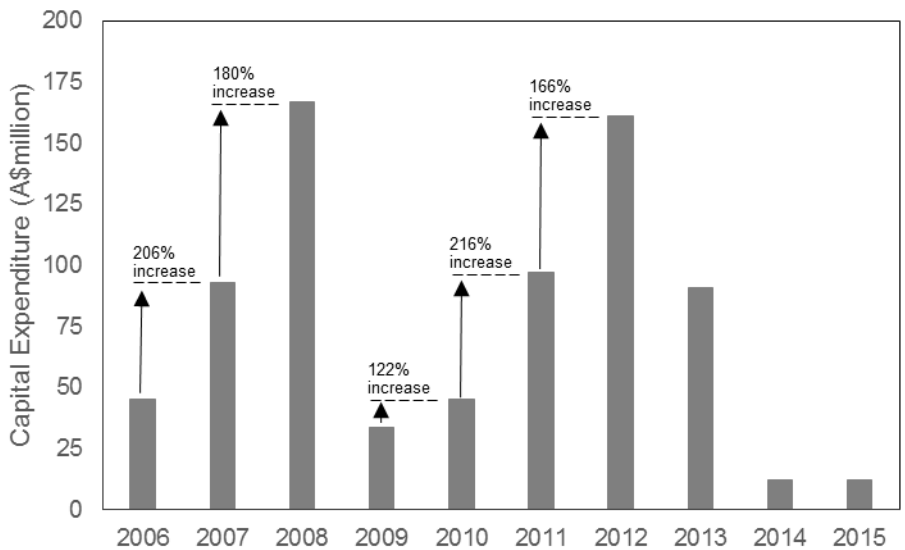

Figure 6.3: Capital expenditure at Ranger Mine, 2006 - 2016. (ERA, 2008a; ERA, 2009; ERA, 2010; ERA, 2011; ERA, 2012; ERA, 2013; ERA, 2014; ERA 2015)

Climate impacts at the Ranger Mine also implied additional capital and operating costs associated with:

- removal of temporary excess water from the pit (ERA, 2007a)
- raising the height of the tailings storage facility three times for a total cost of AU$72 million (ERA, 2008a; ERA, 2009; ERA, 2013).
- installation of a new water treatment facility to treat contaminated floodwater at the site (ERA, 2009).
- access and service impacts to the local town of Jabiru, which is situated approximately 8 km east of the mine and provides accommodation for the workforce. Jabiru has been affected by extreme weather events, with documented negative impacts on power, water and communication services, and damage to houses and local businesses because of flooding (AECOM, 2010). In addition, local access roads and bridges were damaged due to cyclone activity in 2011-2012 requiring extra funding for repair (WASC, 2011, WASC, 2012).

Based on this summary, ERA have spent an estimated AU$514.5 million on climate related impacts over the 10 years from 2005 to 2015. Over this time, a total of AU$403 million in lost revenue has been estimated due to production issues and/or the need to purchase ore to fulfil contract agreements.

Climate projections to 2030 suggest with high confidence that the temperature will continue to increase at the historical rate (0.9^{o} C - 1.0^{o} C, in minimum and maximum respectively) coupled with an increase in days over 35° C and heat waves. The frequency and the duration of extreme weather events are also expected to increase (Moise *et al*, 2015).

Rainfall variations in all seasons are projected with low confidence for this area with variations ranging from a reduction of 7 mm to an increase of 49 mm (Moise *et al*, 2015). Extreme weather events such as heavy rainfall is projected to increase in frequency in the coming years. The frequency of tropical cyclones is projected to decrease but each event is expected to increase in magnitude (Moise *et al*, 2015).

6.4.2 Olympic Dam

According to the ANRM map of Australia (Watterson *et al*, 2015), the Olympic Dam mine is located in the area referred to as the Rangelands-South sub-cluster. Over the past century, rainfall in this area can be characterised by very dry periods to periods of heavy rainfall (Watterson *et al*, 2015).

The pattern of rainfall during the last century has shown a slight increasing trend, with recurrent cycles of wetter and drier conditions with respect to the baseline average (established 1986-2005). Over this time, very dry periods (2002-2009) usually followed periods of heavy rainfall such as 2011, being also the highest level of rainfall in history (Watterson *et al*, 2015). In terms of seasonal rain patterns, the slight upward trend can be attributed to a higher magnitude of rainfall during the summer in the northwest portion of the area, matched partially by slight decreases of rainfall during the autumn and winter in the southern region of the area. Further, mean temperature near Olympic Dam has risen by 0.9^{o} C over the past 100 years.

On the other hand, minimal published information associated with the impact of extreme weather events at the Olympic Dam mine is available. BHP Billiton has previously documented that their Olympic Dam mining activities have been adversely affected by weather events (BHP Billiton, 2015). These events have been characterised by variations in water supply and increasing temperatures (BHP Billiton, 2012) that have included extended periods of droughts (2002 - 2009) and intense rainfall, storms and strong winds (2010 - 2011). These events have caused the temporary closure of the surroundings roads to the mine (Arid Recovery, 2011) impacting on the supply chain. Recently an extreme storm event, that included intense rainfall (with total precipitation more than double the average for the month), thunderstorms, lightning strikes and strong winds of 95 km/h, caused flooding and a state-wide energy blackout in South Australia that lasted several days (BOM, 2016; AEMO, 2016). Consequently, Olympic Dam had to halt operations for 15 days during September 2016. Estimates of economic losses have not yet been calculated but the event is expected to have impacted production capacity (BHP, 2016). In contrast to the Ranger Mine, Olympic Dam has undertaken water management programs in response to water scarcity issues (RepRisk, 2009, ICMM, 2012). This includes a water saving project implemented in 2004 (ICMM, 2012).

Projected rainfall up to 2030 will strongly reflect natural variations, with average annual rainfall oscillating around ±10% from the baseline average of the period (1986-2005) and seasonal rainfall variances predicted to be around ±20% from the average (Watterson *et al*, 2015). Mean temperature is projected to rise by approximately 0.6^{0}C to 1.5^{0}C by 2030 (with very high confidence) in all future emission scenarios.

6.5 Vulnerability assessment

A vulnerability assessment of the industry has been undertaken based on stakeholder feedback collected via survey methods. The survey focused on sampling the opinions of uranium mining chain participants that include mining and service provider employees, consultants, contractors,

government organisations, local communities and non-governmental (not-for-profit) organisations (NGOs). The survey was designed with questions based on historical climate impacts documented at the Ranger Mine and at Olympic Dam; and the consideration of climate risks that are expected to increase at these sites in the future. Existing vulnerability was measured by asking participants to indicate the most influential climate risks, their frequency and impact they may have had on their company's operations or their immediate environment e.g. "From your experience, what are the most influential climate conditions that most affected your company/organisation or community". Additionally, participants were asked about the possible indirect impacts they have experienced. Future vulnerability was assessed by asking participants to provide an estimate, based on present vulnerability, of the future vulnerability e.g., "If the climate risks identified become greater how would you rate the impact to your company/organisation/community"?

Adaptive capacity was qualitatively assessed through the evaluation of the current site risk management plans against known climate risks. Participants were asked to self-assess their sites ability to deal with the effects of climate risks through the implementation of current policies and procedures documented in their vulnerability assessment and risk reduction plan/s. Future adaptive capacity was assessed based on the perception of present adaptive capacity e.g. Participants were asked what types of changes do you think are required to improve the adaptive capacity of your company/organisation?

This survey was delivered via the internet to uranium mining stakeholders in Australia between the end of February and June 2016. Respondent data was analysed in IBM SPSS statistics software (V.22) using several tests. Due to the small number of responses (250 persons were contacted but just 21 of them completed the survey), an analysis of independence was conducted using the Fisher's exact test only.

To run a Fisher's test, 96 cross tabulations between responses and categories were performed. These associations were generated for all multiple-choice responses and respondent categories classified by:

a) geographical location (whether they are located in the Northern Territory or South Australia);
b) position or role in the company; and
c) level of experience (0 to 10, 11 to 19 and 20 or more years).

These categories provided an assessment of significant variation in survey responses. Values of $p < 0.05$ indicate that the distribution of responses is significantly different between the category test groups. Values of $p \geq 0.05$ suggest that there is no significant difference between groups of respondents.

Weighted averages of rating and ranking responses were also used to interpret (and rank) the survey responses. To do this, respondents were asked to rate or rank several statements regarding their

organization's experience or capacity through a grading scale. The proportion of respondents who selected each grade, to arrive at one average rate or rank, weighted the scores.

6.6 Profile of respondents

The selection of the participants for this survey was based on having a background and experience related to uranium mining and/or the uranium industry (including nearby communities) at either of the Olympic Dam or Ranger Mine sites.

There were 21 survey respondents across a broad cross section of the community that included past and present contractor, consultant companies, transport companies, state government, community services, community members and NGOs and mine employees. Their roles varied greatly from professional management positions, engineers and scientists to administrative staff and community members. Most respondents had more than 20 years of experience in the uranium industry. A summary of the respondents' profile is provided in Table 6.1.

Table 6.1: Profile of survey respondents

Organisation type	**Responses**	**Role/Position**	**Responses**
Mining company	3	Management	14
Mining services	1	Engineer	1
Contractor	3	Scientist	1
Consultant	5	Administrative staff	2
Transport-roads trucking	1	Community member	1
Government-State	3	NGOs	1
Community Services	1	Coordinator	1
		Location	
None (member public/local community)	2	Northern Territory	5
Other (not specified)	2	Queensland	1
		New South Wales	1
		Victoria	2
Total	**21**	South Australia	12

6.7 Present vulnerability assessment

The following sections describe the results of the survey conducted to evaluate the historical and estimated vulnerability and adaptive capacity of the uranium mining industry to climate change risks within Australia.

Respondents were questioned on climate conditions that most affected their companies/organisations/communities both in terms of how influential the nominated climate event was and how frequently it occurred. Respondents were also asked to rate their organisation's overall risk exposure to climate conditions. Most respondents (65%) indicated that intense rainfall/flooding have been the most influential weather event/s in the past. This is despite the two mines being located in different climate zones. Respondents from South Australia listed "heat waves" as an influential climate risk, with a much higher tendency ($p=0.04$) than those in the Northern Territory. Respondents with at least ten years of experience were also more likely to cite "heat waves" as an influential climate risk ($p=0.05$) and respondents with 20 or more years of experience reported heavy rainfall and flooding as the most common climate risk ($p=0.03$). Surprisingly, these results suggest the occurrence of heat waves has been more common in South Australia than the Northern Territory in the last 10 years. Over a broader period of time (more than 20 years), heavy rainfall and flooding appears to be the most influential climate risk at both locations.

According to the respondents of the Northern Territory, the frequency of climate risks varied from "once a year" to "once every 10 years" for climate risks such as intense rainfall/flooding, heat waves, storms, fires and droughts. In the case of South Australia, the frequency of climate risks varied from "once a year" to "less than once in 20 years" for risks that included intense rainfall/flooding, heat waves, droughts and storms. In addition, state government representatives indicated that extreme weather events caused issues every year and consultants documented that climate risks are a constant issue when companies undertake environmental impact assessments.

The last question in this section was to rate the exposure of their companies/organisations/communities to climate risks, from a scale of 1 to 10 where one was low exposure and 10 high exposure. See the Table 6.2.

Table 6.2: Rate of exposure to climate risks

	N	Average Score	p value location SA	p value location NT	p value years of experience 0 -10	p value years of experience 11-19	p value years of experience 20 or more	p value management
Droughts	15	3.20	0.154	0.286	0.882	0.193	0.197	0.197
Fires	14	3.93	0.793	0.815	0.389	0.285	0.804	**0.021**
Heat waves	16	4.75	0.211	0.522	**0.000**	0.052	0.239	0.935
Storms	14	5.07	0.762	0.249	0.515	0.168	0.501	0.762
Intense rainfall/flooding	20	4.90	0.876	0.077	0.604	0.088	0.354	0.295
Other	3	3.67	0.667	0.667	NULL	NULL	NULL	NULL

In contrast to the earlier question, where those with at least ten years of experience cited “heat waves” as the most influential climate risk, for this question it was respondents with 10 or fewer years of experience who rated the risk of exposure to “heat waves” higher than the rest of the sample with the difference being statistically significant. This suggests that in the last 10 years the industry has been more exposed to heat waves than any other climatic event. In addition, from a management perspective the industry is more exposed to fires (P=0.02).

Respondents were asked to identify the main impacts to their company/organisation/community that climate events have had, with the possibility to identify more than one response. The results are provided in Table 6.3.

Table 6.3: Impacts caused by climate risks

	% (n=21)	p value location SA	p value location NT	p value years of experience 0 -10	p value years of experience 11-19	p value years of experience 20 or more	p value management
Financial performance	45.0%	.465	.625	.604	.145	.157	.426
Loss of revenue	60.0%	.388	.535	.693	**.049**	.113	.545
Increased costs	60.0%	.113	.465	.307	.344	.612	.187
Operational disruption	70.0%	.455	.657	.483	.681	.455	.613
Delayed production	45.0%	.205	.217	.604	.145	.157	.574
Quality of production	10.0%	.653	.368	.447	.716	.653	.521
Supply of essentials (water, energy, telecommunications, labour or materials)	40.0%	**.054**	.465	.704	.656	.612	.545
Transportation of the product	20.0%	.153	.162	.282	.491	.102	.343
Health and safety of workers	55.0%	**.040**	.625	.221	.421	.465	.574
Infrastructure and equipment damage	40.0%	.612	.153	.307	.344	.612	.545
Other (specified)	10.0%	.147	.632	.553	.716	.347	.521

p-values for the null hypothesis of equal percentage of agreement between the nominated group and the rest of the sample

Most respondents (70%) identified operational disruption as the main climate related impact followed by loss of revenue and increased costs, health and safety of workers, delay in production, financial performance, and damage to infrastructure/plant and equipment. A less significant impact was the supply of essential inputs and services (e.g. water, energy, and telecommunications), infrastructure, plant and equipment damage, transportation of products and quality of production.

Respondents from South Australia showed a higher tendency to single out the “supply of essential inputs or services” (p=0.05) and the “health and safety of workers” (p= 0.04) as impacts to their organizations. Respondents with 11 to 19 years of experience were more likely to discount the loss of revenue as a relevant impact to their organization, compared to the other respondents (p=0.049).

The comparison between mine locations has shown that the South Australian respondents reported greater sensitivity to “supply of essential inputs or services” as well as “health and safety of workers”

than respondents from the Northern Territory. This result might be due to the fact that Olympic Dam (577 km from Adelaide) is located further from a city compared to Ranger Mine (230 km from Darwin), making the former more vulnerable to disruptions in the supply chain due to limited options for site access. Access to Olympic Dam has previously been impacted by extreme weather events such as flooding and storms, which caused road closures - affecting the normal supply of materials, equipment and resources. In fact, Olympic Dam was closed 15 days in early October 2016 due to failure of electricity transmission after a major storm (BHP Billiton, 2017).

The impacts of climate change were further explored exclusively for mining company employees. The responses are presented in Table 6.4. Most respondents (60%) identified tailings and waste management facilities as being the most impacted by extreme weather events, followed by ore extraction, processing and transport within the mine (access and haulage) and maintenance activities. Processing and transporting outside the mine were also mentioned (road, rail, and port) but were not rated highly. The personal assessment provided by mining company employees suggests that their companies are sensitive to climate risks especially when tailings/waste management facilities are considered.

Table 6.4: Climate impacts on mining operations

	% (n=20)	**p value location SA**	**p value location NT**	**p value years of experience 0 -10**	**p value years of experience 11-19**	**p value years of experience 20 or more**	**p value management**
Ore extraction	50.0%	.103	**.024**	.778	.778	.738	.083
Processing	40.0%	.738	.548	.667	.667	.548	.667
Transport within the mine site (access and haulage)	50.0%	.500	.738	.222	.222	**.024**	.500
Transport outside the mine site (road, rail, and port)	30.0%	.500	.167	.467	.467	.167	.708
Tailings/waste management facilities	60.0%	.262	.071	.667	.667	.548	.167
Mine planning	10.0%	.500	.400	.800	.800	.600	.300
Maintenance activities	50.0%	.103	.262	.778	.222	.262	.083
Exploration	0.0%	1.00	1.00	1.00	1.00	1.00	1.00
Other (Specified)	0.0%	1.00	1.00	1.00	1.00	1.00	1.00

p-values for the null hypothesis of equal percentage of agreement between the nominated group and the rest of the sample

By location, the Northern Territory respondents reported more sensitivity (p=0.024) to climate events in the ore extraction area. This suggests that Ranger has faced more issues associated with production when extreme weather events are considered. In fact, pit operations have been halted at least 4 times in 10 years due to flooding (ERA, 2007a; ERA, 2008a; ERA 2012, ERA 2013). Dividing respondents by years of experience, those with more than 20 years identified that the most sensitive area to climate risks is "transport within the mine site". This suggests that haulage roads within the mine site have been affected by flooding in the last 20 years, leading to impacts on production.

Indirect impacts were examined through an assessment of the influence of external companies/organisations affected by climate events and their flow-on effects at the respondents' own company/organisation. The results are provided in Table 6.5.

Table 6.5: Types of external companies/organisations affected by climate events that have affected the respondents' own company/organisation.

	% (n=20)	**p value location SA**	**p value location NT**	**p value years of experience 0 -10**	**p value years of experience 11-19**	**p value years of experience 20 or more**	**p value management**
Mining company	30.0%	.455	.657	.517	.681	.545	.387
Local community	25.0%	.307	.751	.073	.399	.296	.517
Mining services (engineering, maintenance, drilling, labour)	15.0%	.656	.509	.399	.404	.656	.319
Transport company	25.0%	.693	.751	.634	.601	.693	.517
Utility company (water, energy, telecommunication)	25.0%	**.051**	.282	.634	.601	.693	.517
Not applicable	35.0%	.608	.439	.594	.270	.251	.664
Other (please specify)	5.0%	.400	.800	.750	.850	.600	.300

p-values for the null hypothesis of equal percentage of agreement between the nominated group and the rest of the sample

Based on the survey results, 30% of the respondents considered that climate related impacts on a mining company had flowed-through to produce secondary impacts on the respondent's own organisation in some way. Of the respondents, 25% indicated that the local community, utility companies and transport companies had impacted upon them in some way and 15% indicated that direct impacts on mining services had affected them. Respondents from South Australia showed a higher tendency to mention "utility company" (water energy, and telecommunications) as particularly affecting them (p=0.05). There was a high proportion (35%) of respondents who considered this

question as being “not applicable”. This could suggest that the respondents consider the mining company is the most influential participant in the supply chain.

Participants were further questioned regarding the impacts their own company/organisation can generate on others when affected by climate events. The ranking obtained were mining company most affected (3.20), following by surrounding environment (3.73), local community (3.83), and transport company (4.23). The least affected in the industry were manufacturing (6.18), the customer’s company (4.92), mining services (4.64) and construction (4.30).

These results show how the uranium mining industry can be affected both directly and indirectly by climatic conditions and weather extremes. In addition, other members of the regional supply chain such as upstream, downstream and regional stakeholders can also be affected if the mining company is affected by climate conditions e.g. water consumption by Olympic Dam mine in a water competitive environment (Mudd, 2008). This suggests that the participants are linked as members of a chain of activities or a network with several nodes as CIPS (2013) suggested.

6.8 Future vulnerability assessment

Company/organisation or community to risks if there was an increase in the frequency, magnitude, duration and/or extent of climate events in the future. The majority of respondents considered that the exposure would increase if intense rainfall is more frequent in the future, followed by, in order of importance, storms, heat waves, fires, and droughts. Compared to the evaluation of present vulnerability, it seems that intense rainfall/flooding will continue to be the most influential climate risk for future vulnerability. On the other hand, storms are considered to become a greater risk than heat waves in the future.

A question was posed about factors that could increase the vulnerability of the respondents’ company/organisation or community to climate conditions. The results are presented in Table 6.6.

Table 6.6: Factors that can increase the vulnerability to future climate conditions

	% (n=19)	p value location SA	p value location NT	p value years of experience 0 -10	p value years of experience 11-19	p value years of experience 20 or more	p value manage ment
Age of assets	52.6%	.430	.333	.556	.124	.115	.444
Design of assets	57.9%	.337	.574	.336	.624	.449	.071
Geographical location	73.7%	.366	.258	.084	.376	.336	.172
Operational process / method used	21.1%	.525	.648	.258	.470	.085	.272
Frequency of climate events	84.2%	.296	.530	.376	.422	.624	.376
Intensity and magnitude of climate events	73.7%	.634	.728	.603	.624	.664	.603
Impact on labour availability/productivity	52.6%	**.017**	**.033**	.184	.542	.115	.119
Other (please specify)	0.0%	1.00	1.00	1.00	1.00	1.00	1.00

p-values for the null hypothesis of equal percentage of agreement between the nominated group and the rest of the sample

In response, the most (84.2%) cited factor that will increase vulnerability to climate conditions is the change in frequency of extreme climatic events. This was followed by the intensity and magnitude of these events and geographical location. Design of assets was also a significant factor cited by respondents, followed by age of assets and impact on labour force availability or productivity. The impact on labour force availability or productivity was the most critical factor for respondents from South Australia (p=0.017). Conversely, respondents from Northern Territory did not rate this factor as being critical (p=0.033). Overall, this suggests that future vulnerability of the industry would be climate dependent if no steps are taken to increase the adaptive capacity of operations through re-design or renewal of assets or by securing the labour force availability and productivity. The selection of the critical factors differed in both locations and are considered site specific.

Respondents were also asked to identify new impacts to their companies/organisations that may occur should the climate risks identified previously increase in the future. Respondents could select more than one option. Operational disruption was identified as the area with highest impact (84.2%), followed by an increase in costs (78.9%) and loss of revenue and health and safety of workers (both 68.4%). Respondents from South Australia reported higher concern about the health and safety of workers if climate risks are greater in the future (p=0.01). Other significant factors identified were financial performance (63.2%), delays in production (57.9%), and infrastructure/plant and equipment (47.4%). Compared to the present vulnerability assessment, “operational disruption” remains as the

main impact for future vulnerability, however, it is expected to be more prevalent in the future (84.2% vs 70%). Higher response rates were also shown between future and current impacts for loss of revenue (68.4% vs 60%), increased costs (78.9% vs 60%), health, and safety (68.4% vs 55%). This means respondents anticipate for the future more climate impacts. The "quality of production" was not considered at risk for the future and the "transportation of the product" has remained at the same level of impact (26.3%).

With regards to which aspects of mining operations were identified as being most at risk in the future, tailings and waste management facilities received the highest rating (66.7%), followed by the processing plant, transport within the mine site, and transport outside the mine site (all at 44.4%). In this question, the comparison with the present vulnerability assessment is difficult to interpret due to the lack of data. However, the general perspective of the respondents between the present and future impacts on the mine site and associated infrastructure did not change significantly.

Respondents were asked to comment on the potential for an increased need for resources such as water, energy, telecommunication, labour, technology, and knowledge because of climate change. Half of the respondents (52.6%) estimated that the demand for water and energy would increase. Other significant resources that would be in demand would be knowledge/expertise (42.1%) and labour (31.6%). This result coincides with the key elements (water and energy) used currently by the mining industry and continue to be a critical part of the operational efficiency of a mine. Participants indicated that "knowledge or expertise" in these fields would be required to face the future climate changes.

The flow-on impacts from another company/organisation to their own company/organisation in the future were considered. For this question, respondents were able to choose more than one option. The results are presented in Table 6.7.

Table 6.7: Impacts from other organisation/company to their own business or community

	% (n=19)	p value location SA	p value location NT	p value years of experience 0 -10	p value years of experience 11-19	p value years of experience 20 or more	p value management
Mining company	68.4%	.472	.656	.656	.502	.528	**.041**
Local community	52.6%	.056	.550	.126	.256	**.024**	.221
Mining services (engineering, maintenance, drilling, labour)	42.1%	.201	.656	.262	.498	.166	.133
Transport company	36.8%	.324	.443	.557	.593	.676	.210
Utility company (water, energy, telecommunication	47.4%	.377	.647	.258	.586	.377	.676
Other (Specified)	0.0%	1.00	1.00	1.00	1.00	1.00	1.00

Most of the respondents indicated that flow-on impacts from mining companies could affect their operation, followed by those from the local community, utility companies, mining services and transport companies. Respondents in management positions had a higher likelihood to mention mining companies as a source of future risks for their organization (p=0.041). Respondents with more than 20 years of experience did not consider the local community as a particularly significant source of future vulnerability (p=0.024). This suggests that the mining company is considered the most influential in transferring impacts to others in the industry supply chain. The future impact is expected to be higher compared with the present vulnerability assessment (68.4% vs 30%). Another significant difference is local community, which is considered almost 100% more influential than in the assessment of present vulnerabilities (52.6% vs 25%) as well as utility companies (47.5% vs 15%) and mining services (42.1% vs 15%). This suggests that in the future, the industry would be more prone to be indirectly affected. However, from a management perspective (p=0.041) the mining company is the most influential in the supply chain. According to Walker *et al* (2007), there is a coordinator member or leader partner in a chain that is the most important part of the chain, in this case is mining company.

6.9 Present adaptive capacity

The survey queried adaptive capacity in terms of the plans (mainly through the Risk Management Plan, RMP) and preparedness (nature of the approach, existence of vulnerability assessment and a risk assessment plan) employed by the uranium mining industry to face with climate risks. The survey

asked respondents to rate their organisation's current RMP on a range of characteristics on a scale from 1 (poor) to 10 (excellent).

Overall, respondents gave the highest rating (8) to the quality of their organisation's RMP in terms of "the clarity of the guidelines and procedures to follow in the case of a climate event", followed by the "the clarity in the various positions, roles and responsibilities of the personnel required to respond to the event" with a rating average of 7.78. The adequacy of current risk mitigation procedures and response contingency plans (7.56) and communication within the company/organisation (7.35) also rated well, suggesting the RMPs were considered well prepared in these four aspects. The lowest rated items were the revision of the RMP to cope with the dynamic changes in the future (7.00), the clear identification of climate risks in the current risk management plan (6.65), and the level of communication between the company and other related organisations (e.g. energy, water, transport, and communication company) which was rated at 6.22. Overall, the results show that all RMP characteristics received a rating above 5, which suggests a reasonable level of adaptive capacity is present in the industry at the present time. Nevertheless, some areas must be improved to ensure the changing climate is considered.

Most of the respondents (61.9%) indicated that they considered the approach of their company/organisation to dealing with climate events was proactive (anticipatory or preventative). Even though short and long term were not considered in the question, respondents from mining companies pointed out that they have a proactive approach in the short term but there is a lack of long term planning. In the case of local communities, it was indicated that there is not a proactive approach (i.e. without having been suitably prepared in advance) when it comes to community services, contractors or community members. This suggests these organisations could be the most vulnerable part of the industry at the present time, as they lack preparedness and/or information to face extreme weather events, especially in remote communities in the Northern Territory (Veland *et al,* 2010; Boon, 2015).

6.10 Future adaptive capacity

Respondents were asked to rate their current RMP against its overall ability to cope with more frequent or more extreme climate risks on a scale from 1 (poor) to 10 (excellent). The responses were varied with 38% rating their RMP at a score 4 to 5. This is below the mid-point of the scale (5), so it could be inferred that most RMPs would not cope well with future climate risks. Approximately 20% scored their plan between 6 and 7, and the remainder of the respondents (33% - who were mainly

from government organisations) scored their RMP between 8 and 10. This suggests that just one portion of the industry is currently well prepared for future climate risks.

As part of the future adaptive capacity evaluation, respondents were asked about the existence of a vulnerability assessment and a risk reduction plan at their location. Most responded “no” (45.8%), a significative percentage were ‘unsure” (33.3%) and a small percentage (8.3%) stated having a vulnerability assessment plan. Some respondents pointed out that “they don’t know what a vulnerability assessment is” or that “they are a small consultancy” and “they have reduced budget”. In regard to the existence of a risk reduction plan, most of the respondents (80%) stated they “don’t have one” or were unsure of the existence of such a plan. Only 12% confirmed they had one.

Respondents were asked to select preferred options from a list of proposed changes to improve the adaptive capacity of their organisation for future climate conditions. The majority of respondents (73.7%) indicated that operational procedures were a measure to improve the adaptive capacity, followed by management procedures (52.6%), work practices (42.1%) and administrative procedures and management approach/leadership (both 31.6%). These results suggest that respondents of the uranium industry are aware that their adaptive capacity can be improved by making changes to their operational and management procedures.

6.11 Discussion of results

This study provides a review and assessment of the past impacts related to climate conditions and climate risks for the Australian uranium industry (focused on the Ranger and Olympic Dam mines) and a future vulnerability assessment (based on past experience and future expected conditions) of the industry for climate change. The uranium industry was considered to be composed of a broad set of participants: not just the mining companies per se, but also contractors, consultants, mining services, government agencies (state and local), non- government agencies, community members and community services.

In a first section, a detailed review of the annual activity and sustainability reports of the mining holding companies was conducted for the period 2005-2015. As an example, in the case of Ranger Mine, this review allowed the identification of climate impacts on business performance (in terms of decrease of production, loss of revenue, forced purchase of uranium in the spot market, increase of costs and additional capital expenditures) and in field operations (e.g. operational pit flooding, tailings storage facilities flooding, partially/full halt of mine operations, blocked access to the high-grade ore by flooding and infrastructure damage). The identification of past impacts at Ranger Mine allowed an estimation of the economic cost of AU$529.7 million in additional investment (reactive measures) and

loss of revenue over 10 years of AU$403 million. Given this analysis is confined to one mining operation; it is easy to infer that this represents a lower bound in the estimation of costs for the industry.

The results of our survey provided data to evaluate the climate vulnerability of the industry to assess the depth that climate impacts the industry in the past and will face in the future.

6.11.1 Climate perceptions

In general, the results of the survey suggest that the uranium mining industry in Australia may have differing perceptions about climate change or climate risks compared to the broader mining industry. This study was limited to uranium mining supply chain participants, and the sample is therefore too small to infer a significant requirement across the whole mining industry in Australia. However, these results may signify an important positive change has occurred.

In a previous study undertaken by Loechel *et al* (2013b) that included a significant cross section of the mining industry as well as local government representatives, the mining company respondents reported "less concern" about past and future climate risks. In contrast, most of the respondents of this study (>95%) reported climate risks as an influential impact to their company/organisation or community both in the past and expected in the future. In fact, they reported increased percentages in all climate impacts. The results of the present survey contrast with the study by Loechel *et al* (2013b), where the mining respondents didn't consider the risk of climate change an important concern, neither in the present nor in the future. The authors suggest that this may be due to low belief/scepticism about the issue in the past. Another explanation for the difference may be that the industry has been negatively influenced by more climatic impacts since 2013. Furthermore, this result could be attributed to the fact that uranium has been proposed as a potential substitute for other energy sources to produce electricity (e.g. coal) (WNA, 2012) thus, might be more in tune to the impacts that climate change might have on them based on experiences to date.

6.11.2 Present vulnerability

Regarding the present vulnerability assessment, intense rainfall/flooding and heat waves were identified as the most influential climate risks for the industry. Responses varied in intensity among participants, especially according to location (respondents from South Australia tended to mention heat waves with higher frequency than other groups), and years of experience (respondents with up to 10 years of experience mentioned heat waves whereas respondents with more than 20 years of experience mentioned intense rainfall/flooding).

There is a similarity between the climate risks mentioned by the participants in this research and the results from Loechel *et al* (2013b), Mason and Giurco (2013) and Hodgkinson *et al* (2014). In both this study and Loechel *et al* (2013b), the most frequently mentioned climate risk by respondents was intense rainfall/flooding, even though this research includes the Olympic Dam mine located in an arid region. This suggests the great influence of intense rainfall that leads to flooding in South Australian mining (Hodgkinson *et al*, 2014).

Regarding exposure to climate risks, respondents in the industry identified storms, intense rainfall/flooding and heat waves as the main events. The trend of this response also varied according to years of experience: respondents with up to 10 years of experience considered the exposure to heat waves with higher concern than other respondents. In both locations, storms and intense rainfall/flooding have caused issues such as flooding in the operational pit at Ranger Mine and tailings storage facilities (ERA, 2008a; ERA, 2011; ERA, 2012) or the blackout at Olympic Dam mine during September 2016 (AEMO, 2016). Meanwhile, heat waves involve risks to the health (fainting, cramps, exhaustion, fatigue and heat stroke) and safety of workers whether the mine operation is on the surface or underground (Hunt, 2011; Maurya *et al* ,2015) and negatively influence work performance (ERA, 2007b; Hodgkinson *et al* 2014). More specifically, ERA (2007b, 2008b) developed a program to avoid the deterioration in workers' health from heat stress. In a similar vein, BHP Billiton (2009b) developed a plan for heat management. In addition to this, in the light of recent heat waves, the Government of South Australia has developed a strategic plan to prepare for intense heat waves that focuses on the wellbeing of local workers (GSA, 2016).

Climate impacts previously identified, such as operational disruption, increased costs, financial performance, delays of production, health and safety of workers, and loss of revenue were highlighted by the survey results. In addition, climate impacts over business performance were identified, such as delays in production, supply of essentials (water, energy, telecommunications and labour availability) transportation of the product, health and safety of workers, and quality of production. These climate-related impacts coincide with the results of previous studies (Mason and Giurco, 2013; Loechel *et al* 2013a, b, Hodgkinson *et al*, 2014) undertaken in mining generally, in Australia.

Some differences in responses between locations were identified. South Australian respondents presented more sensitivity to supply of essential inputs than respondents from Northern Territory. Moreover, additional sensitives in the mine site were identified such as transport within and out of the mine site, processing, planning, and maintenance activities.

In this survey, Australian uranium industry respondents categorised tailings/waste management facilities at the greatest at risk, followed by ore extraction, processing, transport within the mine site

(access and haulage), and maintenance activities with the same level of negative influence in their businesses. By location, respondents from Northern Territory reported more sensitivity to ore extraction area; this is confirmed by the initial results of historical climate impacts that have affected the Ranger Mine.

In contrast with these results, the Canadian study undertaken by Pearce *et al* (2009) uranium mining respondents reported low sensitivity to climate risks. They considered climate risks to their operations were not climate dependent because the mines were underground and the damage to infrastructure and equipment damage at the surface were estimated as less significant (Pearce *et al* 2009).

Respondents in this study identified the company/organisation or community that can cause indirect impacts (flow-on) in the own company. Mining companies were found to be most affected followed by local community, utility companies, and transport companies with the same level of impact. Differences in responses according to location were also detected e.g. utility company was selected by South Australian respondents in higher tendency than other respondents. The remote location of Olympic Dam was emphasised by the massive blackout in September 2016. In that occasion, it took 15 days to restore the supply of electricity, since the need for visual inspection and reparations took longer in that isolated location (AEMO, 2016). Conversely, mining companies and the surrounding environments were established as being the most influential for causing impacts on other members of the industry. These results show that the uranium mining industry is sensitive both directly and indirectly to climate risks and also that the participants of the industry are connected to each other as nodes (CIPS, 2013). In addition, only a minority (17%) of the local government representative participants in the study undertaken by Loechel *et al* (2013b) indicated that their organisations had experienced indirect effects (flow-on) from other sectors in the past. This contrasts with the majority (95%) of respondents in this study who reported indirect (flow-on) effects from other companies/organisations.

6.11.3 Present adaptive capacity

The adaptive capacity assessment (by means of evaluating the effectiveness of current RMPs) found a reasonable level of adaptive capacity in the industry. This was because some items of the RMP were well evaluated by the respondents such as clarity of guidelines, procedures, roles/responsibilities in the case of a climate event, adequacy of the RMP, and communication within the organisation. Conversely, other items such as regular update of the plan, clear identification of the climate risks, and the level of communication with related companies/organisations (water, energy, transportation, and communication companies) were rated lower. In addition, it was found that more than half (61.9%) of

the industry respondents had a proactive approach in the short term but they had no long-term planning to face climate risks.

In the current study, the collaboration between organisations for adaptation planning through the RMP was perceived to be negatively impacted by poor communication. This is in contrast with the results of Loechel *et al* (2013b) where the participants (mainly from government organisations) stated that there were good relationships (92%) with related organisations for working on climate adaptation planning. The difference in results could be attributed to the significant loss of employees in the industry over the past few years, in fact, employment in the mining industry has decreased in the last 5 years by 4.9 percent (LMIP, 2016). It may also be attributed to a lack of continuity in employment organisations with the mean time spent at a mining company less than 3 year.

Half of the participants in this study stated that they are aware of a proactive approach in their organisation to deal with extreme weather events. Specifically, most of them (85.71%) indicated there is some type of risk management plan in place to deal with the current climate. However, the perceived effectiveness of the plans varied. Therefore, the previous study by Loechel *et al* (2013b) found only 13% of mining company, and 46% of local government respondents indicated their organisation had any plan or policy in place to deal with climate risks.

6.11.4 Future vulnerability

This study also explored the future vulnerability to climate change of the uranium industry, using an estimation of the future exposure and sensitivity provided by the respondents of the survey. The future estimations were taking as reference the past climate risks faced by respondents and showed greater exposure to intense rainfall/flooding and storms and less exposure to heat waves in both locations were expected. This result contrasts with the results of Pearce *et al* (2009) and Loechel *et al* (2013b) where respondents dismissed an increase of vulnerability due to climate change in their operations. However, in part the exposure estimation to these climate risks coincided with the estimations of BHP Billiton (2011), C2ES (2013), and Lacey (2013).

The results of this study also suggest an increase of impacts across the business operations (financial performance, loss of revenue, increased costs, operational disruptions, delayed production, supply of essential inputs, transport of product, health/safety of workers, and infrastructure plant & equipment damage) if the climate risks are greater in the future. Differences in responses according to the location were detected, e.g. respondents from South Australia were more concerned about the labour force availability and productivity. This result coincides with the potential climate change impacts projected by BHP Billiton (2011). Regarding mine sites, tailings/waste management facilities were selected as

the greatest at risk followed by transport, maintenance activities and ore extraction with the same level of negative influence in their businesses. In contrast, results obtained by Pearce *et al* (2009) suggest surface infrastructure damage by climate conditions were irregular and insignificant.

Factors that play a key role in the increase of future vulnerability were explored in the survey, including change in the frequency, intensity, and magnitude of the climate risks. In addition, the geographical location, the age and design of the assets, labour force availability and productivity were also identified as key factors for future vulnerability. Differences between results from each location were detected in the data analysis: South Australian respondents were more likely to consider labour force availability and the productivity as critical factors for future vulnerability than respondents from Northern Territory. These results highlight the future vulnerability and climate dependence of the industry and the need to plan adaptation strategies to increase the adaptive capacity. It was also emphasized that the vulnerability to climate change is a specific condition of a location and the nature of mining operation as was suggested by Smit and Wandel (2006), this can present different future needs to improve the adaptive capacity.

The potential increase in the requirement of resources (water, energy, telecommunication, labour, technology and knowledge) due to climate change was highlighted by this study. Water, energy and knowledge/expertise about climate change, were found to be independent of location. The increasing demand of these resources, especially in water, energy and labour have been anticipated in other literature (Mudd, 2008; Torrisi and Trotta, 2013; Hodgkinson *et al*, 2014).

Regarding indirect impacts, mining companies were stated as being the most influential to transfer impacts to others in the industry supply chain with a higher impact expected in the future (68.4 vs 30). Another remarkable difference between the present vulnerability assessments, is that local community was considered highly more influential in the future (52.6 vs 25) in transferring climate impacts to others. These results suggest the industry would be more sensitive to indirect impacts in the future.

6.11.5 Adaptive capacity

Regarding the ability of the uranium industry to be resilient to climate change, this study found that the 38% of industry respondents indicated their organisation is not currently ready for greater climate risks in the future if employing the same RMP. In contrast, the 33% of the industry respondents (mainly government organisations) would be able to successfully deal with influences brought by climate change.

Regarding the existence of a vulnerability assessment or a risk reduction plan, just a very small proportion of the participants in this study indicated that they know of a climate change-related vulnerability assessment or a risk reduction plan in their businesses. In addition, an apparent poor level of knowledge in climate change concepts was highlighted by respondents because of the high percentage of “no” or “unsure” responses when queried about these themes.

Finally, this study found that the adaptive capacity of the industry to climate change could be improved by changes in the operations in the mine site, as well as their management procedures, work practices, administrative procedures, and management approach/leadership. Some of these proposed changes (administrative procedures, management or leadership approach) have been seen as barriers to the climate adaptation process (Productivity Commission, 2012).

6.12 Conclusions

This study reveals the most influential climate risks for the uranium mining industry and how these have affected operations in the past, as well as the likely future impacts in South Australia and Northern Territory. Past-exposure was based on a review of company reports supplemented with the responses to the survey. Both factors were used to pose further questions to respondents regarding their estimate of future vulnerability. Furthermore, past direct and indirect climate-related impacts to organisations involved in the uranium supply chain have been revealed, as well as likely future impacts together with information that outlines the factors that could increase the vulnerability of these operations in the future. The results of this study suggest that the impacts (financial performance, loss of revenue, increased costs, operational disruption and delayed production) of climate risks will be greater in the future, further increasing the vulnerability of the industry to extreme weather events. An increase of stress upon resources such as water, energy and telecommunications, labour, technology and knowledge in the light of future climate change and key factors that can increase the vulnerability were highlighted with the results of the survey. Despite most of the participants in this study claiming that their company/organisation has a risk management plan to deal with current climate conditions, there were significant weaknesses identified in these plans. Further, few companies appear to have performed a vulnerability assessment or have developed a climate change related risk reduction plan. This outlines a need of knowledge about each of these procedures within the industry. It was clear that the adaptive capacity of the industry could be further improved by strategic changes to operational procedures and management practices. Finally, a further study is necessary to explore the links (as nodes) between the companies related (supply chain) in mining.

7 Preparedness for climate change across the supply chain

Further detailed analysis of the vulnerability assessment has been accepted as a paper in a Q1 Journal (provided Appendix III). The reference is provided below.

Pizarro, J, Sainsbury, B, Hodgkinson, J, and Loechel, B, (*in press*). Australian uranium industry climate change vulnerability assessment, *Progress in Nuclear Energy*.

The paper has been reformatted and included herein for completeness.

7.1 Background information

The energy sector represents the most polluting activity worldwide. In 2010 it contributed 35% of total Greenhouse Gas Emissions (GHGs) (Bruckner *et al*, 2014). Within the energy sector, electricity is the end-use of energy consumption with the greatest utilization occurring in the most recent years (Buckner *et al*, 2014). The emerging economies of China and India have sustained an accelerated increase in the global electricity consumption, and demand is expected to increase a further 69% by 2040 (EIA, 2016). With this growth, so too is an expected increase in GHGs. In this context, global efforts to reduce GHGs through improvements in conversion efficiency, transmission, distribution and the use of alternative (low carbon) energy sources have been sought. Among the alternative energy sources that are well developed and widely available is nuclear power. While uranium for energy generation produces a range of hazardous pollutants that require rigorous procedures for containment, it is nevertheless a lesser GHG pollutant compared with other sources. For example, lifecycle emissions of nuclear power are 29 tonnes CO2e/GWh compared to 888 tonnes CO2e/GWh for coal (WNA, 2011). Considering this, an increase in demand for uranium is expected in the future (NEA and IAEA, 2016). To date, the demand for nuclear power has been constrained by factors such as the Fukushima Daiichi accident (based on bad public perception); increased costs of construction of power plants; higher discount rates for nuclear related investments; increased safety requirements; and the high cost of extraction versus the low spot price of the last 6 years (Hayashi and Hughes, 2013; AG, 2016).

Australia has 31% of the total worldwide uranium resources (MCA, 2016), and, at the present time (2017) there are three operating uranium mines (WNA, 2016a). This study only considers the Ranger Mine (owned by Energy Resources of Australia – ERA) and the Olympic Dam Mine (owned by BHP Billiton) since they represent more than 80% of the domestic Australian uranium oxide output in the years 2013 to 2015, and 12% of the global demand (WNA, 2016). Historically, both mines have been

affected by extreme climate related events with negative economic impacts for their stakeholders. A detailed review of the climate impacts on the operations can be found in Pizarro *et al*, (2017).

A review of the existing literature has shown a significant gap in research related to the concept of mining vulnerability associated with climate change. This paper seeks to identify members of the uranium supply chain at each of the Ranger and Olympic Dam Mines and use them to complete a vulnerability assessment to future climate change scenarios. This assessment has used the "lessons learned" from past extreme weather events to estimate the future vulnerability. Expected climate change conditions have been identified by a review of the historical climate conditions and the projected future climate conditions at the mine locations.

7.2 Historical and projected climate conditions

A review of the historical climate conditions at each the Ranger and Olympic Dam Mines along with climate projections are presented below. The climate projections have been established by Climate Change Australia (2015) and are presented as Representative Concentration Pathways (RCPs). There are four pathways (RCP2.6, RCP4.5, RCP6 and RCP8.5) that have been considered in this research. Each of the pathways has been characterised by Radiative Forcing (RF). RF is the change of energy in the atmosphere due to greenhouse gas emissions (Solomon *et al*, 2007). The greater the RF, the great the emission. A summary of the future scenarios is provided below.

- RCP 2.6: It represents an early effort by all pollutant sectors to reduce their emissions and consequently the radiative force to 3W/m2 (with 490 ppm of CO2) by the middle of the 21st century and decline to 2.6 W/m2 by 2100 (Van Veurren *et al*, 2011; Jubb *et al*, 2016).
- RCP 4.5: Stabilization of the radiative forcing at 4.5W/m2 (with 650 ppm of CO2) without excess that value after 2100 (Van Veurren *et al*, 2011).
- RCP 6: Stabilization of radiative forcing at 6 W/m2 (with 850 ppm of CO2). It is expected that stabilization will occur after 2100 with the application of new technologies and strategies (Hijioaka *et al*, 2008).
- RCP 8.5: Continued increase of emissions reaching a peak of CO2 of 1370 ppm, which leads to a radiative forcing of 8.5 W/m2 by 2100 (Riahi *et al*,2007).

Owing to the uncertainties in the climate projections, the IPCC (2007) developed a confidence language, which uses qualifiers such as ‘very high’, ‘high’, ‘medium’, ‘low’ and ‘very low’ for the level of certainty of the projections. The same definitions have been used herein.

7.2.1 Ranger Mine

The Ranger Mine is located 251.5 km east of Darwin in the Northern Territory. The closest meteorological station to the mine is the Jabiru Airport Station, located 2.7 km away. In the Darwin region there are three seasons that include a wet season (December to March) that is characterised by a hot and humid climate. This season overlaps with the monsoon / cyclone season (November to April) and a dry season that exists the rest of the year (Parkinson, 1996; BOM, 2016a; Moise *et al*, 2015). Climate characteristics of this area include an annual mean maximum of 34.3 ^{0}C and minimum temperature of 22.6 ^{0}C. Annual mean rainfall has been measured at 1563 mm (BOM, 2016a) and evapotranspiration at 4.6 mm (BOM, 2016b).

The mean temperatures in this region have showed an increase of between 1.0 ^{0}C in the north east and 0.90C for the north west, for the period 1910-2010 (Moise *et al*, 2015). A warming tendency is expected in the future including an increase in minimum and maximum temperatures with very high confidence (Moise *et al*, 2015). By 2030, an increase of mean temperatures of 0.5^{0}C to 1.3^{0}C is expected in all RCPs. By 2090, a larger increase in temperatures (1.3^{0}C to 5.1^{0}C) is expected for RCP 4.5 and RCP 8.5 (Moise, *et al*, 2015).

Historically, this region has experienced droughts and periods of above average rainfall in the last century (Moise *et al*, 2015). The variation in annual mean rainfall is expected to be ±10% by 2030 relative to the annual average of the period 1986-2005 (Moise *et al*, 2015).

Extreme high temperate events are expected to increase in magnitude, frequency and duration (Moise *et al*, 2015) with a very high confidence in all RCPs (Moise *et al*, 2015). A summary of the expected change in heat wave conditions is presented in Table 5.1. It should be noted that Moise *et a*l (2015) focuses on climate projections under RCP 4.5 and RCP 8.5.

Table 7.1: Heat waves in different RCP and periods of time for Darwin (after Moise *et al*, 2015)

Temperature	Current days	RCP 4.5 (2030)	RCP 4.5 (2090)	RCP 8.5 (2090)
Over 35^0 C	11	43 (25 to 118)	111 (54 to 211)	265 (180 to 322)
Over 40^{0}C	0	0	0 (0.0 to 0.2)	1.3 (0.2 to 11)

Heavy rainfall intensity is expected to increase with high confidence, since a warmer atmosphere (in a warmer climate) can retain more moisture (Sherwood *et al*, 2010). However, the magnitude of this change has been estimated with low confidence (Moise *et al*, 2015). Cyclone intensity is projected to increase with medium confidence, but decrease in frequency (Moise *et al*, 2015). The duration of

droughts is projected to increase mainly under RCP 8.5. Table 2 presents the projected average temperatures and rainfall for the Ranger Mine for the future years of 2030 and 2090.

Table 7.2: Averages for Ranger Mine area for two periods of time in the future (2030 and 2090) for RCP 4.5 and 8.5 (after Moise *et al*, 2015).

	Baseline 1995	RCP 4.5 (2030)	RCP 8.5 (2030)	RCP 4.5 (2090)	RCP 8.5 (2090)
Temperature ^{0}C	31.4	32.4	32.8	33.6	35.2
Rainfall (mm)	965	958	978	1014	979

In each of the RCP scenarios, increased temperature and rainfall can be expected at this location.

7.2.2 Olympic Dam

Olympic Dam is located in the driest state on the driest continent on earth (Torrisi and Trotta, 2013) and is situated 15.3 km north of the town of Roxby Downs in South Australia. The closest meteorological station is located at the Olympic Dam Aerodrome. Historical climate data at this location has recorded an annual mean maximum temperature of 27.8 ^{0}C a minimum mean of 12.6 ^{0}C. Annual mean rainfall of 151.5 mm has been recorded with evapotranspiration of 5.9 mm (BOM, 2017).

Surface temperatures have shown a significant increase since 1910 with mean temperatures rising by 0.9 ^{o}C. Daytime maximum temperatures and overnight minimum temperatures have increased by 0.8^{0}C and 1.0 0C respectively since 1910 (Watterson *et al*, 2015). Temperatures are expected to continue to increase at this location, with high confidence (Watterson *et al*, 2015). By 2030, warming is expected to reach 0.6 ^{o}C to 1.3 ^{o}C above the current average for all RCPs (Watterson et al, 2015). By 2090, the projected temperature increase will be 1.3^{o}C to 5.1 ^{o}C under RCP 8.4 and 8.5 (Watterson *et al,* 2015). The incidence of frost is expected to decrease with high confidence 2090 under RCP 4.5 and RCP 8.5.

Rainfall projections are highly variable. By 2030 the annual mean variation expected is ± 10% and by 2090 under RCP 8.5 it is expected to decrease 4%. Seasonal mean changes of rainfall are expected to ±20% in all RCPs (Waterson *et al*, 2015)

However, extremes related to rainfall are expected to increase in intensity with high confidence, but the magnitude of this change has been estimated with low confidence. For example, by 2090 under RPC 8.5 is expected an intense rainfall 20% larger. Drought duration is projected to increase with medium confidence, however, the change in frequency and intensity have been estimated with low

confidence under the RCP 8.5. Heat wave frequency, intensity and duration are also projected to increase with a very high confidence. Table 7.3 presents the projected average temperatures, and rainfall and drought factor for Olympic Dam for the future years of 2030 and 2090.

Table 7.3: Averages for Olympic Dam area for two periods of time in the future (2030 and 2090) (after Watterson *et al*, 2015)

Variable	Baseline 1995	RCP4.5 (2030)	RCP 8.5(2030)	RCP4.5 (2090)	RCP8.5(2090)
Temperature ^{0}C	28.4	29.8	29.9	30.8	32.7
Rainfall (mm)	318	273	293	293	285
Drought factor	8.6	8.8	8.7	8.8	8.9

In each of the RCP scenarios, temperature is expected to increase, rainfall is expected to decrease, and the drought factor is expected to increase.

7.3 Identification of the Australian uranium supply chain

During the 1980s a supply chain was defined by the synchronisation of internal processes within a firm e.g. purchasing, processing, delivery and sales (Noémi, 2012). As these processes expanded, they reached beyond the limits of the company, demanding the coordination of numerous external organizations (Noémi, 2012).

Today, supply chain members contribute through integrated processes as one organisation rather than separate companies. This is achieved through sharing information (data), knowledge, and the common goal of satisfying the customer's demand (Noémi, 2012). Through this approach, maximum efficiency is obtained (Bessant *et al*, 2003; Walker *et al*, 2007).

The literature provides numerous definitions of a modern supply chain (La Londe and Masters; 1994, Metzer *et al*, 2001; Noémi, 2012; Christopher, 2016). However, these definitions rely on the physical flow of products from the source (suppliers) to the sink (customer). However, as described above, what really provides the competitive advantage to the firms is the information flow rather than the physical flow of goods (Sherer, 2005; Walker *et al*, 2007). This approach considers the customer as the primary source of information for the firms, thus the information flow originates from the customer and passes to the suppliers (Sherer, 2005; Walker *et al*, 2007). This is the approach used in this study for the identification of the uranium supply chain members.

7.3.1 Identification of supply chain stakeholders

Stakeholders have been previously defined by many sources:

- "any group or individual who can affect or is affected by the achievement of the firms' objectives" (Freeman, 2010).
- "people who are adversely or positively impacted by our operations, those who have an interest or those who have an influence on what we do" (BHP Billiton, 2009).
- Individuals or groups who have an interest, a right or ownership in the project, and can contribute to, or be impacted by, either the work or the outcomes of the project. Walker *et al* (2007).

It is obvious that the identification of stakeholders can be performed from different criteria, such as social science (Gibson, 2000), corporate responsibility (Vos, 2003), management/economists (Freeman, 2010) and project management (Walker *et al*, 2007). More recently, Falck *et al* (2015) used the definition provided by IAEA (2006) to identify uranium mining stakeholder. They grouped the stakeholders in four categories: using economic, social, institutional and commercial relationships. It is clear from the definitions that the identification of stakeholders is usually based upon two basic questions. Who are they? And; what are their interests? (Gibson, 2000; Walker *et al*, 2007; Freeman, 2010; BSR, 2011). Considering the previous questions, it must be noted that stakeholders can change over time as well as their stakes or interests (BSR, 2011).

The identification of stakeholders for the Australian uranium supply chain has been completed based on the historical analysis of company reports (Freeman, 2010). In addition, stakeholders have also been identified based on their interests or rights (including ownership), as well as groups who can be affected or benefit from the activities of the mines. A total of 18 groups of stakeholders for each mine (Olympic Dam and Ranger Mine) have been identified and are presented in Figure 7.1.

Walker *et al* (2007) have further categorised members of the supply chain into upstream stakeholders (paying customers and end users), downstream stakeholders (suppliers and contractors), and the project sponsor or coordinator/champion group (Bessant *et al*, 2003; Walker *et al*, 2007). In addition, external stakeholders can be identified as a local community, independent individuals or groups who feel affected by the project, research teams, and invisible stakeholders (e.g. family support network) involved in the delivery project (Walker *et al*, 2007). The 18 stakeholders associated with the supply chains for each of the mines have been categorised as either upstream, downstream or external and are presented in Figure 7.1.

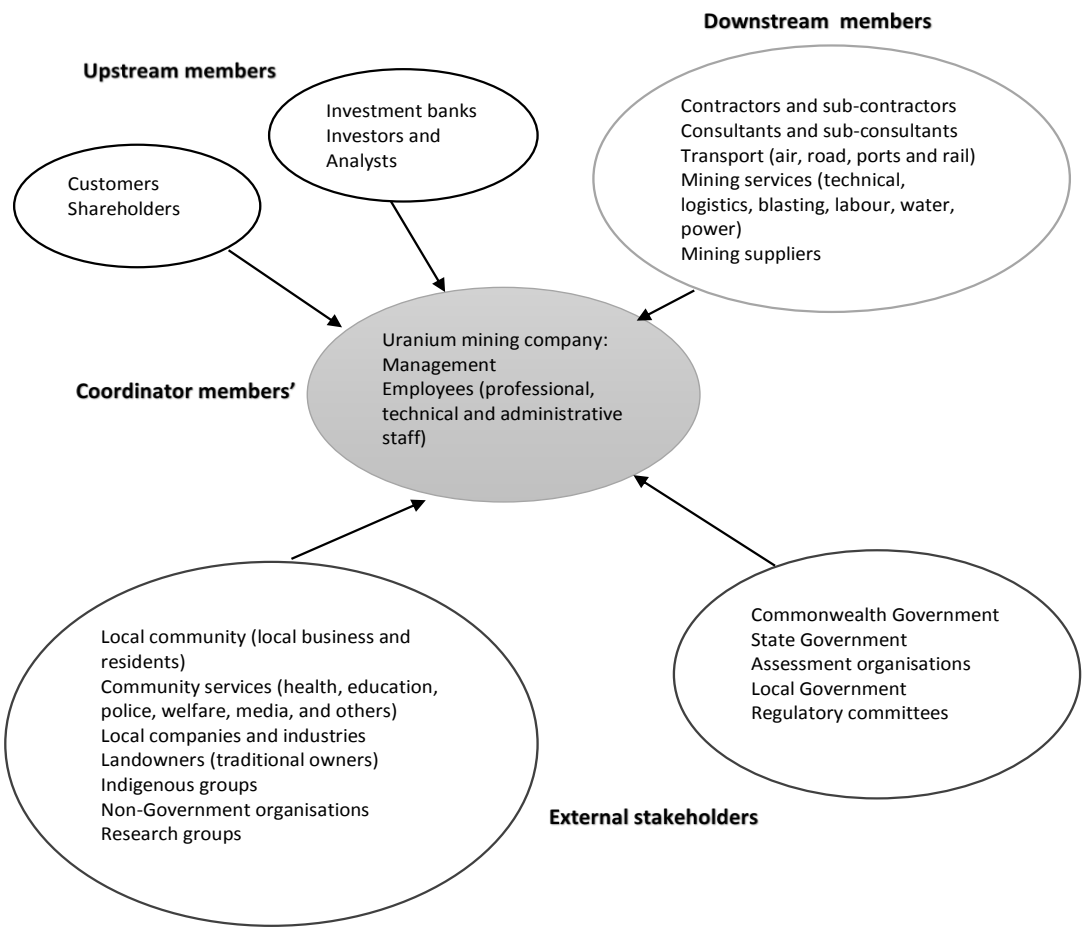

Figure 7.1: Representation of the uranium supply chain members (upstream, downstream members, coordinator member) and external stakeholders in Australia

7.4 Vulnerability assessment methodology

Vulnerability has been considered a function of exposure, sensitivity and adaptive capacity to climate change (Smit and Wandel, 2006; Füssel and Klein, 2006; Füssel 2007, Pearce *et al*, 2009; Ford *et al*, 2010). The same conceptual framework for vulnerability assessment that was applied to the Canadian mining industry developed by Pearce *et al* (2009) has been used in this research.

Exposure / sensitivity has been assessed through historical parameters such as climate event magnitude, frequency and impacts and their expected future parameters based on the RCP scenarios (summarised in Section 2). Scarcity or consumption of resources (e.g. water, energy) and factors that increase vulnerability (e.g. labour market) were considered to estimate the future vulnerability at each of the sites based on their identified supply chain member contributions. Adaptive capacity was considered through (a) the evaluation of Risk Management Plans (RMP) and their ability to deal with

climate risks both in a reactive and proactive manner, and (b) the existence of a vulnerability assessment or a Risk Reduction Plan. This assessment required input from stakeholders which has been collected via survey methods. A complete summary of the survey methodology and participants is presented in (Pizarro *et al*, 2017).

Survey participants were classified into the three groups identified in Figure 1. Each of the uranium mines (Ranger and Olympic Dam) have been considered as the leading partner/co-ordinator in each of their supply chains (Bessant *et al*, 2003 and Walker *et al*, 2007).

The survey data was analysed using the IBM SPSS statistical software (V.22). Fisher's exact test was used to process data for questions containing categorical data values (e.g. types of climate risks, impacts of climate risks or flowed-though impacts), jointly with cross tabulations between the past and future cases. For questions with ordinal data (e.g. rate of exposure or flow-on impacts), the Kruskal-Wallis test was applied. When analysing the data for these tests, values of $p < 0.05$ indicate a significant difference in the distribution of responses between the groups considered (with respect to the rest of the sample). Values of $p>0.05$ indicate the absence of a significant variation of responses between the groups of participants. Weighted averages of rankings and ratings were used to interpret the responses when the Kruskal-Wallis test did not provide any significant result. A summary of the survey results is provided below.

7.5 Consideration of current climate risks

Respondents perceptions of their organisation's current vulnerability to climate events (based on their own experience) was analysed to provide a historical account.

7.5.1 Ranger Mine

The Mining and Downstream groups at the Ranger Mine considered intense rainfall and flooding as the most influential climate events to affect their organisation at the present time, with 100% of respondents in these groups selecting this option. This result is consistent with the data gathered from company reports before conducting the survey (Pizarro *et al,* 2017). The supply chain of the Ranger Mine has previously been affected by intense rainfall and flooding (most of the time due to cyclones) (ERA, 2007b, ERA 2012; (Pizarro *et al*, 2017).

The External group members most frequently selected storms (66.7%), heat waves, (50.0%) and intense rainfall/flooding (40%) as the most influential climate events. In fact, members of the External group, mentioned storms with a higher tendency ($p=0.028$) than members of the other groups in this

chain. This may be a result of a reduced capacity to deal with excess water from storms of this group due to their reduced size (compared to the mine) and/or dispersed nature.

7.5.2 Olympic Dam

The Mining group considered intense rainfall and heat waves (both 75%) and storms (50%) to be the most influential climate events at Olympic Dam. The Downstream group selected intense rainfall/flooding (75%), followed by droughts (37.5%) and heat waves (25%). The External group considered heat waves (80%) to have been the most influential climate event, followed by droughts (40%).

Some differences in responses were detected in this chain. For example, members of the Downstream group did not select storms as a significant climate event (p=0.048) unlike other groups of the supply chain. Further, members of the External group did not consider intense rainfall/flooding to have been a relevant climate event, in contrast to other groups in the survey (p=0.040).

7.5.3 Discussion

The Mining Group members of both supply chains identified that intense rainfall/flooding is the most influential climate risk that they face, despite the location of both mines being in very different climatic zones – Ranger being tropical and Olympic Dam being arid. For both locations, it was interesting to note that there were chain-members located in other states e.g. some members of Olympic Dam's supply chain were located in Queensland and Victoria or some members of Rangers supply chain were located in New South Wales.

The results of Olympic Dam's supply chain suggest that in an arid climate, the extreme weather events, such as intense rainfall/flooding, have a strong impact on all the supply chain members including the mining company, ports, and power supply. These results are consistent with Hodgkinson *et al* (2014). In addition to intense rainfall/flooding, the members of the Olympic Dam supply chain added that heat waves and droughts were also influential climate risks. Heat waves and droughts are common extremes in areas of arid climate (RDA Far North SA, 2016). Specifically, the mine's location has experienced heat waves, on average, of 94 days per year in the last 30 years, with temperatures over 35°C (Watterson *et al*, 2015) and extended periods of drought such as in 1996 to mid-2010, which was called "the millennium drought" (BOM, 2015). Additionally, heat waves are perceived to be a health issue by the local government and regulators organisations (Hodgkinson *et al*, 2014; Xiang, 2014; SafeWork SA, 2015).

7.5.4 Frequency of climate risks

The members of each supply chain estimated different frequencies of climate risks that they had been exposed to. Members of the Ranger Mine supply chain reported a frequency between “twice a year” to “once every 10 years” but the majority (36.4 %) agreed on “once every 3 years”. Members of the Olympic Dam supply chain estimated a risk frequency that varied from “three or more times a year” to “less than once climate event in 20 years”. However, the majority (23.5%) of the members selected “three or more times a year”. This is a significant value of climate related events at both locations that is certainly impacting the financial results of the operations. Heavy rainfall and cyclone activity intensity are expected to increase with high confidence at Ranger increasing the severity of these events. Heat waves frequency, intensity, and duration are projected to increase with a very high confidence at Olympic Dam, increasing the severity of dry climate condition in the area.

7.6 Exposure (current and future)

Members of each mining supply chain (for Ranger and Olympic Dam) were asked to rate their exposure to the climate risks that they had previously experienced. Respondents were asked to consider several climate risks and estimate their future exposure on a rating scale from 1 (least exposed) to 10 (most exposed).

7.6.1 Ranger Mine

The survey results for the Ranger Mine associated with the rating of exposure to climate risks (current and future) are provided in Table 7.4.

At the Ranger Mine, the highest average rating of exposure to current climate events was reported by the Mining group and corresponded to intense rainfall and flooding (9.50), followed by storms (8.00). The Downstream group reported the same climate risks, while the External group reported being most exposed to storms (5.17) and intense rainfall (5.67).

Respondents were asked to consider several climate risks and estimate their future exposure. Both the Downstream and External groups gave a higher rating for each future climate risk than the Mining group, which gave the same future average rate (9.50). The Mining group had a higher tendency towards rating intense rainfall/flooding the risk than other groups of the chain (Asymp. Sig. =0.029). The Downstream group rated their future risks in the same order as their current risks, however, their future risk/s were rated higher. The External group reported they expect to be more exposed to storms (4.80) followed by heat waves and intense rainfall/flooding (4.60).

Overall, the members of the Ranger Mine supply chain considered that they are currently are, and expect to become, more exposed to climate related risks in the future with the greatest risks considered rainfall/flooding, storms, and heat waves. This is because they have faced economic and operational impacts in the past due to climate events (ERA, 2007a; ERA, 2011; ERA, 2012, Pizarro *et al*, 2017). Based on climate predictions outlined in Section 2, it is obvious that the mine will be increasingly more exposed (as identified by survey participants) to rainfall/flooding events in the future.

Table 7.4: Rating of exposure (current and future) across the supply chain of Ranger Mine

	Present n=11									**Future n=11**								
Average rating of exposure	**Mining (n=2)**			**Downstream (n=3)**			**External (n=6)**			**Mining (n=2)**			**Downstream (n=3)**			**External (n=5)**		
	Average	**x2 (df=1)**	**Asymp. Sig.**	**Average**	**x2 (df=1)**	**Asymp. Sig.**	**Average**	**x2 (df=1)**	**Asymp. Sig.**	**Average**	**x2 (df=1)**	**Asymp. Sig.**	**Average**	**x2 (df=1)**	**Asymp. Sig.**	**Average**	**x2 (df=1)**	**Asymp. Sig.**
Droughts	1.50	0.357	0.550	2.50	0.00	0.947	2.00	0.48	0.487	2.00	0.64	0.422	4.00	0.07	0.799	3.40	0.09	0.766
Fires	4.50	0.627	0.428	2.50	0.02	0.885	2.83	0.28	0.597	5.50	0.89	0.346	4.00	0.03	0.853	2.75	1.48	0.224
Heat Waves	4.50	0.004	0.949	3.00	1.19	0.276	3.83	0.21	0.644	5.50	0.41	0.524	4.00	0.77	0.379	4.60	0.84	0.361
Storms	8.00	3.220	0.073	5.00	0.19	0.667	5.17	0.19	0.667	7.50	0.59	0.441	7.00	0.03	0.860	4.80	0.96	0.327
Intense rainfall/flooding	**9.50**	**4.746**	**0.029**	6.00	1.03	0.310	4.67	0.20	0.652	9.50	3.62	0.057	7.67	0.16	0.691	4.60	2.28	0.131
Average score	5.50			4.25			3.33			5.75			5.83			4.00		

x2 (df=1): Values of the Chi Square Distribution of the Kruskall Wallis Test with 1 degree of freedom.
Asymp. Sig. = Asymptotic significance.

7.6.2 Olympic Dam

Results of the average rating of exposure (current and future) across the Olympic Dam supply chain are presented in Table 7.5.

Table 7.5: Average rating of exposure (current and future) across the supply chain of Olympic Dam mine

	Present			Future		
Average rating of exposure	**Mining (n=3)**	**Downstream (n=8)**	**External (n=5)**	**Mining (n=4)**	**Downstream (n=8)**	**External (n=6)**
Droughts	1.00	3.50	4.20	3.00	4.43	4.40
Fires	1.00	3.25	4.20	1.67	5.00	4.60
Heat Waves	6.33	3.40	5.75	6.50	5.57	6.00
Storms	5.00	4.50	3.50	7.67	6.17	4.60
Intense rainfall/ Flooding	4.67	4.75	3.20	8.33	6.75	4.60
Average score	3.60	3.88	4.17	5.67	5.59	4.84

With respect to current conditions, the External group reported being more exposed (4.17) to climate events, followed by the Downstream (3.88) and the Mining groups (3.60). The External group considered itself to be more exposed to heat waves, fires and droughts. Members of the Downstream group considered that they are more exposed to intense rainfall/flooding (4.75) and storms (4.50). The Mining group reported they are more exposed to heat waves (6.33) which was the highest rating observed in this chain, followed by storms (5.00).

The future exposure was rated higher than the current case across all the five climate risks proposed. The Mining group considered themselves most exposed (5.67) giving the highest rating for intense rainfall/flooding (8.33) and storms (7.67). This coincides with the report by BHP Billiton (2015). The Mining group considered that they are less exposed to droughts (and related fires) than the other two groups, which reflects their confidence in their water management program. The ongoing management of water for the mine will be a primary issue since drought conditions are expected to increase at this location in the future (See section 7.2.2).

7.7 Sensitivity (current and future)

Information was compiled about the general impacts that members of the supply chain have faced due to climate risks and how they expect these risks to change in future.

7.7.1 Ranger Mine

Results of a sensitivity (present and future) across the Ranger Mine supply chain are presented in Table 7.6. A comparison between current versus future results is presented.

Each of the members of the supply chain selected operational disruption as the main climate risk impact with 100% of the Mining and Downstream group respondents, and 60% of the External group respondents reporting operational disruptions as a result of climate impacts. In addition to this, the Mining and Downstream groups identified production delays and loss of revenue as the most frequent impacts from climate events. Additional impacts such as financial performance and increased costs were mentioned by the Mining group, however, supply of essential resources and transportation were identified by the Downstream group as critical issues.

Having considered greater future climate risks, the Mining group identified the same impacts (financial performance, loss of revenue, increased costs, operational disruption, and delayed production) to those in the current case. They identified infrastructure as being at more risk in the future. This has the potential to increase capital expenditure budgets.

The Downstream group identified that some impacts are expected to increase in the future - financial impacts (66.7% vs 100%) and other impacts are expected to decrease - operational disruption (100% vs 66.7%). Across all members of the supply chain, operational disruption and increased costs were identified to be the major impacted areas in the future.

Some additional differences between group responses were detected. For example, in the current case, loss of revenue was not considered a relevant impact ($p=0.015$) by members of the External group (compared to the other participants). Furthermore, the health and safety of workers was not considered relevant ($p=0.042$) in the future by members of the Downstream group. Financial performance ($p=0.031$) together with loss of revenue ($p=0.012$) were not identified as being important for members of the External group. This is probably a short-sighted point of view if they do not have a diverse client and/or community base. The members of this group are more concerned about the environmental or community damage related to uranium mining operations than they are about economic/operational issues related to climate change (ECNT, 2014).

Table 7.6: Climate impacts reported across the Ranger Mine supply chain

	Present						Future					
Climate impacts	**Mining**		**Downstream**		**External**		**Mining**		**Downstream**		**External**	
	n=2	**p value**	**n=3**	**p value**	**n=5**	**p value**	**n=2**	**p value**	**n=3**	**p value**	**n=6**	**p value**
Financial performance	100.0%	.150	66.7%	.346	0.0%	.057	100.0%	.283	100.0%	.141	0.0%	**.031**
Loss of revenue	100.0%	.260	100.0%	.124	0.0%	**.015**	100.0%	.380	100.0%	.225	0.0%	**.012**
Increased costs	100.0%	.260	66.7%	.531	20.0%	.136	100.0%	.493	66.7%	.664	75.0%	.672
Operational disruption	100.0%	.510	100.0%	.355	60.0%	.436	100.0%	.620	66.7%	.521	100.0%	.365
Delayed production	100.0%	.183	100.0%	.072	20.0%	.245	100.0%	.239	66.7%	.500	25.0%	.295
Quality of production	50.0%	.230	33.3%	.330	0.0%	.496	50.0%	.163	0.0%	.761	0.0%	.688
Supply of essential inputs or services	50.0%	.650	66.7%	.346	0.0%	.057	50.0%	.670	66.7%	.371	25.0%	.437
Transportation of product	50.0%	.430	66.7%	.133	20.0%	.657	50.0%	.507	33.3%	.664	0.0%	.224
Health and safety of workers	50.0%	.697	33.3%	.407	60.0%	.622	50.0%	.620	0.0%	**.042**	75.0%	.514
Infrastructure/ plant & equipment damage	50.0%	.650	33.3%	.654	40.0%	.699	100.0%	.199	33.3%	.565	50.0%	.637
Average score	75.0%		66.7%		22.0%		80.0%		53.3%		35.0%	

7.7.2 Discussion

In this chain, the members of Mining group reported the greatest sensitivity to climate conditions in the past and they also estimated that they would be one of the most sensitive groups to climate change in the future. This result is consistent with the climate projection in the area since heavy rainfall is expected to increase in all RCPs considered. Furthermore, cyclone activity is expected to increase in intensity with high confidence. In fact, this group has been severely affected in the past by floods in the operational pit, floods in the Tailings Storage Facilities (TSF), leading to a halt of operations. As a result, planned production has decreased, and the financial performance has been affected (ERA, 2007a; ERA, 2011; ERA, 2012, Pizarro *et al*, 2017). However, this group has undertaken adaptation measures such as the commission of a brine concentrator (value at A$220 million) to improve its water management capability in the wet season (ERA, 2012).

Downstream group members' responses indicated that they expected the health and safety of workers in the future to be less sensitive than the other groups. This suggests that this group might implement adaptation measures for protecting workers under future climate change such as heat stress training programs (ERA, 2007b; ERA, 2013c).

7.7.3 Olympic Dam

Results of the sensitivity (current and future) across the Olympic Dam supply chain are presented in

Table 7.7. The Mining group considered several items as having been impacted (75%) by climate risks including financial performance, loss of revenue, operational disruption, and health and safety of workers. Operational disruption (87.5%) was the most popular selection by The Downstream group followed by increased costs and supply of essential inputs (62.5). Members of the External group were most likely to select health and safety of workers (60%) followed by loss of revenue, increased costs, supply of essential inputs, and infrastructure damage, all of which scored 40% of the preferences.

Table 7.7: Climate impacts reported across the Olympic Dam mine supply chain

	Present						Future					
Climate impacts	**Mining**		**Downstream**		**External**		**Mining**		**Downstream**		**External**	
	n=4	**p value**	**n=8**	**p value**	**n=5**	**p value**	**n=4**	**p value**	**n=8**	**p value**	**n=4**	**p value**
Financial performance	75.0%	.159	50.0%	.393	0.0%	.057	75.0%	.363	75.0%	.156	0.0%	**.031**
Loss of revenue	75.0%	.328	50.0%	.613	40.0%	.459	75.0%	.514	87.5%	.087	25.0%	.130
Increased costs	50.0%	.672	62.5%	.387	40.0%	.459	100.0%	.224	62.5%	.428	50.0%	.328
Operational disruption	75.0%	.693	87.5%	.246	20.0%	**.012**	75.0%	.635	87.5%	.445	50.0%	.179
Delayed production	50.0%	.604	50.0%	.504	0.0%	**.038**	50.0%	.705	62.5%	.333	25.0%	.295
Quality of production	0.0%	.578	0.0%	.296	20.0%	.504	0.0%	.688	12.5%	.565	0.0%	.688
Supply of essential inputs or services	25.0%	.468	62.5%	.128	40.0%	.699	50.0%	.563	37.5%	.561	50.0%	.563
Transportation of product	0.0%	.306	37.5%	.274	0.0%	.219	25.0%	.672	50.0%	.134	0.0%	.224
Health and safety of workers	75.0%	.396	37.5%	.199	60.0%	.622	75.0%	.514	62.5%	.668	75.0%	.514
Infrastructure/ plant & equipment damage	50.0%	.532	25.0%	.274	40.0%	.699	50.0%	.637	25.0%	.156	50.0%	.637
Average score	47.5%		46.3%		26.0%		57.5%		56.3%		32.5%	

Regarding the expected future impacts, members of the Mining group agreed that greater climate risks would lead to "increased costs" (100%). They estimate future impacts will be the same as those experienced at present, apart from the supply of essential inputs or services (25% vs 50%) and transportation of product (0% vs 25%). Members of the Downstream group reported a varied tendency towards estimating future likely climate risks. In this group financial performance (50% vs 75%), loss of revenue (75% vs 87.5%), delayed of production (50% vs 62%), transport of product (37.5% vs 50%) and health and safety (37.5% vs 62.5%) increase in the future. The quality of production (not previously mentioned) was considered to be affected in the future. This may be directly related to the access to high quality ore. In the External group, impacts are expected to increase for all cases mentioned except loss of revenue, which decreased from 40% to 25% in future. Across this chain, all respondents identified that the Mining group would have the most potential affect from climate risks, now, and in the future.

Differences between group responses were detected e.g. in the current case, members of the External group do not estimate operational disruption ($p=0.012$) and increased costs ($p=0.038$) as relevant climate-related impacts compared with the other two groups. In addition, financial performance ($p=0.031$) was considered to be only of future relevance by the External group.

7.7.3 Discussion

Almost all groups reported being sensitive to varying degrees of climate risks in most of the economic and operational impacts. This is particularly relevant if according to climate projections presented in section 7.2.2, the mean temperature, heat waves and rainfall are expected to increase in all RCPs.

The Mining group was the most sensitive to climate risks at present (and in the past). They estimated they would also be the most sensitive out of all the other groups in the future. This group showed more concern about the internal economic impacts such as financial performance, loss of revenue and increased cost in the present and future case compared with the other groups. In contrast, the results discussed by Pearce *et al*, (2009) indicated that uranium mining participants reported to have more concern about external market fluctuations than the internal impacts that can cause the climate change on mining. This included potential impacts to both ore extraction and surface equipment, but it should be noted that the climate in the Canadian uranium mining areas is different to that in Australian uranium mining areas. The specific impacts on mining operations selected by participants in this study, such as operational disruptions or damage to infrastructure were also identified as important in a previous study (Hodgkinson *et al*, 2014).

The External group of this chain considered there to be lesser impact by climate risks at present than in future. They also showed lower concern on the financial performance and loss of revenue in the present and future case compared with the other two groups. This suggests that the members of this group (mainly community, NGOs and Government representatives) are not concerned about the economic issues related to climate risks, however, they consider health and safety of workers to experience the greatest climate-related in the future.

7.8 Specific climate impacts at the mine site

Mining group respondents of both chains were asked about what aspects of the mining operation were currently (or have been historically) impacted by climate related conditions. The most commonly selected aspects were tailings/waste management facilities (63.6%) and transport within the mine site (54.5%). Ore extraction, processing, and maintenance activities were also identified as having been impacted (45.5%), in contrast with transport outside the mine site (36.4%) and mine planning (9.1%).

A comparison of the historical to the future expectations is not possible due to a lack of survey responses; however, the results can be discussed in isolation. With this in mind, tailings/waste management facilities were most commonly selected as being affected by respondents of the Mining group (66.7%), followed by processing (44.4%), transport within and outside the mine site (44.4%), and ore extraction (33.0%). Respondents were least likely to select maintenance activities (20.0%) and mine planning (11.0%) as being affected in the future. Although there appears to be a difference in both cases (current and future), this may be attributed to the unanswered questions.

7.9 Indirect flow-through impacts

In order to gather information about indirect climate impacts faced by supply chain members and external stakeholders, respondents were asked about the 'flow-through' effects of climate impacts from other organisations. This allowed the identification of which organisations have historically affected their own organisation. In turn, they were likewise asked to identify, under current climate conditions, what organisations might be affected by 'flow-on' climate events from their own organisation. The results for each of the chains is presented below.

7.9.1 Ranger Mine

Based on the sum of responses that were "not applicable", "other" and/or "skipped" (45.2%) it was difficult to sort the responses for this chain in a meaningful way. Nevertheless, it was determined that

respondents were least likely to select that a Mining company (9.1%) would produce 'flow-through' impacts onto their own organisation under the current climate conditions. Regarding the future conditions, respondents were most likely to select the local community (54.6%) as indirectly affecting their own organisation through climate related risks, followed by Utility companies and the Mining company (both 36.4%). Mining services (27.3%) and Transport companies (18.2%) were least identified as likely to produce flow-through impacts affecting one's own organisation in a future climate event.

7.9.2 Discussion

In spite of the low survey response to these questions, there is evidence that the Ranger Mine has been affected by flow-through impacts, such as closure or restricted access to the main access road which was closed due to flooding for almost a month in 2007, and for two weeks in 2014 (ERA, 2008b; TAMS, 2014). The Port of Darwin has also has been closed several times because of cyclone activity including Cyclone Monica in 2006 that caused late arrival of a transport vessel with supplies for the mine. These incidents meant that the company was not able to fulfil a production schedule and had to purchase 316 tonnes of uranium to fulfil client contracts (ERA, 2007a).

The respondents indicated that in the future, the local community would be the most affected by flow through effects. However, the local government has undertaken adaptation measures including setting up a Flood Mitigation Advisory Committee for Darwin and the rural areas in 2015, which include the community, local businesses, emergency services, local council and government. The local government is also concerned about the implementation of risk/impact mitigation measures with several investments in the region to reduce the impact of flood events (NTG, 2011; NTG, 2015).

7.9.3 Olympic Dam

External respondents estimated that the most indirect (flow-through) risk affecting their own organisation would be the mining company (70.1 %) and the local community (52.9 %) in the future. Other members of the chain considered their own organisation likely to be affected in the future by transport and utility companies, and mining services, all reporting 41.2%.

The Mining services group was identified as the least affected by flow-through impacts in both the present and future cases. Furthermore, the Mining Company was found to be the most affected by flow-through impacts in the future. This was similarly indicated by Hodgkinson *et al* (2014) where participants of the mining supply chain identified climate impacts on mining infrastructure, transport (ports), and energy (electricity outages). In 2016 Olympic Dam was affected directly and indirectly by a severe storm

(extreme rainfall, strong wind, and lighting) (BOM, 2016), which caused a widespread blackout across the state of South Australia. This storm forced the shutdown of the mine for 15 days and resulted in an economic loss for the mining company of AU$137 million (BHP, 2017a).

7.10 Indirect flow on impacts

A survey question was posed that considered flow-on impacts from the respondents' own organisations to other organisations. For this, respondents were asked to rank from 1=most affected to 8 =least affected the indirect flow–on impacts on their current supply chain.

7.10.1 Ranger Mine

The results for the Ranger Mine are presented in Table 7.8. The Mining group has been identified as the most affected by flow-on impacts (3.92), followed by the Downstream group. By Sector, the Mining Company (1.00) was reported as the most affected within the whole chain followed by the surrounding environment (3.18). No significant differences between groups were detected in this question.

Table 7.8: Ranking of indirect (flow-on) impacts across the supply chain of Ranger Mine

Flow-on impacts	**Mining (n=2)**	**Downstream (n=3)**	**External (n=6)**	**Weighted average**
Mining company	1.00	1.00	1.00	1.00
Local community	2.00	8.00	5.50	5.55
Construction	nr	4.00	4.00	4.00
Manufacturing	8.00	6.00	5.00	5.82
Transport Company	4.00	2.00	6.00	4.55
Customer company	4.50	3.00	8.00	6.00
Mining Services	nr	3.50	7.00	5.83
Surrounding environment	4.00	5.00	2.00	3.18
Average score	3.92	4.06	4.81	

nr: no response

The Ranger Mine has been affected by flow-on impacts in the past, such as flooding of the Arnhem Highway (ERA, 2006), the Jabiru township (ERA, 2007b) and its surrounding roads throughout Kakadu National Park (ERA, 2008b).

7.10.2 Olympic Dam

The results for the Olympic Dam Mine regarding flow-on impacts are presented in Table 7.9

Table 7.9: Ranking of indirect flow-on impacts across the supply chain of Olympic Dam mine.

Flow-on impacts	Mining (n=2)			Downstream (n=8)			External (n=3)			Weighted
	Average	x2 (df=1)	Asymp. Sig.	Average	x2 (df=1)	Asymp. Sig.	Average	x2 (df=1)	Asymp. Sig.	average
Mining company	4.50	0.11	0.738	2.63	0.00	1.000	5.33	2.65	0.104	3.54
Local community	7.00	0.40	0.528	4.71	0.21	0.649	3.00	1.82	0.178	4.66
Construction	7.00	1.74	0.187	4.71	0.68	0.411	3.00	0.76	0.384	4.66
Manufacturig	8.00	1.43	0.231	6.43	0.34	0.557	4.00	3.99	**0.046**	6.11
Transport Company	4.00	0.02	0.900	4.13	0.07	0.794	3.50	0.21	0.644	3.96
Customer company	3.00	0.39	0.530	5.14	0.42	0.518	3.33	1.40	0.237	4.39
Mining Services	2.00	2.74	0.098	4.29	0.09	0.768	5.33	1.49	0.222	4.17
Surrounding environment	6.00	1.74	0.187	3.43	0.43	0.511	5.00	0.30	0.587	4.18
Average score	5.25			3.03			5.17			

x2 (df=1): Values of the Chi Square Distribution of the Kruskall Wallis Test with 1 degree of freedom.
Asymp. Sig. = Asymptotic significance.

Based on the survey results, only one difference in responses between groups was detected to this question. Members of the External group ranked manufacturing as being most likely to be affected (Asymp. Sig. =0.046) by flow-on impacts from their own organisation.

The Downstream group of the supply chain of Olympic Dam mine was considered as the most affected (3.03) by flow-on impacts within the chain followed by External group (5.17). By sectors, the Mining Company also received the highest average rating (3.54) for likelihood of being affected by flow-on impacts, followed by Customer Company (3.96) and Mining services (4.17).

This is confirmed since engineering companies, consulting companies or maintenance companies (belonging to the Mining services group) have been affected by the increased cost of safety shutdown of critical elements of the mine site, and extra working hours for personnel, when Olympic Dam mine stopped its operations after the severe storm of September 2016 (Burns *et al*, 2017).

7.11 Factors that can increase future vulnerability

The survey results have revealed that there is concern associated with increasing vulnerability of a range of factors in both of the mine supply chains. These factors include: the age and design of assets,

geographical location, type of operation, the frequency of climate events, intensity and magnitude of the events, and impact on labour force availability.

7.11.1 Ranger Mine

The respondents of the three groups within the Ranger Mine's supply chain indicated that geographical location and frequency of climate events were the major factors likely to increase their vulnerability to future climate risk. This is important since both factors are not able to be controlled. For this mine, the design or age of assets was not considered as particularly relevant factors by any group. This may be a result of significant capital investment in the recent years. Some adaptation measures to modify assets have been performed, mainly by the Mining group, including a rise (three times) of the wall of the tailings storage facility, construction of a brine concentrator, and additional pond water storage capacity (ERA, 2012).

7.11.2 Olympic Dam

All of the Olympic Dam supply chain groups identified the frequency of climate events and impact on labour force availability as having the most future vulnerability. Labour force availability can be indirectly affected by an impact of climate change e.g. water scarcity or power outages at the mine site may lead local communities relocating which could cause a deficit in the labour force (Hodgkinson *et al*, 2010). The design of assets was relevant for members of the Mining group only since this group has already considered the impact of climate change on their infrastructure. For example, the expansion project of Olympic Dam mine considered measures such as additional freeboard in the TSF, levees, and the sea walls in the port facility (BHP, 2009a).

7.12 Increase of resources to continue operating

Respondents were asked to indicate any increase in resources they might expect in the future to continue operating in response to climate change. Resources were clarified as being water, energy, inputs (materials and equipment), labour, infrastructure, technology, and knowledge and expertise.

7.12.1 Ranger Mine

The Mining group of this chain most frequently indicated that their energy needs would increase (100%), followed by labour, technology, and knowledge/expertise (50% each). In the Downstream group, the most popular resources nominated were water, energy, infrastructure, technology and

knowledge/expertise. However, it was not possible to sort these into a descending order as they were all selected an equal number of times (50%). The External group most commonly selected energy (40%) as the resource most likely to increase in the future as a result of climate change. None of the groups indicated that the demand of Inputs (materials and equipment) would be expected to increase in the future.

7.12.2 Discussion

All the members of the chain agreed that energy is the most likely resource required in the future to increase. However, based on ERA (2013b) there was no forecasted variation in energy consumption even when the underground mine expansion was considered. It is expected in this case that Rio Tinto (2016ab) has committed to energy efficiency measures in the future. Rio Tinto has already introduced trials of new technologies at its operations (Rio Tinto, 2014b; Rio Tinto, 2016ab). Furthermore, as part of the increasing need for knowledge/expertise and understanding about climate change, the Australian Government has prepared adaptation/strategy plans for the surrounding region such as Kakadu National Park (Australian Government, 2010) and the local government has undertaken adaptation plans for the local community (WASC, 2010).

7.12.3 Olympic Dam

All members of the Olympic Dam supply chain agreed that the need for water, energy, labour, and knowledge/expertise resources may increase in the future. In addition to these, the Downstream group members also considered that improved infrastructure would be required. Overall, members of both supply chains estimated an increase in demand of almost all resources in the future. Similar to the Ranger Mine results, a potential increase in Inputs (including materials and equipment) was dismissed by all respondents.

7.12.4 Discussion

Water scarcity can impact the productivity of a mine, especially in the case of Olympic Dam where there is little surface water in the proximity to the operations. Considering the mean annual rainfall is expected to decrease in the future at this location, this could have a significant impact on the operations. Both the mine and nearby towns (Roxby Downs, and Andamooka) rely on groundwater extracted from the Great Artesian Basin (Torrisi and Trotta, 2013). Olympic Dam has implemented a plan for sustainable water use, which includes a water efficiency program to reduce water demand (Torrisi and Trotta, 2013).

In addition, the local community has been advised on water saving and water sustainability (Roxby Downs Council, 2014).

The most commonly occurring extreme weather event at the mine's location is heat waves during the summer, resulting in an increase in electricity consumption (Pilli-Sihvola *et al*, 2010). Electricity consumption in a typical summer day (January) in South Australia can reach 2,011 MW but during a heat wave it can increase to 3,399 MW (historical record reached in January 2011) or 3,281 (January 2014) which is an increase of 69.02% and 63.15% respectively (ESAA, 2015). Heat waves are expected to increase in frequency, intensity and duration in this area (Watterson *et al*, 2015) leading to higher electricity consumption as cooling becomes a priority. Olympic Dam is the largest single client of Electranet (the distribution company in South Australia). Olympic Dam's annual electricity consumption is about 7% of the total electricity consumption in South Australia (BHP Billiton, 2009d), having a significant impact to the increase in electricity demand during a heat wave. In addition, uranium extraction is an energy and water intensive operation (Schneider *et al*, 2013). Energy and water resource supplies may be affected by extreme weather events in the future, and subsequently the mine's operations (Hodgkinson *et al*, 2010). The survey results confirm the concern for these two resources (water and energy) that may become stressed in the future as a result of climate change.

7.13 Current adaptive capacity

The current adaptive capacity of organisations was assessed by asking respondents to rate a range of items in their Risk Management Plan (RMP) with a scale from 0: low to 10: excellent. In addition, there were questions posed regarding organisational approach to deal with climate risks (results expressed in percentages), whether a vulnerability assessment and a risk reduction plan had been undertaken, and the identification of opportunities from climate change.

7.13.1 Ranger Mine

The results of the evaluation of the RMP across the supply chain of the Ranger Mine are presented in Table 7.10.

Table 7.10: Evaluation of the Risk Management Plan across the supply chain of Ranger Mine

Evaluation of the Risk Management Plan (RMP) to Climate Risks at Ranger Mine's supply chain	**Mining (n=2)**			**Downstream (n=2)**			**External (n=4)**		
	Average	**x2 (df=1)**	**Asymp. Sig.**	**Average**	**x2 (df=1)**	**Asymp. Sig.**	**Average**	**x2 (df=1)**	**Asymp. Sig.**
How well identified are the key climate-related risks in the Risk Management Plan (RMP)?	5.00	0.85	0.36	6.50	0.00	1.00	7.00	0.42	0.52
How relevant/specific is the RMP to the actual site or operation?	8.00	0.33	0.56	6.50	0.33	0.56	8.00	0.54	0.46
How adequate are the current risk mitigation procedures and response/contingency plans?	8.50	0.60	0.44	7.00	0.11	0.74	7.25	0.08	0.77
How clear are the various positions, roles and responsibilities of the personnel required to respond to the event?	9.00	1.28	0.26	6.50	1.28	0.26	8.00	0.04	0.83
How clear are the guidelines and procedures to follow in the case of a climate event?	9.00	0.67	0.41	6.00	1.81	0.18	7.75	0.01	0.93
How well is the RMP communicated to staff?	6.50	0.28	0.60	7.00	0.01	0.91	7.25	0.00	1.00
How regularly is the RMP updated?	7.50	0.12	0.73	7.50	0.22	0.64	7.50	0.54	0.46
How effective is the communication between the other companies/organisations related with your company e.g. Energy, Water, and Transport, Communication Company or other?	3.50	**4.16**	**0.04**	5.50	0.15	0.70	7.75	2.30	0.13
Average score	7.17			6.56			7.56		

x2 (df=1): Values of the Chi Square Distribution of the Kruskall Wallis Test with 1 degree of freedom.
Asymp. Sig. = Asymptotic significance

Members of the External group gave the highest overall score (7.56) for their RMP. The relevance of the RMP for their operation and the clarity of the roles to act in the event of a climate incident were the items that received the highest score (8.00) in this group. A high proportion (83.3%) stated they have a

proactive approach to dealing with climate risks; however, no members of this group indicated their organisation had conducted a vulnerability assessment or had developed a risk reduction plan. Due to the high percentage of "unsure" responses in the previous questions (60.0% and 66.6% respectively), it may be inferred that there is a lack of knowledge about these two concepts. This group did not identify any opportunities that may arise from climate change for their business.

Members of Mining group gave an overall average rating of 7.17 to their RMP and provided good scores (according to the scale) for each item listed apart from effective communication that only scored 3.50. ERA has undertaken stakeholder engagement programs for other purposes e.g. expansion plan to mine underground (ERA, 2013a), so the adaptive capacity to communicate with companies- related exists it just needs to be mobilised in this case. The Mining group identified that they have a proactive approach when dealing with climate risks (100%) and know about the vulnerability assessment (50%) and risk reduction plans in place (50%). However, similar to the External group, they did not identify any opportunities that may be derived from climate change.

The Downstream group gave the lowest overall score for their RMP (6.56), reporting the regular update of their RMP as the highest score (7.50), followed by the communication to the staff and the adequacy of the plan, (both scored 7.00). Members of the Downstream group reported to have mainly a proactive approach (66.66%) to deal with climate risks. However, 66.66% of respondents reported that they did not have a vulnerability assessment and a risk reduction plan within their operations.

7.13.2 Discussion

Considering the evaluation of the RMP, the approach to dealing with climate risks and the existence of a vulnerability assessment and a risk reduction plan, it seems that the Mining group of this chain is the best prepared to meet climate change challenges. The Downstream group appears to be the least prepared although the reason for this is not clear. This group consists mainly of contractors and consultants, and while they may be small organisations, they are required to comply with the same requirements in all aspects as the outsourcing companies (ERA, 2007b). In addition, in 2005 ERA undertook a program to upgrade the contractor's management system, which included the assessment of critical risks (ERA, 2007b). The results of this research presented herein, suggest that compliance may have slipped in the decade since this program was undertaken.

7.13.3 Olympic Dam

The results of the evaluation of the Risk Management Plan across the supply chain of the Olympic Dam Mine are presented in Table 7.11.

Table 7.11: Evaluation of the Risk Management Plan across the supply chain of Olympic Dam mine

Evaluation of the Risk Management Plan (RMP)	**Mining (n=4)**			**Downstream (n=8)**			**External (n=4)**		
to Climate Risks at Olympic Dam's supply chain	**Average**	**x2 (df=1)**	**Asymp. Sig.**	**Average**	**x2 (df=1)**	**Asymp. Sig.**	**Average**	**x2 (df=1)**	**Asymp. Sig.**
How well identified are the key climate-related risks in the Risk Management Plan (RMP)?	7.75	1.45	0.23	5.88	1.21	0.27	7.33	0.60	0.44
How relevant/specific is the RMP to the actual site or operation?	8.50	2.69	0.10	**6.00**	**5.70**	**0.02**	8.00	0.85	0.36
How adequate are the current risk mitigation procedures and response/contingency plans?	8.25	0.98	0.32	7.13	0.27	0.60	7.25	0.06	0.80
How clear are the various positions, roles and responsibilities of the personnel required to respond to the event?	8.50	0.78	0.38	7.38	0.11	0.74	7.25	0.14	0.71
How clear are the guidelines and procedures to follow in the case of a climate event?	8.50	0.37	0.54	7.13	0.35	0.55	8.00	0.29	0.59
How well is the RMP communicated to staff?	7.75	0.68	0.41	7.00	0.08	0.78	7.33	0.06	0.81
How regularly is the RMP updated?	7.50	0.61	0.44	6.13	1.23	0.27	6.67	0.02	0.88
How effective is the communication between the other companies/organisations related with your company e.g. Energy, Water, and Transport, Communication Company or other?	6.00	0.00	0.97	6.63	0.34	0.56	5.75	0.20	0.65
Overall average rating	7.84			6.58			7.19		

The highest overall average rating for an RMP (7.84) was provided by the Mining group. They also gave the highest score for individual items identified in the question except for effective communication between related companies, which was the lowest score (the same response as Ranger Mine). In this group, three items were evaluated highly, including relevance of the RMP to the site of operation, clarity of roles/positions, and clarity of guidelines and procedures (all 8.5). Respondents stated they had a mainly proactive approach (75%) for dealing with climate risks, they have performed a vulnerability assessment (50%), they have a risk reduction plan (50%) and they have identified potential opportunities from climate change (25%).

Members of the External group gave an overall rating average of 7.19. They considered their RMP was relevant and specific for the site of operation (8.0) and the guidelines and procedures to follow in a climate event are well defined (8.0). Communication between companies was once again identified as with the lowest score (5.75). Members of this group reported a mainly reactive approach (60%) to dealing with climate change, with the highest percentage of "unsure" responses in the chain regarding the existence of a vulnerability assessment, risk reduction plan and identification of opportunities (60%, 80% and 60% respectively).

In this supply chain, the members of the Downstream group gave the lowest overall rating (6.58) to their RMP and also the lowest rating for any single item of the plan, namely the relevance of the RMP to their situation (6.00). They reported having both a proactive and reactive approach (50% for each). They also provided a strongly negative response to the existence of a vulnerability assessment and a risk reduction plan (both 87.5%). They have not identified operational opportunities from climate change. Further, members of Downstream group reported more concern (Asymp. Sig. =0.02) about the relevancy of their RMP for the site of operation, explaining the lower rating compared to the other groups.

7.13.4 Discussion

Based on the previous results, it seems that the Mining group is the best prepared in this supply chain. This group gave a good rating for their RMP, they have mainly a proactive approach, they have knowledge about a vulnerability assessment and a risk reduction plan and they were the only group that identified opportunities that may arise from climate change although those opportunities were not specified. Some members of this group stated that "climate change is well understood" or "vulnerability assessment will be complete in 2016".

In contrast, the Downstream group appears to be the worst prepared to face climate risks: this group gave the lowest overall score to their current RMP. Members of this group reported a high percentage

of “no” answers to the questions relating to the existence of a vulnerability and risk reduction plan. This suggests there may be a lack of knowledge of these concepts driven by poor communication or there may be no plans. This is confirmed by direct comments from respondents such as “have not heard about this”. They were unsure in the identification of opportunities, which also supposed a lack of knowledge in this matter.

7.14 Future adaptive capacity

In order to estimate the current supply chain’s future adaptive capacity, the respondents were asked to provide an overall rating of their RMP with respect to how well it would cope with greater future climate risks. The comparison between the current cases versus future is presented below.

7.14.1 Ranger Mine

Similar to the previous highest overall rating given by the Ranger Mine, External group members also gave the highest overall rating for the future adaptive capacity. However, the External group’s rating of their RMPs for future conditions was lower than for current conditions (7.56 current versus 6.00 future). The Mining group also gave a lower score for their RMP for coping with future events than they did for current conditions (7.17 versus 5.50). This result is in contrast with the estimate by ERA (2012), where the company stated they are confident they will be able to manage future climate events.

The Downstream group again returned the lowest overall score (6.50 vs 4.33). Nevertheless, some members of this group, such as Ports or Rail, present a proactive approach to dealing with climate risks and climate change (Darwin Port Corporation, 2012; ARA, 2012).

7.14.2 Discussion

Based on the previous results, the External group of this supply chain might have the best RMP to face climate change. In fact, members of this group have shown increased interest and concern to bring climate change concepts to all communities might be in an attempt to increase the adaptive capacity. Until a few years ago, indigenous communities showed a lack of, or unclear, knowledge about climate change (Petheram *et al*, 2010). More recently, programs administered by national and local government have provided climate change adaptation advice. These programs have included the climate change action plan NTG (2011), the Flood Mitigation Advisory Committee (NTG, 2015) or the Kakadu National Park: Climate change Strategy (AG, 2010) to provided knowledge to communities.

7.14.3 Olympic Dam

For the Olympic Dam mine supply chain, the Mining group again returned the highest RMP score, even though the score given for handling future conditions was lower (current 7.84 vs future 7.00). This was followed by the Downstream group (current 6.58 vs future 6.38) and the External group returned the weakest RMP score for coping with future conditions (current 7.19 vs future 6.00). From these results, the Mining group may be the best prepared. Members of the Mining and Downstream have the best RMP for climate change. In fact, members of Downstream group such as Ports have undertaken several measures to reduce the risks of climate change, including a vulnerability assessment for the region and the identification of adaptation measures (AdaptWest, 2015; AdaptWest, 2016).

7.15 Changes needed to improve the adaptive capacity

7.15.1 Ranger Mine

The members of the Ranger Mine supply chain considered changes might be needed to improve adaptive capacity. The results are provided in Table 7.12.

Table 7.12: Changes posed across the supply chain of Ranger Mine

Options posed in the question	**Mining n=2**	**p value**	**Downstream n=3**	**p value**	**External n=4**	**p value**
Management procedures	50.0%	.717	0.0%	.141	75.0%	.233
Administrative procedures	0.0%	.493	0.0%	.336	75.0%	**0.04**
Operational procedures	100.0%	.493	33.3%	.194	100.0%	.224
Work practices	0.0%	.330	0.0%	.180	75.0%	.178
Technical changes	100.0%	.076	33.3%	.664	25.0%	.672
Management approach/leadership	50.0%	.565	33.3%	.751	25.0%	.593
Not applicable	0.0%	.761	33.3%	.343	0.0%	.563
Other (please specify)	0.0%	.917	0.0%	.875	0.0%	.833
Average score	**37.5%**		**16.7%**		**46.9%**	

The Mining group were most likely to select operational procedures and technical changes as needed to improve adaptive capacity. They also selected management procedures and management approach as being of significance. The Downstream group selected operational procedures, technical changes, and management approach with equal frequency (33.3%). The External group identified operational procedures with greatest frequency (100%), followed by management procedures, administrative

procedures and work practices (all 75%). Further, members of the External group selected administrative procedures in a higher proportion (p=0.04) than the other groups. They also enumerated the highest number of changes required to improve the future adaptive capacity.

7.15.2 Discussion

All members of this chain selected operational procedures as the most important change required to improve their adaptive capacity. It was suggested that this change could be achieved by modifying the current risk identification processes, considering the cumulative impact of climate risks over the infrastructure, implementing measures that address the risks identified, monitoring the risks and identifying measures to ensure they are suitable and developing local climate projections to evaluate potential risks (Mason and Giurco, 2013). Further, Rio Tinto has recognised the value of integrating climate change factors into its business management and planning (C2ES, 2013).

For members of the External group (mainly NGOs, Government organisations and communities) administrative and management procedures are a matter of concern if they do not change in the future. This is because administrative procedures can facilitate or impede adaptation to climate change (Productivity Commission, 2012; Hussey *et al,* 2013). In addition, local government has already discussed the high vulnerability to climate change and that it is important to adapt at all levels (government, business, communities and individuals) (WASC, 2010).

7.15.3 Olympic Dam

The members of the Olympic Dam supply chain estimated that changes in all aspects posed in the question are required (in different percentages) as can be seen in Table 7.13. For the Mining group, the most significant changes identified were operational procedures and work practices (both 75%). The Downstream group members also considered operational procedures more frequently (75%), followed by management procedures, work practice, and management approach (all 37.5%). The External group identified operational and management procedures (both 50%) as the most critical areas needing change. Importantly, the three groups considered operational procedures as being the most critical aspect that should be changed.

Table 7.13: Changes mentioned across the supply chain of Olympic Dam mine

Changes posed in the question	Mining n=4	p value	Downstream n=8	p value	External n=4	p value
Management procedures	50.0%	.637	37.5%	.444	50.0%	.637
Administrative procedures	25.0%	.672	25.0%	.572	25.0%	.672
Operational procedures	75.0%	.672	75.0%	.572	50.0%	.328
Work practices	75.0%	.178	37.5%	.561	25.0%	.437
Technical changes	25.0%	.672	12.5%	.218	25.0%	.672
Management approach/leadership	25.0%	.593	37.5%	.553	25.0%	.593
Not applicable	0.0%	.563	12.5%	.751	25.0%	.437
Other (please specify)	25.0%	.167	0.0%	.667	0.0%	.833
Average	**37.5%**		**29.7%**		**28.1%**	

7.15.4 Discussion

In this supply chain operational procedures were selected as the most important aspect to be changed to improve adaptive capacity and some members have already acted. For example, BHP Billiton integrated climate change into its expansion planning process for the Olympic Dam mine (although expansion planning was postponed in 2012), including analysis of the climate projections for the project location and how they can affect the operational procedures and the physical impacts of the operations (BHP Billiton, 2009a; BHP Billiton, 2015). Furthermore, they have analysed and assessed how to increase the business resilience in response to climate change. Changes have been made to operational procedures (BHP Billiton, 2015) such as a sustainable water usage (Torrisi and Trotta, 2013), energy efficiency use, low emission technologies, and training (BHP Billiton, 2015). The local government of South Australia has prepared vulnerability assessment and adaptation planning reports, which included members of this supply chain such as Mining, Roxby Downs community, and Transport (Port Augusta, Roads and Railways) (Hodgkinson *et al*, 2014; RDA Far North SA, 2016).

7.16 Conclusions

This research has provided analysis of the vulnerability that the uranium supply chains in Australia have to climate change. This study has shown that both supply chains have the capacity to respond to current climate risks. However, the capacity to anticipate future climate risks, including a vulnerability assessment or risk reduction plan appears to be very limited. The vulnerability assessment revealed the various aspects of sensitivity (direct and indirect) to climate change in both supply chains with a special

focus on the impacts on mining companies. It was shown that vulnerabilities are location-specific. The most vulnerable group for the future was identified as the Mining group in both chains. They were also identified with the greatest capacity to adapt. At both locations, the least prepared group is the Downstream group suggesting that these groups may require the most assistance to reduce their vulnerability.

Based on the RCP scenarios, it likely that in all scenarios that there should be an expected increase in rainfall intensity at the Ranger Mine and decrease in rainfall at Olympic Dam. Based on the results of the survey, it is evident that both of these locations have been impacted by severe storms and drought in the past resulting in increased operating costs and lost revenue. This study has revealed that the adaptive capacity across the uranium supply chain might require some changes at various levels (operational and administrative), especially in administrative procedures which are perceived as a constraint to be better prepared to face climate change. It was shown that the chains are strongly connected and weaknesses within any of the links can have flow-on impacts to others that may negatively impact the whole chain. It has been revealed that the communication between companies is the weakest item within the Risk Management Plans and this is certainly an easy area to improve. There is a need for a more in-depth study to identify specific adaptation needs and options that can be implemented across the chains.

8 Adaptation Options

This chapter provides background information about the adaptation process and its determinants. Further, adaptations needs were identified after the vulnerability assessment to the uranium supply chain and the external stakeholders. Further adaptation options were proposed, and they were assessed according to an economic technique (Multi-Criteria Analysis).

8.1 Adaptation process

Adaptation is the final outcome of a process which involves the identification of needs after conducting a vulnerability assessment and consequently the analysis of adaptation options. The implementation of the adaptation options is the final goal of this process. The process has been conceptualised in Figure 8.1.

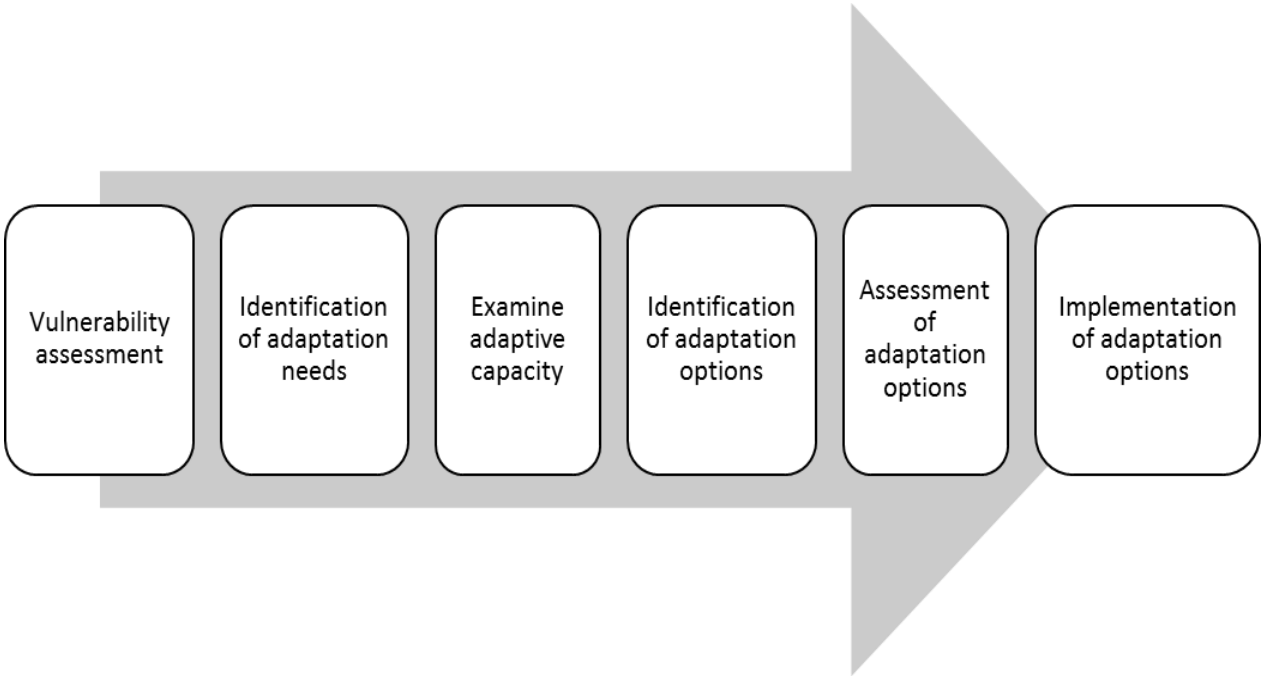

Figure 8.1: Process of adaptation to climate change Identification of adaptation needs

8.2 Adaptation needs and adaptive capacity

The goal of the adaptation process is to make a permanent change in a system. To complete this, knowledge of risks and vulnerabilities are required to identify the needs and options associated with adaptation (Adger *et al*, 2005; Klein *et al,* 2014).

The scope of adaptation needs can be classified as, social, institutional, engagement, information and resources. They are described below.

8.2.1 Social needs

Individuals belonging to different human systems/groups have different vulnerabilities since vulnerability is impacted by age, health, social status, level of education, etc. (Smit *et al*, 2001; Smit and Pilifosova, 2003ab; Smit and Wandel, 2006; Smit *et al*, 2008; Adger *et al* 2009).

In the context of this study, social needs have been classified in accessibility of human capital, financial assets, political regulations, management approach and administrative procedures.

Previous chapters have shown that the vulnerability in uranium mining varied according to geographical location e.g. Ranger Mine supply chain reported vulnerability due to excess water in its operations. The Olympic Dam supply chain reported vulnerability associated with limited access to the resource (especially in droughts).

A specific assessment of the Risk Management Plan (RMP) has allowed the identification of adaptation needs in both supply chains.

8.2.2 Institutional and private organisations needs

Institutions provide the conditions that enable or constrain adaption planning. At the national or international level, institutions provide policies and programs to implement adaptation strategies through legal frameworks and allocation of economic resources (Adger, 2001; Adger *et al*, 2007). National governments play a key role in adaptation planning since they allocate resources to local institutions (according to priorities), establish regulations, and create the institutional structures and policies for the local governments. Through the application of these measures, they might reduce the risk and increase the adaptive capacity of vulnerable regions (Agrawal, 2010). This study incorporates the feedback of local institutions such as local government, state government, NGOs and industry organisations.

The implementation of successful adaptation measures requires the commitment and collaboration of the private sector (Agrawal, 2010; Agrawala, *et al* 2011). However, the actions taken by this sector have been slow to materialize and their sharing of knowledge and experiences has been limited to date (Agrawala *et al*, 2011).

After a reluctant beginning in recognizing climate impacts and a low concern for future impacts of climate change that were documented by Loechel *et al* (2013b), today, the uranium mining industry in Australia has reported they have begun to implement adaptation measures (Pizarro *et al*, 2017). In addition, national, state and local governments have attempted to fill the gap of knowledge of the communities through the implementation of information and action plans to face climate change such as AECOM (2010), Climate Change Action Plan by Darwin City of Council (2011), Kakadu: Vulnerability to Climate Impacts developed by BMT WBM (2010) for the Australian Government or AdaptWest (2015).

8.2.3 Adaptive capacity

Climate change literature places capacity at the opposite spectrum of vulnerability since adaptive capacity is seen as a way to reduce the vulnerability to a specific hazard (Smit and Wandel, 2006). Thus, high vulnerability can be linked to low adaptive capacity (Adger *et al*, 2004; Downing and Patwardhan, 2004; Smit and Wandel, 2006). However, these two terms are not necessarily opposite since some communities with high vulnerability might have a high adaptive capacity as Gaillard (2010) has suggested. Several types of adaptation capacity have been identified below.

8.2.3.1 Capacity to anticipate the risk

This capacity to anticipate risk is not related to the projection of climate risks using climate models. Rather, it refers to the capacity of a human system (e.g. a mine) to be aware of and plan for the damages that can be caused by a climate risk. It also includes the consideration of previous climate-related impacts to the system to reduce the risk and impacts of future events (Lavell *et al*, 2012).

It includes the ability to operate a series of factors that include measures, tools, guides and procedures to reduce or control future risks (Cardona *et al*, 2003). Further, there are different stakeholders, interests, and legislation that can influence the capacity of risk prevention. Actions to reduce exposure and vulnerability focused on one group of stakeholders of a system (project) can increase these two elements in another group of stakeholders (Birkmann, 2011).

As was shown in the previous chapter, the stakeholders of a project (or a community) are linked. Consequently, it is not enough to consider the interests of just one group of stakeholders to evaluate adaptation strategies (Adger *et al*, 2004). All must be considered.

8.2.3.2 Capacity to respond

This capacity outlines the ability of institutions/organisations to react or respond after a natural hazard occurs (Lavell *et al*, 2012). This capacity requires previous (ex-ante) preparation, planning and investment (Lavell *et al*, 2012).

Wisner (2001) has suggested that the capacity to respond is not enough to reduce the risk, sometimes measures of response can turn into a permanent solution. This is reactive. The capacity to respond must be aligned with risk reduction strategies to obtain an effective management not just focus on emergency response measures (Chatterjee, 2010).

8.2.3.3 Capacity for recovery

Capacity to recover refers to the capacity or ability to rebuild after a natural disaster event such as floods or cyclones. It depends on the degree of the impact and the community capacity to rebuild (e.g. livelihoods) (Cardona *et al*, 2014). In the case of mining this capacity can be associated with the capacity to implement measures according to the events. For example, Ranger Mine faced different flooding in its TSFs, its capacity to recover relies on the capacity to lift the walls of the TSFs three times (ERA, 2012).

8.2.3.4 Determinants of adaptive capacity

According to the literature there are six determinants of adaptive capacity for communities and human systems. These are: economic resources, technology, information, skills, infrastructure, and institutions (Smit and Pilifosova, 2003ab). They are summarised below.

- **Economic Resources**: Take the form of economic assets, capital resources or financial means (Smit and Pilifosova, 2003b). Economic resources allow or facilitate the adaptation to climate change. The amount required in mitigation or adaptation strategies can be a significative investment (World Bank, 2010). Recently, mining companies such as Rio Tinto and BHP Billiton have shown greater commitment to invest economic resources in adaptation to climate change (Rio Tinto, 2014ab; BHP Billiton, 2015). Economic conditions are a determinant of adaptive capacity.
- **Technology:** society can take advantage of technology to facilitate greater adaptation to climate change, e.g. weather forecast or energy efficiency (UNFCC, 2006; UNFCC, 2009). The contribution will depend on the availability and access to new technologies (UNFCC, 2006). In fact, many of adaptation strategies such as more effective warning systems, better

infrastructure or flood measures are based on advances in technology (Smit and Pilifosova, 2003b). In mining, new technologies are related to sustainable extraction of resources, infrastructure, reduction of energy use, water efficiency, and adaptation to climate change (Rio Tinto, 2014b; Hodgkinson *et al*, 2014; ERA, 2016).

- **Information and skills**: poor knowledge and skills in climate change science can be related to a limited adaptive capacity (AECOM, 2010a; Casey *et al*, 2015). In mining, there is a need to improve the knowledge and skills to facilitate adaptation strategies to climate change (Loechel *et al*, 2013ab; Hodgkinson *et al*, 2014).
- **Infrastructure**: most of the current infrastructure is designed for the historical climate conditions, with limited understanding of its capacity to cope with future climate conditions. (AECOM, 2010b). In fact, about 40% of the economic impacts of climate change relate to infrastructure (AECOM, 2010b). In 2008 the Australian Academy of Technological Sciences and Engineering (ATSE) stated *"(there) is a need to assess the impact of climate change on Australia's physical infrastructure on a regional basis using risk assessment methods to provide overview of the likelihood of consequence, risks, and adaptation capacity of the Australia's physical infrastructure*". Unfortunately, performing changes to design and construction standards, while reducing vulnerability, can cost up to 40% of the initial construction cost (Frangopol and Tsompanakis, 2014). Previously, both the mine's infrastructure as well as the associated infrastructure such as ports and power supply have been identified as impacted by climate conditions (Hodgkinson *et al*, 2014). Specifically, the Ranger uranium mine has reported several impacts to its infrastructure by climate events and has invested capital into modifying existing design. E.g. the raising the height of the tailings storage facilities on three occasions. (Pizarro *et al*, 2017).
- **Institutions:** the role of institutions (religious, educational, professional and social organisations) to climate change adaptation is crucial. They can enable or limit the adaptation process (O' Riordan and Jordan, 1999; Wales *et al*, 2012). The support of institutions is often cited as a barrier in the adaptation process (Smit and Pilifosova, 2003b).

8.2.3.5 Categories of adaptation options

The identification of risks and vulnerabilities provide the basis for identifying adaptation options. As the science of climate adaptation has evolved, various categories of adaption have been identified, including a wide range of actions through different sectors that include (after Nobel *et al*, 2014; Klein *et al* 2014):

- **Structural or physical:** in the mining context this option involves solutions of an engineering nature, built environment; and/or technology e.g. the commission of a brine concentrator (ERA, 2013) or increasing the height of the tailing dam to improve water management process (ERA, 2007a; ERA, 2008a; ERA, 2012).
- **Social:** consist of adaptation measures that focus on areas that include education, information (map of vulnerabilities, and warning systems), and behaviour (preparation of evacuation plans). In the mining context this might include developing a Risk Management Plan and/or government action plans (Darwin Council, 2011; RDA Far North SA 2016) to improve the knowledge and awareness of communities about climate change.
- **Institutional:** involve the fostering of adaptation measures through such things as economics (taxes, subsidies, and insurances), laws and regulations (building standards, water, and land regulations), and policies and programs (national and local adaption plans, landscape and water management, and others). As an example, the state government of South Australia has developed some institutional frameworks to guide the adaptation of communities, businesses, NGOs, research groups, local governments, and state agencies DEWNR (2016).

The next section details some factors that can limit the implementation of adaptation options.

8.2.3.6 Opportunities and constraints of adaptation options

Factors that facilitate adaptation planning and implementation of the adaptation options, are called "opportunities for adaptation". Factors that prevent the adaptation process are called "constraints" (Adger *et al*, 2009). These two factors are defined and described by Klein *et al* (2014) in detail. A summary is provided below.

Opportunities are factors that allow or facilitate the planning and implementation of the adaptation objectives or responses. An adaptation opportunity is different from an adaptation option in that the latter is specific to reach an adaptation objective. Opportunities to reach adaptation are:

- Increasing Awareness: this refers to positive engagement, effective communication of potential risks and stakeholder participation in the process.
- Increase in Capacity: this can be done by means of research, education, training, and development of social and human capital.
- Tools: the existence of vulnerability assessments, risk assessments, and economic approaches to support the decision making (cost and benefit, cost effectiveness, and multi-criteria analysis) can create an opportunity of adaptation.

- Policy: incorporating standards in design and planning of infrastructure.
- Learning: this refers to the incorporation of past experience to future planning, monitoring and evaluation.
- Innovation: this means to take advantage of the technological development, through the use of more efficient technology, infrastructure, and communications.

Constraints of adaptation are factors that prevent, stop or delay the implementation of adaptation options (Klein *et al*, 2014). At the present time, there is no general agreement on its definition or assessment (Smit *et al,* 2008).

Literature suggests, constraints to adaptation are a combination of factors such as social norms, laws, management procedures, prioritisation, way of thinking, and others (Smit *et al*, 2008; Adger *et al*, 2009; Moser and Ekstrom, 2010). The existence of several constraints can limit adaptation options, opportunities and consequently the adaptation process (Klein *et al*, 2014). Some constraints identified by the literature are knowledge, awareness, technology, physical, economic, and financial constraints (Adger *et al* 2007; Pearce *et al*, 2009; Dale *et al*, 2011; Milfont, 2012; Preston 2013b).

8.2.3.7 Adaptation deficit

Since several constraints can limit or delay adaptation options this can cause, to some degree, an adaptation deficit (Klein *et al*, 2014). A deficit in this case refers to the gap between the current state of the system and a state that would minimise adverse impacts from existing climate conditions and variability that would affect the adaptive capacity (Burton, 2004; Burton and May 2004; Parry *et al*, 2009). It is critical to minimise an adaption deficit with appropriate adaptation measures and risk management procedures (Hallegate, 2011ab). Reducing the adaptation deficit will lead to a reduction in climate-related damages and economic losses (Parry *et al,* 2009).

8.3 Adaptation in the Australian uranium mining industry

In the past years, the Australian mining industry was focused on the implementation of mitigation measures to reduce emissions rather than developing adaptation measures (Loechel *et al*, 2013b). For this reason, there are a limited number of mining researchers considering adaptation associated with climate change in Australia (Hodgkinson *et al*, 2010; Loechel *et al*, 2013ab; Hodgkinson *et al*, 2014, Mason and Giurco, 2013; Delphi Group 2014, Pizarro *et al*, 2017). Some of these pioneering studies (Loechel *et al*, 2013ab; Hodgkinson *et al*, 2014; Mason and Giurco, 2013) have focused on the

identification of adaptation measures proposed by stakeholders. To date, no studies that document the evaluation of proposed adaptation strategies for the mining industry have been published.

8.3.1 Identification of adaptation measures at the Ranger Mine (2006-2016).

The following section details the adaptation measures undertaken by Ranger Mine, identified through annual and sustainability reports over the 10-year period (2006-2016). These measures were undertaken to face the impact of cyclones and heavy rainfall/flooding. Further, the cost of these measures and the economic losses in this period are detailed below (Table 8.1). The measures can be considered reactive at the time they occurred.

Table 8.1: Reactive adaptation measures taken by Energy Resources of Australia (ERA)

Year	Measures taken
2006	• A new water treatment plant was commissioned that increased the capacity to manage excess rainfall • Planning to increase height of the tailing storage facility to improve the water management process and prevent spills (ERA, 2007a) Expansion of the irrigation capacity, and extended treatment of disposal and pond water (ERA, 2007a)
2007	• Strategies for water removal such as a new land area for irrigation were implemented (ERA, 2008a) • Increased water treatment plant capacity (ERA, 2008a) • Upgrade of the water circuit were implemented (ERA, 2008a) Increased size of the tailings storage facility and the catchment management plans were implemented (ERA, 2008a)
2008	• A new lift (2m height) of the walls of the tailings facility increased the storage capacity • Increase the pond water capacity by 100% A land form trial, and a tailing delivery system.
2009	• Research to increase the capacity to the water treatment process, this includes new evaporation ways (ERA, 2010) • Final lift of the tailings storage facility completed (ERA, 2009)
2010	• Modification of stockpile run-off and the seepage water flows (ERA, 2011) • Improvement of the water catchment around the site to limit rainfall accumulating in critical areas of the mine (ERA, 2011). • Trial of process water treatment project (ERA, 2011). • Initiation of the feasibility study for a brine concentrator (ERA, 2011)
2011	• Installation of an additional pond water treatment plant which doubled the previous capacity of 3.2 billion litres (ERA, 2012) • Raise the height of the tailings storage facility by 4 metres (ERA, 2012) • Review of the water surrounding the tailings storage facility jointly with the Gundjelhmi Aboriginal Corporation (ERA, 2012) • Completion of the brine concentrator feasibility study • Concept study commenced on additional tailings storage facility height increase (ERA, 2012) • Continuous monitoring of waterways in the surrounding areas, especially during the wet season, to protect the environment from the addition of process water (ERA, 2012) • Planning for the construction of a new retention pond of 16 hectare (ERA, 2012). • Development of weed management, controlled burning and revegetation plans (ERA, 2012)
2012	• Increased height (2.3 m) of the tailings storage facility (ERA, 2013) • Commenced the construction of retention pond 6, which provides additional storage and water management capacity (ERA, 2013). • Approval for the construction of a brine concentrator (ERA, 2012).
2013	• Construction of the brine concentrator completed (ERA 2014) • Completion of the contingency pumping system between the tailings storage facility and Pit 3 (ERA, 2014). • Construction completed of retention pond 6 • Completion of the installation of additional ground water monitoring holes (ERA, 2014). • Installation of vertical drains across Pit 1 (ERA, 2014) • Proposed construction of a new levee to avoid flooding in the pit (ERA, 2013).
2014	• A stainless-steel dredge was commissioned to transfer water from the TSF to Pit 3 (ERA, 2015) • Interception trenches around the stockpiles completed • Installation of more than 7,000 vertical drains in the tailings area of Pit 3
2015	• 1,000 metres of water intercept trenches (4 m depth) were installed between the tailings storage facility and Pit 3 (ERA, 2016) • The water monitoring network was improved with the installation of additional 21 wells (ERA, 2016)
2016	• The steel dredge and a pumping system transferred 3 million cubic metres of tailings from the tailings storage facility into Pit 3. New tailings are sent directly to Pit 3. This to prevent spills from the tailings storage facility in the wet season (ERA, 2017).

Costs associated with these adaptation measures (where documented) have been compiled in Table 8.2. Where costs have not been reported the activity alone has been listed.

Table 8.2: Cost of implementation adaptation measures at the Ranger Mine (2006-2016)

Year	Cost
2006	• Water treatment plant: $28 million (ERA, 2007a) • Cost of remove the water from the flooded pit • Cost of the waste removal from the pit walls
2007	• Water treatment plant and the process water circuit: $29 million (ERA, 2008a) • Tailings storage facility: $18 million (ERA, 2008a)
2008	• Pond water capacity: $16.5 million (ERA, 2009) • Tailings storage facility: $29 million (ERA, 2009) • Tailings delivery system: $17 million (ERA, 2009)
2010	• Stockpile run-off and seepage water flows: $9.4 million (ERA, 2011) • The trial of water treatment project: $ 5.8 million (ERA, 2012)
2011	• Tailings storage facility: $52 million (ERA, 2012) • Brine concentrator feasibility study: $80 million (ERA, 2012)
2012	• Brine concentrator construction: $220 million (ERA, 2013) • Tailings storage facility: $25 million (ERA, 2013)
2013	• Contingency pumping system (ERA, 2014) • Construction of additional retention pond 6 • Groundwater monitoring • Installation of vertical drains
2014	• Steel dredge • Interception trenches and vertical drains at Pit 3 and tailings storage facility
2015	• Installation 21 additional wells (ERA, 2015)

The total cost of the previous adaptation measures is A$ 529.7 million which brought to 2016 dollars (using the average annual inflation rate) are equivalent to A$594.8 million. This can be considered a lower estimate due to the unknown costs listed.

Additionally, a detailed list of the economic losses which includes loss of production, mineral purchases and capital expenditure in this period (2006-2016) are shown in Table 8.3, which add up to a total of A$934.5 million (not updated).

Table 8.3: Loss of production, minerals purchases, and increase of capital expenditure.

Year	Economic losses and increase of capital expenditure
2006	• Production decreased from 5910 tonnes in 2005 to 4748 tonnes in 2006 (ERA, 2007a), which is 20% less production than 2005 due to flooding (ERA,2007a). Estimated impact value of $64 million (calculation based on of the potential revenue at the average sale price in 2006 of $24.98 per pound) • The loan of 316 tonnes and repayment afterwards represented a net cost to the company of approximately $5.16 million (calculation based on spot price at the moment of purchase in December 2006 ($84.64 /lb) and subsequent return of the loaned uranium in January 2007 ($92.05/lb) (ERA, 2007). • Therefore, for this year alone there was a total economic loss of 69.16 million.
2007	• 300 tonnes of uranium oxide were lost when the processing plant was shut down (ERA, 2008a) at cost of $20 million (Calculation based on sale price of $30.88 /lb of 2007). • Increased operational costs associated with removing the excess of water from the pit (ERA, 2008a).
2008	• Capital expenditure increased to $166.8 million (2006: 92.9 million), that included the cost of a new water treatment facility (ERA, 2009). • Insurers provided a settlement of $188 million to cover economic losses from 2006 and 2007 (ERA,2009)
2010	• Production decreased from 5,240 tonnes in 2009 to 3,793 tonnes in 2010 because of the extended wet season and the suspension of the processing operations (ERA, 2011). Net profit decreased to $47 million which is 83% less compared with 2009 (ERA, 2011). • Capital expenditure rose to $45 million (2009: $37 million) • ERA had to purchase 925 tonnes of uranium oxide which cost $100.5 million (Calculation based on average spot price during 2010 of US$ 45.96 /lb (ERA, 2011)
2011	• Production decreased from 3,793 tonnes in 2010 to 2,641 tonnes in 2011, representing lost revenues of $144.8 million (Calculation based on the average sale price during 2011). • ERA purchased 2,126 tonnes of uranium oxide in the market to fulfil sales commitments, this purchase cost $253.2 million (Calculation based on the average spot uranium price of US$56.24 during 2011). • Capital expenditure rose by 97 million (2010: 45 million) (ERA, 2012)
2012	• Economic losses of $219 million after tax. The losses in part were derived from the inability to access to the high ore grade in 2011 and early 2012 because of heavy rainfall (ERA, 2013). • Total costs in 2012 increased because of the purchase of 501 tonnes of uranium oxide on the market, because of the wet season in 2011 (ERA, 2013). This purchased cost $55.6 million. • Capital expenditure rose by $161 million (2011: $97 million), the majority of this increase included the costs of increasing the height of the storage facility and the installation of the brine concentrator.
2013	• Capital expenditure ($91 million) was primarily associated with the installation of the brine concentrator (ERA, 2014)
2014	• Capital expenditure was $12 million in 2014; this was associated with the commissioning of the brine concentrator (ERA, 2015).

8.3.2 Adaptation needs identified across the supply chains

The existing adaptation capacity across each of the mines supply chains was assessed by rating their current Risk Management Plan (RMP). Each of the chains was rated through the survey by their (a) approach to deal with climate risks, (b) effectiveness of the current RMP to deal with climate change, and (c) changes proposed to improve the adaptive capacity. Through the results of the survey, the

adaptation needs were identified and have been ranked by the respondent results (in ascending order). Options with a rank below the average were deemed existing adaptation needs.

The adaptive capacity was analysed based on need and adaptation options were proposed for each group in each supply chain.

8.3.2.1 Ranger Mine

Table 8.4, Table 8.5 and Table 8.6 show the needs, adaptive capacity, and adaptation options for the supply chain of the Ranger Mine.

Table 8.4: Adaptation needs, adaptive capacity and adaptation options at Mining group of Ranger Mine supply chain.

	Mining Group-Proactive approach (100%)
A	**Adaptation need:** Improve the effective communication between related companies/organisations (e.g. water, energy, telecommunication, transport or others) **Adaptive capacity: (Information and skills)** Communication between stakeholders plays a strategic role in maintaining a license to operate and in future sustainable development (ICMM, 2013). The company has undertaken successfully communication and engagement activities through meetings, committees and community consultation in the past (ERA, 2013). Technology: ERA have used the company website, quarterly business updates, regular briefings, and bulletins to communicate expansion plans (ERA, 2013). The mine has identified all (or at least most) stakeholders (ERA, 2013) in the past indicating that the capacity to improve effective communication exists. **Adaptation option: (Social-behavioural) A1)** Re-direct resources toward communication of climate change adaptation planning. **A2)** Identification of communication failures with stakeholders by an external adviser.
B	**Adaptation need:** Improve the identification of climate risks in the current Risk Management Plan (RMP) **Adaptive capacity: (Information and skills)** ERA has hazard and risk management procedures according to AS/NZS ISO 31000:2009. They also must comply with Rio Tinto Critical Risk Management procedures (Rio Tinto, 2014a) where climate Risks are categorised as critical (Rio Tinto, 2016). ERA must also maintain a register of environmental risks (ERA, 2013). Historically, the Ranger Mine has been affected by cyclones, intense rainfall and flooding (ERA, 2007a, ERA 2011) and they presented a reactive approach to responding to events. Even though the mine is clearly aware of the climate risks they are exposed to, only 50% of survey respondents reported having vulnerability assessment or risk reduction plan. Infrastructure: ERA has upgraded its infrastructure to face climate impacts (See Table 6.1). This suggests the capacity to improve the identification of climate risks in the RMP exits. **Adaptation option: (Social-educational and informational) B1)** Develop a vulnerability assessment and risk reduction plan to climate change at the mine site. This would provide a rigorous identification of climate risks and their incorporation into the RMP including identification of adaptation measures. **B2**) Use local climate projections (and historical records) of climate extremes and develop specific mine site projections.

C **Adaptation need:** Improve the communication of the RMP to staff

Adaptive capacity: (Technology) It is not clear why only 50% of the survey respondents are aware of the RMP since ERA have best-practise technology and resources (intranet, internet, advance mobile networks, internal staff newsletter, and others). It is assumed that there may be a lack of interest in understanding the scope of the RMP.

Adaptation option: (Social-informational and behavioural) C1) Evaluate the failures of internal communication though an external consulting firm**. (Organisational) C2)** Employees can overcome internal failures of communication using existing resources such as regular meetings and committees, email groups, posters, brochures or another publication to inform the guidelines and procedures of the RMP to all staff **C3)** Promote internal communication activities such as staff engagement, training, communication inductions for inexperienced staff and support groups to promote the understanding of RMP and the climate change issue.

Table 8.5: Adaptation needs, adaptive capacity and adaptation options at Downstream group of Ranger Mine supply chain

Downstream group-Mainly proactive approach (66%)

A **Adaptation need:** Improve the effective communication between companies/organisations related (e.g. water, energy, telecommunication, transport or others)

Adaptive capacity: (Information and skills) Mining contractors and consultants are aware that communication is a key element of sustainability and success (ICMM, 2013). However, issues in communication between parties have been reported by contractors. Reports of poor communication include - communications are not clear or not well defined, and that are without decision making abilities in all levels (MCA and ACA, 2003). (**Technology):** The most effective communication tool at the present time is email, it can be assumed that all companies have access to this resources in some capacity (computer, phone)**.**

Adaptation option: (Organisational) A1) Changes in the internal management approach or leadership, to improve the communication to third parties. **(Social-informational and behavioural) A2)** Assessment of communication failures by their own personnel. Some internal measures can be implemented such as; improve the frequency of communication, by email (e.g. once a week or fortnight) or meetings with the Mining group. This would allow the efficient updating of risks as they occur. Further, it will improve the trust and commitment between supply chain members (Kwon and Suh, 2004). **A3)** Evaluate the communication failures and implement measures for effective communication suggested by an external consulting company.

B **Adaptation need**: Improve the clarity of the procedures and guidelines to follow in the case of a climate event

Adaptive capacity: (Information and skills) According to Rio Tinto (2014a), all its staff, contractors, and consultants must follow the same procedures and guidelines of risk management that they have established. However, some issues with contractors have been identified that include a lack of a clear understanding of the risk (MCA, and ACA, 2003). **Technology:** the internet can facilitate the improvement of this adaptation need; however, this research has found that there are local contractors located in remote areas who use just phone lines (e.g. Limited access to internet data).

Adaptation option: (Social-Informational and behavioural) B**1)** Improving the clarity and understanding of RMP guidelines and procedures can be achieved through the integration of climate risk procedures into the regular meetings at all levels

(Social-Educational) B2) Appointment at each hierarchy level a representative who can clearly understand and communicate the RMP guidelines and procedures to staff. **(Organisational) B3)** Including adaptation/response management to climate risks KPIs for each contractor / consultant engagement. If climate risks are included in the company KPIs, it is suggested that monitoring of the fulfilment of risk management procedures be undertaken.

C **Adaptation need:** Improve the clarity of the roles, positions and responsibilities of the personnel in the event of a climate episode

Adaptive Capacity: (Information and skills) Every contractor must have a risk management plan and procedures (WorkSafe, 2015). This plan should specify the roles / responsibilities in the case of climate risks. It is not clear if climate risks are within the contractors' RMPs.

Adaptation option: (Organisational) C1) Performing test-drills of climate events, with the aim to assess the RMP and test roles and responsibilities. (**Technological) C2)** existing communication resources can be used to identify responsibilities in each role.

D **Adaptation need:** A specific/relevant RMP for the site of operation

Adaptive capacity: (Information and skills) All companies must have an RMP. This includes hazard identification, risk assessment, risk control, and frequency of assessment. However, in this study and MCA and ACA (2003), contractors/consultants reported their RMPs may be inappropriate.

Adaptation option: (Organisational) D1) Risks can vary across the life of a mine. Thus, RMPs should be constantly updated. This can be achieved by a supportive management/leadership approach to minimise risks (including climate-risks). (**Social- Technological-Educational) D2)** Members of this group can use resources publicly available on the internet (e.g. guidelines) to prepare a specific RMP.

E **Adaptation need:** A better identification of the climate risks in the RMP

Adaptive Capacity: (Information, skills, and technology) There is free information about climate projections on websites such as Climate Change in Australia and the Bureau of Meteorology. These websites have information that is easy to read and interpret and includes detailed information for researchers. A shared knowledge of these risks between all parties would facilitate the need of this group.

Adaptation option: (Social-Informational and educational) E1) A better specification (frequency, intensity, and magnitude) of climate risks in the area can be achieved by conducting a review of literature **(Organisational) E2)** Change from a passive to an active strategy to climate change adaptation. This includes the search of shared- knowledge with the Mining company (coordinator of the supply chain) to facilitate the identification of climate risks.

Table 8.6: Adaptation needs, adaptive capacity and options for adaption at External group of Ranger Mine supply chain

	External group-Mainly proactive approach (83.33%)
A	**Adaptation need:** Improve the identification of climate risk in the current RMP **Adaptive capacity: (Information and skills)** Climate impacts have been related to risk management by the Australian Government (2009). Businesses and organisations have been advised to assess climate risks and impacts according to risk management principles. Further, climate risks are included in the management action plan of the Darwin Council (2011) and West Arnhem Regional Council (2017). In these documents climate risks are adequately identified. Climate Change of Australia and the Bureau of Meteorology (BOM) both maintain updated records of climate conditions and extremes. **Adaptation option: (Social-Informational and educational)** A**1)** Improve the climate risks specification (frequency, intensity, and magnitude) by their own personnel. **A2)** Conduct a vulnerability assessment of climate risks through an external consultant that would allow the incorporation of climate risks. **(Organisational) A3)** Change from a passive to a formal active strategy to climate change adaptation. This includes the search of shared- knowledge with the Mining company (coordinator of the supply chain) or other members of the supply chain to identify climate risks together.
B	**Adaptation need** Improve the adequacy of the procedures and response contingency plans **Adaptive Capacity: (Information and skills)** Public organisations have an RMP in the case of an emergency. It is assumed they are based on the previous experience with similar risks e.g. AECOM (2010a); Darwin Council (2011). **Adaptation option: (Social-educational and informational) B1)** Reviewing the emergency procedures and contingency plans for all kind of risks (including climate risks) to identify the current inadequacies. Some external advice may be required.
C	**Adaptation need:** Improve the communication of the RMP to staff. **Adaptive capacity: (Technology, information, and skills)** There are different communication resources used by organisations such as social networks, bulletins, emails, brochures, official reports, informal and formal meetings. Communication within the council and with the community has been classified as poor, representing a risk by itself for the council's operations (WARC, 2016). **Adaptation option: (Structural -technology) C1)** Evaluate the communication failures by personnel (some external advice might be required). Use existing communication resources to outline the procedures of the RMP to staff. Ideally, incorporate RMP (including climate risks) into organisational meetings. **(Social-Informational and educational) C2)** Improve the understanding of risk management principles by staff, which has been found to be at-best average (WARC, 2016).
D	**Adaptation need:** Improve the regular update of the RMP **Adaptive capacity: (Information and skills)** The RMP should include identified risks, the level of risk, and strategies implemented to manage those risks. However, due to the environment and climate changing, the current RMP might only be appropriate for climate variability but not for climate change (AG, 2006). A regular update of the RMP should include climate risks. **Technology:** Members of this group can access internet, emails, intranet, and other resources to facilitate the regular update of the RMP. **Adaptation option: (Social-Informational and educational) D1)** Test, evaluate and update (e.g. more frequent test-drills) of the current risk management plan**. (Organisational) D2)** Facilitate and support the preparation of monitoring plans and reports**. (Technological) D3)** resources such as software, generic Risk

Management Plans provided by the Australian Government (2015), and templates or guidance provided by local governments (WorkSafe, 2015) can facilitate updating the plan.

8.3.2.2 Olympic Dam

The same analysis for identification of adaptation needs, adaptive capacity, and adaptation options was employed for the supply chain of Olympic Dam mine. These results are shown in Tables 8.7 to 8.9.

Table 8.7: Adaptation needs, adaptive capacity and options for adaptation at Mining group of Olympic Dam mine supply chain

	Mining group-Mainly proactive approach (75%)
A	**Adaptation need:** Improve the effective communication between related companies/organisations (e.g. water, energy, telecommunication, transport or others) **Adaptation capacity: (Institutional-organisational and economic resources)** BHP Billiton promotes effective, open, transparent communication and consultation with its stakeholders (BHP Billiton, 2009). Personnel, external contractors, government representatives, and communities are encouraged to participate in an open and proactive communication to create a sustainable development based on the Health, Safety, Environment and Community (HSEC) principles (BHP Billiton, 2009; BHP Billiton, 2017a). **Technology**: Two-way communication with stakeholders is completed via email, newsletters, and meetings - stakeholders are invited complete a survey by providing their feedback and comments. Further, internal videos and announcements are available in Spanish and English (BHP Billiton, 2017a). **Adaptation option:** Despite the approach described by the company, this adaptation need may have arisen since nowadays is not enough to just transfer information to stakeholders (Skoldeberg *et al*, 2013). They have a wider range of expectations owing to them based on their access to social media (Skoldeberg *et al*, 2013). **(Institutional-Organisational) A1)** Review and assessment of the current communication and engagement program employed to identify the opportunities for improvement. Regarding the internal communication - some external advice may be required **A2)** Improve the consultation techniques - some external advice may be required. **(Social-educational, informational and behavioural) A3)** identify KPIs to improve effective communication. Identify what kind of information is expected from stakeholders; promote the engagement and commitment of corporate goals with staff and stakeholders.
B	**Adaptation need:** Improve the regular update of the RMP **Adaptation capacity:** The company states it has a high standard of risk management and is continually searching for improvements with the goal of "zero" harm. **Economic resources, information, and skills**: the company has invested in numerous programs to achieve its "zero harm" goal e.g. The Field Leadership Program (BHP Billiton, 2017a). **Adaptation option:** Despite the approach of BHP Billiton, the survey respondents rated the RMP capacity to adapt worse in the future (current: 7.78 vs future: 7.00). This clearly demonstrates a need to increase the frequency of RMP updates. (**Organisation) B1)** Re-organisation of the current resources is required (technological resources, existing skills and expertise, communication tools, and corporate approach) to reach the zero-harm approach – all risks considered. External advice might be required.
C	**Adaptation need** Improve the communication of the RMP to staff

Adaptation capacity: BHP Billiton promotes effective, open, transparent communication and consultation with its staff (BHP Billiton, 2009). **Technology**: Two-way communication is completed via email, newsletters, and meetings - staff are invited complete a survey by providing their feedback and comments. Further, internal videos and announcements are available in Spanish and English (BHP Billiton, 2017a).

Adaptation option: (Social-educational, informational and behavioural) C1) Identify the failures of internal communication by an external consultant **C2)** Identify incentives to improve the understanding of the RMP and its impact on staff safety.

D **Adaptation need** Better identification of the climate risks in the RMP

Adaptive capacity: Economic resources, technology, information and skills: The procedure for the identification of climate risks and opportunities is unknown. The company states they have a risk- based approach to identify the vulnerabilities in their assets (BHP Billiton, 2017a). However, according to survey results only 50% of respondents of this group reported to have a vulnerability assessment and risk reduction plan that they were aware of.

Adaptation option: (Structural or Physical -technological, Social-informational) D1) Develop a site-specific projection of climate and extremes for the mine-site **(Economic resources) D2)** Invest in the improvement of the vulnerability assessment to acquire a better identification of climate risks and their impacts on the operations.

Table 8.8: Adaptation needs, adaptive capacity and options for adaption at Downstream group of Olympic Dam mine supply chain

	Downstream group-Proactive and Reactive (both 50%)
A	**Adaptation need**: A better identification of the climate risks in the RMP **Adaptive capacity: (Information and skills)** Contractors and consultant companies in this group have identified different risks in their operations that include; chemicals, dangerous goods, transportation, environment and others. Based on these results it was not possible to determine if there is a clear identification of climate risks and management in this group. Respondents from this group also reported high percentages (87.5%) of "no" responses when they were asked about the existence of a vulnerability assessment or risk reduction plan to climate risks. **Adaptation option: (Social- educational and informational) A1)** Perform a vulnerability assessment and a risk reduction plan by qualified personnel **A2)** Obtain additional information about climate risks from other members of the chain e.g. Mining group **(Organisational-economic resources) A3)** Additional funding might be needed to contract an external company to develop this assessment. A vulnerability assessment should provide the input and opinion of local stakeholders.
B	**Adaptation need** A specific/relevant RMP appropriate for the site **Adaptive capacity: (Institutional)** All mining contractors and consultants in South Australia must comply with the preparation of a risk management plan (DSD, 2016). This plan should have generic elements such as risk identification, consequences, and control measures (SafeWork, 2014). SafeWork (2014) has classified the general risks of an operation; however, a specific RMP for each operational site should be developed by each contractor or consultant. **Adaptation option: (Social-educational and informational) B1)** Develop a specific site RMP which involves a vulnerability assessment for all risks including climate risks. This task can be undertaken by existing personnel with external advice. **(Organisation- economic resources) B2)** Request a vulnerability assessment by an external consulting company.
C	**Adaptation need:** Improve the regular update of the RMP **Adaptive capacity: (Information and skills)** Their current RMP has valuable information (and it is the basis of any update) about the past risks in all areas of operations (if it is specific to the company and not generic)**. Technology:** Existing and future technology can facilitate the update and distribution of the RMP. **Adaptation option: (Social-Informational and skills) C1)** Regular update of the RMP according to the changing risks and conditions of the operations. Regular communication/feedback with the stakeholders can facilitate the update**.** External advice is required. **C2)** Increasing the frequency of updates by improving the knowledge of the staff who contribute to the risk management at the site. **(Technological) C3)** Technological resources e.g. risk management software can be used to facilitate the update.
D	**Adaptation need** Improve effective communication between related companies/organisations (e.g. water, energy, telecommunication, transport or others) **Adaptive capacity: (Organisational)** The co-ordinator member (Mining company) of this group promotes open and two-way communication between members. They are engaged through emails, bulletins and formal and informal meetings (BHP Billiton, 2017a). All members have the opportunity to provide feedback by filling out a survey.

	Adaptation option: (Social-informational and behavioural) D1) Identify communication failures through external advice. **D2)** Improve third-party communications. External advice may be required.

Table 8.9: Adaptation needs, adaptive capacity and options for adaption at External group of Olympic Dam mine supply chain.

	External group-Mainly reactive approach (60%)
A	**Adaptation need**: Improve effective communication between related companies/organisations (e.g. water, energy, telecommunication, transport or others) **Adaptive capacity: (Institutional-organisational)** the coordinator member of this chain promotes the communication with the community by engagement in activities that include newsletters, reports, consultation surveys, workshop groups and social networks (BHP Billiton, 2017a). They also have implemented a complaint (and consultation) mechanism by website, emails, in person and by post. Local newspapers, council activities and displays in the council office, website, emails and meetings are used to improve communication. It is considered that these resources might facilitate the communication with the coordinator member of this chain but not between third parties. **Adaptation option: (Institutional-programs) A1)** The same communication resources mentioned could be implemented to identify communication failures between companies, organisations and/or the community. **A2)** Assessment of communication failures and implementation of better communication plan by an external consultant may be required. **A3)** Since the supply chain should work as one integrated system to maximize efficiency (Bessant *et al*, 2003; Walker *et al*, 2007), it should include the support from the coordinator company and government organisations to support and promote the effective communication of all supply chain members.
B	**Adaptation need** Improve the timeframe of the regular update of the RMP **Adaptive capacity: (Information and skills)** Some members of this group reported their RMP and the action plans are reviewed annually (Roxby Downs Council, 2015), while others reported that their RMPs should be tested, reviewed and updated as required (DEWNR, 2016). **Adaptation option: (Technological) B1)** Current technology can be used to update existing RMPs as needed. External advising may be needed. **(Social-informational) B2)** Searching share-knowledge with other members of this chain to facilitate a consistent regular update between all. This might include the new parameters expected for climate events in the future.

8.3.3 Assessment of adaptation options

In this section an explanation of the techniques available in the literature for assessment of adaptation options, the criteria of assessment, and weighting logic applied in this study are provided.

8.3.3.1 Techniques of assessment

Adaptation options are considered an investment by companies / organisations. This investment can provide both benefits and costs since they can be quantified and monetized. Thus, economics techniques can be used to evaluate and prioritise them. Existing methods include: The Cost and Benefit analysis (CBA), Cost Effectiveness analysis (CEA), and Multi-criteria analysis (MCA) (Noleppa, 2013, UNFCC, 2002). There are other techniques of economic modelling that utilise Partial Equilibrium (PE) and General Equilibrium (GE) models to analyse costs and benefits from the economic point of view (Noleppa, 2013) – however, they are significantly more complex.

The selection criterion of an appropriate technique should be based on the data obtained (Noleppa, 2013). If it is possible to quantify and monetarise all costs and benefits of an adaptation option a CBA can be conducted. On the other hand, if it is possible only to quantify costs, a CEA must be employed. If it is not possible to quantify the costs or benefits, then an MCA must be used. According to the data obtained from the survey, a Multi Criteria analysis was used for this study. The details of the analysis are described below.

8.3.3.2 Multi Criteria Analysis

Multi-Criteria Analysis is useful when there is more than one adaptation option to prioritise and a decision between the options according to different criteria is required (Dixit, and McGray, 2013). It is a simple technique that combines qualitative and quantitative data. The weighting and scoring are however subjective. This makes this method weak and lacking in transparency. However, it is the only method that can be used when cost and benefits cannot be quantified, and the prioritisation of adaptation options is required (Dixit and McGray, 2013; Noleppa, 2013). There are different methods which differ in complexity. In this study, a method of medium complexity was used and is considered adequate.

Based on the qualitative data obtained from the survey, quantitative data for prioritisation was added. For this purpose, the criteria for assessing the adaptation options were weighted and scored in each scenario.

The general steps to carry out a MCA are:

- Identification of assessment criteria
- Identification of performance of the adaptation options
- Assignation of weights
- Conduct a sensitivity analysis (to consider uncertainties)

In the following sections the five criteria employed in this study are detailed, the weighting is assigned as well as the scoring of performance to prioritise the adaptation options across both uranium supply chains in Australia.

8.3.3.3 Criteria of assessment

To evaluate if the adaptation options are good enough to meet the adaptation needs, they must be assessed based on independent and clear criteria. Variation between criteria is important in the successful performing of an MCA, otherwise, it is not useful. Literature (Smit and Pilifosova, 2003b; Preston *et al*, 2013; AECOM, 2010a; Dixit and McGray, 2013) provide the basis for selecting evaluation criteria.

Cost-Efficiency: Costs have been the centre of the debate in adaptation to climate change. Owing to the importance, their estimation must be as accurate as possible (Parry *et al*, 2009). Adaptation options and their associated costs are considered an investment. The Australian mining industry has identified upfront costs as barriers to adaptation to climate change and (Loechel *et al*, 2013b).

Efficiency, as a measure of how resources (e.g. time, economic resources, or knowledge) are converted into results (Capriolo *et al,* 2015). The efficient use of resources can be seen as the basis for sustainable development (Hotta, 2011). In this framework, the adaptation options should be as efficient as possible (Smit and Pilifosova, 2003b).

Effectiveness: It is the extent to which the adaptation need has been met. This can vary in different areas of climate change e.g. reducing exposure or increasing adaptive capacity (Capriolo *et al*, 2015). A need to develop tools or techniques to assess the effectiveness (or performance) of adaptation options is required at the present time (Mullan *et al* ,2015).

Speed of implementation: There is limited published literature associated with the speed of implementation (and its importance) for adaptation option/s. It has been found that some factors such as cultural, social, political, and environmental may delay implementation. Thus, it is very important to

obtain the acceptance of stakeholders early on to ensure time impacts are minimised (Mimura *et al*, 2014; Capriolo *et al*, 2015).

Historically there has been a rapid development of adaptation strategies/options/plans; however, their implementation phases are still in early stages of development (Mullan *et al*, 2015). These time delays between planning and implementation have previously been considered:

1. "*The first major challenge is to bridge the gap between the needs of decision makers and the available evidence and tools* "(Mullan et al, 2015). Despite the improvement of climate change science, sometimes the results in this area (e.g. climate projections) are difficult to understand or interpret by the intended end users and decision makers.
2. How will adaptation strategies be funded? (Mullan *et al*, 2015). The majority of literature does not mention finance. E.g. total cost and financing options. There is a need to improve the knowledge about costs and benefits of adaptation (Mullan *et al*, 2015).
3. A lack of appropriate assessment tools to determine if adaptation strategies are effective at reducing vulnerability. Developing a better monitoring and evaluation framework for adaptation strategies is key to assure future political support and funding (Mullan *et al*, 2015).

Human capital: This criterion refers to the level of education, information and training that people have to address climate adaptation options (Noble *et al*, 2014). Authors such as Sovacool *et al* (2012) or Chinowsky *et al* (2011) have found a positive relationship between the level of education and the successful selection of adaptation options. A low level of education can act as a barrier to climate adaptation (Noble *et al*, 2014; Loechel *et al*, 2013ab). Increasing education, training, and access to information about climate change to support adaptation is a key factor in a successfully implemented program (Noble *et al*, 2014). In the Australian mining industry, the lack of knowledge and/or training of climate change has been reported as a barrier to adopt adaptation strategies (Loechel *et al,* 2013ab, Mason and Giurco, 2013, Mason *et al*, 2013; Pizarro *et al*, 2017).

Benefits of adaptation: The investment in adaptation measures to face climate change in the mining industry can create internal and external benefits for stakeholders (BSR, 2011). For example, mining companies who have worked traditionally in a single mineral have been diversifying their production to other minerals. This reduces their dependency on a single commodity / location in response to climate risks (BSR, 2011). Another example is the desalinisation plant proposed by BHP Billiton (2009b) to reduce its dependence of fresh water to operate. The plant can also provide an alternate source of water for the Upper Spencer Gulf and Eyre Peninsula regions (BHP Billiton, 2009b).

Each of the criteria described above, can be assessed in Table 8.10 below.

Table 8.10: Assessment criteria for adaptation options

Assessment Criteria	
Cost-Efficiency	Does this adaptation option need additional investment? Is this investment proportional to the outcome?
Effectiveness	Does this adaptation option meet the adaptation need?
Speed of Implementation	What is the timeframe to implement this adaptation option?
Human capital	Does this adaptation option require external advice?
Benefits	Does this adaptation option have benefits?

8.3.3.4 Performance of the adaptation options (scoring)

Identifying the performance of adaptation options for each of the criteria outlined in Table 6.9 is a key part of performing an MCA (Dixit, and McGray, 2013). When the outcomes of selected adaptation options have previously been determined, or if there is enough information available to understand the outcomes, then assigning scores becomes less difficult. It is important to note that each criterion must have a clear and objective methodology applied to assess their performance. This can include data from the literature, expert's feedback, surveys and workshops with stakeholders, or even specific studies to determine performance (Dixit, and McGray, 2013).

If the adaptation options identified are new and have not applied before, and if their performance is intangible and there is no information available to prepare an objective scoring, then assigning a numerical score to rate performance may become difficult. In this case, the score become a subjective "guess" influenced by the preference of the person who is performing the analysis (Dixit, and McGray, 2013). In these cases, it is better to employ qualitative descriptions instead of numerical scoring as Dixit and McGray, (2013) suggest.

During the course of this research it was not possible to identify an adaptation options assessment that had been completed in mining in Australia or overseas. Furthermore, the information available to

develop an objective score was limited. As a result of this, a study undertaken by AECOM (2010a) was used as a baseline reference to score the adaptation options identified in this study.

Three levels of scores were defined for the analysis – presented in Table 8.11. If the adaptation option satisfied one of the categories (high, medium or low), scores of 3, 2 and 1 were assigned respectively.

Table 8.11: Criteria and scoring employed in this study.

	High	**Medium**	**Low**
Cost-efficiency	No additional investment is required-low cost	Some additional investment is required-medium cost	External funding is required e.g. loans
Human capital	There is no need of additional personnel	Some external advice or personnel is required	External company is necessary
Speed of implementation	1 year or less.	More than 1 year but less than 3 years	More than 3 years
Effectiveness	High potential to meet the adaptation need	Moderate potential to meet the adaptation need	Low potential to meet the adaptation need
Benefits	There are internal and external benefits for adaptation.	There are internal benefits for adaptation	Benefits are not clear

High=3 points, Medium=2 points, and Low=1 point.

8.3.3.5 Assignment of weights

The assignment of weights to each criterion must reflect their ultimate importance (Dixit, and McGray, 2013). There are different techniques of assigning the weighting that include expert or stakeholders' evaluation, interviews, and surveys. Each of these techniques can be time consuming and evidence is needed to support the weighting decision (Dixit, and McGray, 2013). When stakeholders are participating in this process, their weighting will reflect their own personal views. In the absence of objective stakeholders' judgment, weighting can be determined using published literature. In this case, the use of the same weight for all criteria is generally acceptable, so they will have the equal value in the decision-making process (Dixit, and McGray, 2013).

For this assessment, published literature regarding mining climate-adaptation (when available and related to a criterion) or general literature in climate adaptation was used to support the weights assigned to each criterion. They are shown in Table 8.12.

Table 8.12: Weights assigned to each criterion

	Literature related	Importance to climate adaptation	Weights
Cost-efficiency	Parry *et al* (2009); Nollepa (2013); World Bank (2010), Mason and Giurco (2013); Loechel *et al* (2013ab); Capriolo *et al* (2015); Hotta (2011); Smit and Pilifosova (2003b); AECOM (2010a); Pearce *et al*, (2010); Ford *et al* (2009); Acclimatise (2010); Pearce *et al* (2009); Mason *et al* (2013); BHP Billiton (2015)	This literature has revealed the high importance of cost and efficiency in climate adaptation. Often costs are associated with uncertainties. Further, as adaptation options can be seen as an investment, costs become an important barrier to adaptation.	0.4
Human capital	Pearce *et al* (2009); Ford *et al* (2009); AECOM (2010a); Sovacool *et al* (2012); Chinowsky *et al* (2011), Loechel *et al* (2013ab); Hodgkinson *et al* (2014); Noble *et al* (2014); Mason and Giurco (2013), Pizarro *et al* (2017); Rio Tinto (2014);	This literature has emphasised the importance of education, information, skills, and training in climate adaptation	0.3
Speed of implementation	Mimura *et al* (2014); Delphi Group (2014); Capriolo *et al,* 2015; Mullan (2013); Loechel *et al* (2013b);	Implementation plans for adaption options are still in an early stage (Mullan, 2013). Further, barriers to implementation such as costs, cultural, institutional or knowledge have been identified (Loechel *et al*, 2013).	0.1
Effectiveness	Capriolo *et al* (2015); Mullan *et al* (2013); Delphi Group (2014); Noleppa (2013)	Monitoring plans and evaluation frameworks of adaptation options are still limited (Mullan, 2013). However, development plans and frameworks for evaluation are crucial to ensure the support of decision and policy makers (Mullan, 2013).	0.1
Benefits (or opportunities)	Ford *et al* (2009); Smit (2013); BSR (2011); World Bank (2010); Delphi Group (2014); BHP Billiton (2016); Pizarro *et al* (2017); Rio Tinto (2015); ERA (2016); BHP Billiton (2015); Loechel *et al* (2013b);	Companies and organisations did not identify neither benefits nor opportunities of climate change in this study. However, mining companies have reported benefits and opportunities for their businesses, but they have not associated them to climate adaptation or clearly described it as such (Rio Tinto, 2014; ERA, 2016; BHP Billiton, 2015).	0.1

The total sum of weights of all criteria should not exceed 1 (or 100%).

8.3.4 Uncertainties

Uncertainties in climate change science are considered an issue in their own right. They are present in a wide variety of sources such as global and local climate projections, timing, the impacts of climate change, expected losses, future socio-economic trends, adaptation strategies and the evaluation of

these strategies (Noleppa, 2013). Owing to the uncertainties involved, the assessment of climate change impacts and the effectiveness of adaptation options is a difficult task. Due to the difficulty assigning weights (as a result of the uncertainties), several strategies have been developed to deal with them.

A scenario analysis or sensitivity analysis was completed for this study. For this technique, the weights for each criterion are varied based for number of alternative scenarios (Noleppa, 2013). Weights represent evidence, preferences, and values provided by specific people (either policy or decision makers, researchers or community members). This technique was used due to the uncertainties associated with this research that include the exact magnitude of the climate impact across both supply chains, and the direct benefits of adaptation. For this reason, three scenarios were considered for the assessment. The criteria were weighted differently in each scenario to ensure the analysis was more robust.

8.3.5 Prioritisation of adaptation options

Adaptation options were prioritised in three scenarios with different weights assigned for each criterion. A programmed Microsoft Excel tool available at AdaptationCommunity.net provided by Competence Centre for Climate Change was employed in this study. The weighting for each scenario is detailed below and is a summary is shown in Table 8.12.

Scenario I, weighting for each criterion outlined in Section 8.3.4 applied.

Scenario II, considered each criterion with the same weight (Dixit and McGray, 2013)

Scenario III, considered cost-efficiency and human capital with the same, highest weights (0.3), speed was considered with a second degree of importance (0.2), and effectiveness and benefits the lowest importance with 0.1 each.

Table 8.13: Summary of weighting for each criterion in each scenario considered

	Scenario I	Scenario II	Scenario III
Criterion	**Weighting**	**Weighting**	**Weighting**
Cost-efficiency	0.4	0.2	0.3
Human capital	0.3	0.2	0.3
Speed of implementation	0.1	0.2	0.2
Effectiveness	0.1	0.2	0.1
Benefits	0.1	0.2	0.1

The results of this prioritisation for each group of both supply chains are shown in the following sections. It should be noted the normalization of weighting and scoring was a challenge, especially in this exploratory assessment. The information about the implementation and performance of adaptation measures is limited in the literature. It is generally expected that a robust analysis can be performed with the support of stakeholder feedback.

8.3.5.1 Mining group of Ranger Mine

This section describes the results of prioritisation of adaptation options including the assessment criteria, combined scoring (performance and weighting) and three scenarios for the Mining group. Table 8.14 presents the results.

Table 8.14: Combined scoring of adaptation options at Mining group of Ranger Mine.

Option	Description	Scenario I	Scenario II	Scenario III
A1	Re-direct resources towards communication of climate change adaptation planning	2.7	2.8	2.7
A2	Identification of communication failures with stakeholders by an external adviser	2.3	2.6	2.4
B1	Develop a vulnerability assessment and risk reduction plan to climate change at the mine site	2.2	2.4	2.3
B2	Use local climate projections (and historical records) of climate extremes to develop mine site projections to improve the identification of climate risks in the RMP	2.5	2.4	2.5
C1	Evaluate the failures of internal communication through an external consulting firm	2.6	2.6	2.6
C2	Using internal communication tools to improve the information of guidelines and procedures to the staff	1.9	2.2	2.0
C3	Promote internal communication activities such as staff engagement, training, communication inductions for inexperienced staff and support groups to promote the understanding of the RMP and climate change	2.6	2.6	2.6
	Average	2.4	2.51	2.44

The levels of prioritisations are shown in Table 8.15. In this group the adaptation option A1 – Redirect resources towards communication of climate change adaptation planning had the highest priority in all three scenarios. This result highlights the importance of improving the effective communication with stakeholders (e.g. water, energy and transportation companies) in the adaptation context. The next prioritised options focused on improving the communication of the RMP to the staff (C1 and C3 shown in Table 8.15) in the three scenarios.

Table 8.15: Prioritisation of adaptation options at Mining group of Ranger Mine.

Prioritisation	Scenario I	Scenario II	Scenario III
1	A1	A1	A1
2	C1, C3	A2, C1, C3	C1, C3
3			
4	B2		B2
5	A2	B1, B2	A2
6	B1		B1
7	C2	C2	C2

It is clear that the Ranger Mine Mining Group consider that redirecting their existing resources towards climate change adaptation planning is of the highest priority in all possible scenarios. The highest priority is given to the improvement of communication with stakeholders. Further, these results suggest that the mine staff have already been significantly affected by climate change (ERA, 2007a; ERA 2011; ERA, 2012) and are concerned that the impact will be greater in the future. It is clear that all mine staff are being educated on the process and take it seriously (C2EC, 2013).

8.3.5.2 Downstream group Ranger Mine

The combined scoring of the adaptation options proposed for the Downstream Group of the Ranger Mine in the three scenarios are shown in Table 8.16 on the next page.

Table 8.16: Combined scoring of adaptation options at Downstream Group of the Ranger Mine.

Option	Description	Scenario I	Scenario II	Scenario III
A1	Changes in the internal management approach or leadership to improve the third party's communication	2.6	2.6	2.5
A2	Assessment of communication failures by the own personnel	2.3	2.4	2.3
A3	Evaluation of the communication failures and implement measures by an external consulting company	1.9	2.2	2.0
B1	Integration of climate risks procedures into the regular meetings at all levels.	2.5	2.4	2.5
B2	Appointment of a representative who can clearly understand and communicate the RMP guidelines and procedures to the staff.	2.7	2.4	2.7
B3	Including adaptation/response management to climate risks KPIs for each member of this group to facilitate the engagement.	2.4	2.2	2.3
C1	Performing test-drills of climate events to assess the RMP, roles, and responsibilities.	2.6	2.6	2.6
C2	Existing communication resources can be used to identify responsibilities in each role.	2.7	2.4	2.5
D1	Supportive management approach to update the relevant/specific RMP for the site	2.4	2.2	2.3
D2	Using resources publicly available on the internet (e.g. guidelines) to prepare a specific RMP	2.6	2.6	2.6
E1	Conducting a literature review to obtain a better identification of climate risks.	2.0	2.0	1.9
E2	Change from a passive to active strategy to climate change adaptation.	2.4	2.4	2.4
	Average	2.43	2.37	2.38

The level of prioritisation options varied in the three scenarios for this group. They are summarised in Table 8.17. The highest combined score of options in Scenario I was related to the improvement of clarity of procedures and guidelines to follow in the case of a climate event (B2) and clarification of the roles and positions to act in the case of a climate event (C2). In the second scenario, the first level of priorities was related to the improvement of effective communication between companies related (A1), the clarity of roles and position to act in the case of a climate event (C1), and the preparation of a more specific risk management for the site of operations (D2). In the third scenario, the first level of priorities is also related to communication between companies (B2).

Table 8.17: Prioritisation of adaptation options at Downstream Group of Ranger Mine.

Prioritisation	Scenario I	Scenario II	Scenario III
1	B2 C2	A1 C1 D2	B2
2			C1 D2
3	A1 C1 D2		
4		A2 B1 B2 C E2	A1 B1 C2
5			
6	B1		
7	B3 D1 E2		E2
8			A2 B3 D1
9		A3 B3 D1	
10	A2		
11	E1		A3
12	A3	E1	E1

The variation in results of this group may be a direct result of their varied business ventures and how often they interact with the coordinator member group. Despite the results being different (compared to the Mining Group) the communication issues are again in the first level of prioritisation in two scenarios (II and III). These results have shown that effective communication plays a key role in adaptation to climate change as Glaas *et al* (2015) suggested.

8.3.5.3 External Group Ranger Mine

The combined scoring for the adaptation options proposed for this group in the three scenarios considered are shown in Table 8.18.

Table 8.18: Combined scoring of adaptation options at External Group of Ranger Mine.

Option	Description	Scenario I	Scenario II	Scenario III
A1	Improve the climate risks identification by the own personnel.	2.7	2.4	2.6
A2	Conduct a vulnerability assessment of climate risks by an external consultant.	1.9	2.2	2.0
A3	Change from passive to active strategy to climate change adaptation. This includes the search of shared-knowledge with other supply chain members.	2.4	2.2	2.3
B1	Reviewing the emergency procedures and contingency plans for all kind of risks to identify inadequacies.	2.6	2.6	2.6
C1	Evaluate the communication failures by their own personnel. Some external advice might be required.	2.2	2.4	2.3
C2	Improve the understanding of risk management principles by staff	2.5	2.4	2.5
D1	Test, evaluate, and update (e.g. more frequent test-drills) the current RMP.	2.2	2.4	2.3
D2	Facilitate and support the preparation of monitoring plans and reports.	2.9	2.8	2.9
D3	Technological publicly available resources (e.g. Software, guidance and templates) can be used for updating the RMP.	2.8	2.6	2.8
	Average	2.5	2.4	2.5

The adaptation options prioritised are shown in Table 8.19 below.

Table 8.19: Prioritisation of adaptation options at External Group of Ranger Mine.

Prioritisation	Scenario I	Scenario II	Scenario III
1	D2	D2	D2
2	D3	B1 D3	D3
3	A1		A1 B1
4	B1	A1 C1 C2D1	
5	C2		C2
6	A3		A3 C1 D1
7	C1 D1		
8		A2 A3	
9	A2		A2

In this group, the highest priority option was for D2 in the three scenarios. This option is related to the need to improve the regular update of the RMP. In the second scenario, the second level of priority was related to the same adaptation need mentioned above (D3) and to the improvement of the adequacy of procedures and response contingency plans (B1).

Members of this group considered the regular update of the RMP the highest priority in all scenarios. This reflects that they understand the dynamic nature of climate change and how it can affect operations. They are aware that their business must be dynamic to operate in a changing climatic environment. It is clear to this group that it is not possible to face climate change with the same operational/leader approach and/or the same historical standards of infrastructure without taking into consideration future climate change (The Climate Institute, 2012).

8.3.5.4 Mining Group of Olympic Dam

Table 8.20 provides the combined scoring of the adaptation options proposed for the Mining Group of Olympic Dam.

Table 8.20: Combined scoring of adaptation options at Mining Group of Olympic Dam.

Option	Description	Scenario I	Scenario II	Scenario III
A1	Review and assessment the current communication program and engagement activities to identify opportunities for improvement.	2.3	2.6	2.4
A2	Improvement of consultation techniques.	2.5	2.4	2.5
A3	Identify KIPs to improve the effective communication.	2.6	2.6	2.6
B1	Re-organisation of the current resources (technical resources, skills and expertise, and others) to the zero-harm approach-all risks considered.	2.6	2.6	2.6
C1	Identify the failures of internal communication by an external consultant.	2.2	2.4	2.3
C2	Identify incentives to improve the understanding of the RMP and its impact on staff safety.	2.9	2.8	2.9
D1	Develop a site-specific projection of climate and extremes for the mine-site.	2.4	2.2	2.3
D2	Invest in the improvement of the vulnerability assessment to allow better identification of climate risks and their impacts on operations.	2.7	2.8	2.7
	Average	2.53	2.55	2.54

Table 8.21 shows the different level of prioritisation of the adaptation options proposed for this group.

Table 8.21: Prioritisation of adaptation options at Mining group of Olympic Dam mine.

Prioritisation	Scenario I	Scenario II	Scenario III
1	C2	C2 D2	C2
2	D2		D2
3	A3 B1	A1 A3 B1	A3 B1
4			
5	A2		A2
6	D1	A2 C1	A1
7	A1		C1 D1
8	C1	D1	

In this group, the highest priority option in all Scenarios was related to improving the understanding of the RMP and its impacts on the staff safety (C2). This priority was identified along with a likely investment to conduct a vulnerability assessment, this to acquire a better identification of climate risks and their impacts on the operations (D2) in Scenario II. These results highlighted the importance for this group of improving the knowledge/training/ information about the principles of the Risk Management related to their RMP. BHP Billiton (2009e) provided a description of the standard risk management procedures which includes risk rating, risk assessment, post-event analysis, risk control, cost-benefit analysis, risk management terminology, and control framework. However, it seems the previous procedures are applied mainly to risks such as radiation exposure, hazardous chemical, noise, and dust. It is not clear if climate hazards are included in this procedure. Further, this group is aware that a vulnerability assessment would be beneficial to identify climate risks.

8.3.5.5 Downstream group of Olympic Dam

The summary of the adaptation options proposed and their combined scoring in the three scenarios are shown in Table 8.22 below.

Table 8.22: Combined scoring of adaptation options at Downstream Group of Olympic Dam

Option	Description	Scenario I	Scenario II	Scenario III
A1	Perform a vulnerability assessment and risk reduction plan by the own qualified personnel.	2.2	2.4	2.3
A2	Obtain additional information about climate risks from other members of the chain (e.g. Mining Group).	2.5	2.4	2.5
A3	A better identification of climate risks undertaken by an external consulting company.	1.9	2.2	2.0
B1	Develop a specific site RMP	2.6	2.6	2.6
B2	Request a vulnerability assessment by an external consulting company.	1.9	2.2	2.0
C1	Regular update of the RMP according to the changing risks and conditions of operations.	2.2	2.4	2.3
C2	Increasing the frequency of updates by improving the knowledge of the staff.	2.7	2.4	2.6
C3	Technological resources e.g. risk management software can be used to facilitate the update.	2.5	2.4	2.5
D1	Identifying the communication failures through external advice.	2.6	2.6	2.6
D2	Improve the third-parties communications.	2.3	2.6	2.4
	Average	2.3	2.4	2.4

Table 8.23 presents the prioritisation obtained for the options.

Table 8.23: Prioritisation of adaptation options at Downstream Group of Olympic Dam mine

Prioritisation	Scenario I	Scenario II	Scenario III
1	C2	B1 D1 D2	B1 C2 D1
2	B1 D1		
3			
4	A2 C3	A1 A2 C1 C2 C3	A2 C3
5			
6	D2		D2
7	A1 C1		A1 C1
8			
9	A3 B2	A3 B2	A3 B2
10			

In this group, the priority option for Scenario I is related to increasing the frequency of update of the RMP (C2). In Scenario II, the highest priorities are related to the relevancy of the RMP to the site of operations (B1) and improvement of communications between companies (D1 and D2). In Scenario III, the highest priority is related to the relevancy of the RMP to the site of operations (B1), increasing of frequency update of the RMP (C2) and the improvement of communication between companies (D1).

The varied priorities in each of the scenarios suggests that the Downstream Group of Olympic Dam are highly vulnerable to a range of factors. This suggests that they need to be included in RMP training and communications. Members of this group are aware their operations are within a changing environment, thus, their RMP must be updating according to the new climate conditions of their locations.

8.3.5.6 External group of Olympic Dam

Table 8.24 presents a brief description of the adaptation options proposed for this group and the combined scoring in each scenario.

Table 8.24: Combined scoring of adaptation options at External Group of Olympic Dam.

Option	Description	Scenario I	Scenario II	Scenario III
A1	Using the existing communication resources to identify communication failures between stakeholders.	2.7	2.8	2.7
A2	Assessment of communication failures and the implementation of better communications plan by an external consultant.	2.0	2.4	2.1
A3	Searching the support of other supply chain members to promote the effective communication.	2.6	2.6	2.5
B1	Current technology can be used to update their existing RMPs.	2.5	2.4	2.5
B2	Searching share-knowledge with other members of the chain to facilitate the regular update of their RMPs.	2.7	2.4	2.6
	Average	2.5	2.5	2.5

Table 8.25 presents the order of prioritisation of the adaptation in the three scenarios.

Table 8.25: Prioritisation of adaptation options at External group of Olympic Dam mine.

Prioritisation	Scenario L	Scenario II	Scenario III
1	A1 B2	A1	A1
2		A3	B2
3	A3	A2 B1 B2	A3 B1
4	B1		
5	A2		A2

In this group, the highest priority of adaptation options in Scenario I, it is related to external communication, in particular, communication failures with the supply chain (A1) and the regular update of the RMP (B2). This reflects this group's possible frustration with a lack of information being distributed and/or delayed distribution. Nowadays, the technology has change the expectation of supply chain participants. They expect to receive a deeper and wider information flow (ICMM, 2013). Further, these results suggest that the management/leadership approach of the members of this group are not facilitating the flow of information across the supply chain, this to identify risks, opportunities and enable proper adaptation as ICMM (2013) points out.

8.4 Summary

This chapter was focused on adaptation needs and options across the uranium supply chain in Australia. It has been revealed that the lack of internal and external communication is one of the main failures identified as barriers to achieve proper climate change adaptation measures across both chains. The improvement of effective communication between related companies (stakeholders) is one of the key aspects to improve. This adaptation need was reported in two of the three groups of Ranger Mine and in all three groups of Olympic Dam. The analysis also revealed the need for improved identification of climate risks in the RMP in both chains. Internal failures such as lack of understanding of the principles of a RMP and deficient communication with the staff in the risk management context were revealed.

9 Conclusions and Recommendations

In light of climate change and the way it has impacted and how it will impact sectors/activities in our society, and because uranium represents an alternative source for electricity generation with lower CO_2 emissions through its life cycle, this research was undertaken to investigate if the supply chain of the Ranger Mine and Olympic Dam has been/will be affected by climate change.

In a preliminary stage, we reviewed and analysed the annual and sustainability reports of the mines owners' companies over the period of 2006 to2016. This analysis was associated with their current and future ability to cope with climate change events.

Main climate impacts identified at Ranger Mine (2006-2016)

- Disruptions of mining and processing operations and flooding in the operational pit.
- Flooding in the Tailings Storage Facilities.
- Blocked access to the high-grade ore .

These events were related to economic losses such as a decrease in production, decrease of revenue, loss of profits due to the need to purchase of uranium in the market at the spot price to fulfil commitments with customers, and the increase of capital expenditure, which add up to a total of A$934.5 million for this period. Furthermore, in this period there were reactive adaptation measures to cope with climate events such as removal of temporary excess water from the pit, raising the height of the tailings storage facility three times, installation of a new water treatment facility, and others. The total cost of these adaptation measures during the study period was estimated to be AS$ 594.8 million.

Main Climate impacts at Olympic Dam (2006-2016)

- Water scarcity issues specially during drought periods (e.g. millennium drought).
- The temporary closure of the surrounding roads to the mine.
- A heavy storm caused a massive black out in South Australia in September 2016, and consequently Olympic Dam had to halt operations for 15 days during that month.

Olympic Dam has implemented water sustainability program in its operations to avoid the depletion of freshwater and causing damage to the other competitors for the use of this resource. The shutdown of Olympic Dam in September 2016 caused an economic loss of A$137 million to the company, further, the mining services companies were also affected by the increased cost of safety shutdown of critical equipment of the mine site.

Furthermore, this research proposed to identify the uranium supply chain participants. This was a challenge because 1) there is not information publicly available and 2) the participance of a supply chain is dynamic in nature. Despite these limitations, 18 groups of stakeholders of each mine were able to be identified, belonging to the supply chain and the external group of stakeholders (State and Local Government, Community, NGOs, Research groups, and others). In order to study at depth how the supply chain of these mines has been affected by climate events in the past and how they will be affected in the future, a vulnerability assessment was conducted. This assessment was carried out through a survey, which was fully designed for the purpose of this research. The 18 groups of stakeholders were classified into three groups: Mining , Downstream and External.

A summary of the key findings and conclusions from the vulnerability assessment are provided below.

- It has been shown that vulnerability is specific to each location.
- The uranium industry is aware of the negative impacts that climate change may have in the future.
- Intense rainfall/flooding was identified as the most influential climate risk independent of the mine location.
- The Mining group (site operator) was identified as the most vulnerable group to future climate change in both chains.
- Indirect flow-through impacts were revealed by the survey. Considering the future case, local community and utility companies were considered as the most affected across the Ranger Mine supply chain. In the case of the supply chain of Olympic Dam, the mining company and local community were considered as the most affected.
- Indirect flow-on impacts to other members of the chain were also revealed by the survey. In this case, the mining company and local community were considered as the most influential in the supply chain of Ranger Mine. Across the Olympic Dam supply chain, mining services, customers, and the transport company were mentioned as the most influential to cause impacts to other members of the chain.
- The future potential increase for demand of resources was also revealed by this study. Across the supply chain of Ranger Mine, energy was estimated as the resource most needed in the future. In the supply chain of Olympic Dam mine water, energy, labour availability and knowledge/expertise were estimated as the resources with higher demand in the future.

An important driver for climate vulnerability is the adaptive capacity of the system. As part of the objective of this research, this capacity was also investigated across both supply chains, thru the

assessment of the current Risk Management Plan (RMP) employed by the company, organisation or community belonging to each chain. Some findings and conclusions are presented below:

- The adaptive capacity is present across both supply chains, but it is limited.
- The Mining group in both supply chains reported the best adaptive capacity in the present.
- The communication between related companies was mentioned as the weakest item across both chains.
- Downstream group reported the weakest adaptive capacity in both chains.
- Factors that can increase the future vulnerability revealed by survey were: the geographical location, frequency of climate events, the age and design of assets, labour force availability, and productivity.
- The current Risk Management Plan might not be adequate to face future climate change.

The assessment of the adaptive capacity allowed the identification of adaption needs across both supply chains and the External group of stakeholders. As was proposed in the aims of this research, adaptation options were proposed to meet the adaptation needs identified previously. Then, an assessment of these adaptation options was performed using the Multi Criteria Analysis (MCA).

This stage was made more difficult since, unlike other sectors of the economy such as agriculture, mining has no evidence about specific adaptation options employed or their outcomes. For this reason, the literature to support this assessment was adapted to the characteristics of the sector. The adaptation options were ranked according to five criteria and in three scenarios. A summary of these results and conclusions are presented below:

- The adaptation needs and the options to meet them are specific to groups of stakeholders and the rank of priority can vary according to the scenario considered.
- Internal communication within the company/organisation and external communication between supply chain participants represent the areas where the greatest opportunities for improvement exist to achieve climate change adaptation across both mines' supply chains
- Lack of knowledge or training about risk management principles, and climate risks identification are also aspects that could be improved.
- Climate risks must be included in the RMP of companies, organisations, and local communities.
- The RMP employed must be specific to operations and locations, otherwise, it will not be useful for the purpose to minimise risks.

- The role's scope to act in the case of a climate event and the procedures to follow must be improved.

Since the literature review was carried out, it was clear that undertaking this research would be a challenge because several gaps were identified, and the information in many topics was limited. This research attempted to contribute to filling those gaps to some degree. However, there is much to do in the mining adaptation to climate change area. We expect this research to be the basis to undertake further studies in this area.

9.1 Recommendations for future work

During the development of this research other opportunities to undertake new research were identified that include:

Assessment of adaptation options

Most of this research was focused on the vulnerability assessment of the uranium mining industry and its supply chain. To develop a more robust assessment of adaption options, the following aspects should be taken into consideration:

- Selection of assessment criteria
- Additional consideration of performance through additional case study review.
- To perform a robust analysis of prioritisation / weighting is suggested to implement a participatory method (e.g. survey, interviews, or workshop).
- Uncertainties should be further considered through techniques such as sensitivity analysis or probabilistic function of cost and benefits.

Impact assessment of climate change across the uranium supply chain

Direct and indirect climate impacts have been identified in the uranium mining industry (these impacts are not limited to this commodity). These impacts have been quantified and monetarised in a very limited way for this study. The following considerations should be considered to undertake further research in this complex area.

- **Climate scenario selection.** There are different sources of climate projections. It is suggested to employ a local climate projection. E.g. projections provided by climate change in Australia (https://www.climatechangeinaustralia.gov.au/en/).

- **Quantification** of direct and indirect impacts can be performed using alternative ways and assumptions, for example, loss of productivity, labour days lost due to increased prevalence of accidents or sickness due to climate variations (i.e. heat stroke), cost of vital production inputs (like water), or the need to see alternative costlier outputs to fulfil contract obligations.
- **Monetarisation** of these costs and benefits where possible. This is often very difficult to achieve, due to the complex nature of climate effects, and the difficulty of finding proper valuations for economic goods not traded in markets, or for which there is no specific determination of cost (like forests, fauna, etc.). A CBA and/or a CEA should be considered.

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Appendix I: Identification of the gaps in the literature

In this appendix a summary of the gaps identified in the literature is presented. The approaches, methods, techniques and historical review of the literature were evaluated in order to examine, synthesise, and analyse them to identify the gaps in the literature and prepare a framework for this research. We also identify limitations and potential areas for further work.

The following table provides a summary of the literature review and the topics analysed by each author. In this review 17 areas of interest for this research were identified.

	Value chain concept and scope	Supply chain concept other industry or area	Supply chain management other industry	Supply chain in mining	Supply chain management in mining	Sustainable development in mining with indicators or not	Climate change and/or climate scenarios	Adaptation and adaptive capacity to climate change	Adaptation to climate change in mining	Vulnerability concept in climate change	Vulnerability assessment in climate change context	Vulnerability assessment to climate change in mining	Vulnerability assessment with indicators	Uncertainties in climate change context	Costs and benefits of adaptation	Economic evaluation of adaptation strategies for mining	Impact assessment in mining industry of climate change
Acclimatise (2010)									X								
ABARE-BRS (2010)								X		X			X				
Arrhenus (1896)							X										
Azapagic (2004)				X		X											
Auld and Maciver (2006)								X						X			
Benn *et al* (2013)				X	X	X											
Accenture (2007)				X	X												
Clark *et al* (1998)								X		X			X				
Cox (1999)		X	X														
Damigos (2011)																	X
Dessai and Hulme (2004)								X			X			X			
Downing and Patwardhan (2002)								X		X	X						
Engle (2011)							X	X									
EBNFLO and AquaResource (2010)																	
Feller *et al* (2006)		X															
Flint and Golicic (2009)		X	X														
Ford *et al* (2009)								X				X					

	Value chain concept and scope	Supply chain concept other industry or area	Supply chain management other industry	Supply chain in mining	Supply chain management in mining	Sustainable development in mining with indicators or not	Climate change and/or climate scenarios	Adaptation and adaptive capacity to climate change	Adaptation to climate change in mining	Vulnerability concept in climate change	Vulnerability assessment in climate change context	Vulnerability assessment to climate change in mining	Vulnerability assessment with indicators	Uncertainties in climate change context	Costs and benefits of adaptation	Economic evaluation of adaptation strategies for mining	Impact assessment in mining industry of climate change
Fussel (2007)							X			X							
Fussel and Klein (2006)										X	X						
John Tyndall (1859)							X										
Joseph Fourier (1878)							X										
Gibson *et al* (2005)		X	X														
Glick *et al* (2011)								X		X	X						
GSF (2011)								X							X		
Gunderson (2000)								X									
Hallegatte *et al* (2011)								X		X	X			X			
Haydoe *et al* (2006)							X										
Herb and Mortsch (2007)								X			X		X				
Hodgkinson *et at* (2010a)				X				X	X	X	X	X					
Hodkinson *et al* (2010b)																	
Hodgkinson *et at* (2013)								X	X		X	X					
ICMM (2013)				X	X			X	X								
ICRISAT (2009)							X	X		X			X				
Houghton *et al* (2001)							X	X		X							
Solomon *et al* (2007)							X	X		X	X			X	X		
Stocker *et al* (2014)							X	X		X	X			X	X		
Loechel *et al* (2013a)				X				X	X								
Loechel *et al* (2013b)									X			X					
Mason and Giurco (2013)								X	X								
Mason *et al* (2013)								X	X								
Marchildon *et al* (2007)								X		X	X		X				
Metzer *et al* (2001)	X	X	X														
Metzger *et al* (2005)								X		X		X					

	Value chain concept and scope	Supply chain concept other industry or area	Supply chain management other industry	Supply chain in mining	Supply chain management in mining	Sustainable development in mining with indicators or not	Climate change and/or climate scenarios	Adaptation and adaptive capacity to climate change	Adaptation to climate change in mining	Vulnerability concept in climate change	Vulnerability assessment in climate change context	Vulnerability assessment to climate change in mining	Vulnerability assessment with indicators	Uncertainties in climate change context	Costs and benefits of adaptation	Economic evaluation of adaptation strategies for mining	Impact assessment in mining industry of climate change
Mudulli and Barve (2011)				X		X											
Nelitz *et al* (2013)								X		X	X			X			
Noleppa (2013)								X						X	X		
NOAA(2012)							X										
O'Brien *et al* (2007)										X	X						
Plaganyi *et al* (2013)		X															
Patnaik and Narayanan (2006)								X		X			X				
Pattara *et al* (2012)		X	X														
Pachauri and Reisinger (2007)								X						X	X		
Parzen (2008)							X	X			X						
Pearce *et al* (2009)							X	X	X	X	X	X					
Pearce *et al* (2010)							X	X	X	X	X	X					
Perry *et al* (2007)										X	X						
Porter (1998)	X																
Preston (2012)										X	X						
Refsgaard *et al* (2013)								X						X			
Rygel *et al* (2006)							X		X			X					
Rowan (2011)							X			X							
Sova (2011)							X			X				X			
Stock and Boyer (2009)	X	X															
Smit and Wandel (2006)							X		X								
Sturgeon (2001)	X																
Tarekegn and Tadege (2006)							X	X		X	X						
Tiburan *et al* (2010)									X	X		X					
UDP (2009)	X																

	Value chain concept and scope	Supply chain concept other industry or area	Supply chain management other industry	Supply chain in mining	Supply chain management in mining	Sustainable development in mining with indicators or not	Climate change and/or climate scenarios	Adaptation and adaptive capacity to climate change	Adaptation to climate change in mining	Vulnerability concept in climate change	Vulnerability assessment in climate change context	Vulnerability assessment to climate change in mining	Vulnerability assessment with indicators	Uncertainties in climate change context	Costs and benefits of adaptation	Economic evaluation of adaptation strategies for mining	Impact assessment in mining industry of climate change
UNFCCC (2009)							X							X			
Van Aalst *et al* (2008)							X		X	X							
Velthoen (2013)	X	X															
Watkiss *et al* (2010)							X							X			
World Bank (2010)							X						X	X			

Summary of Gaps in the Literature

In order to identify gaps in the current literature four main areas of interest have been outlined that include: supply chain, vulnerability assessment, adaptation/adaptive capacity and evaluation of adaptation strategies. A total of 17 gaps were identified between each of these topics. The analysis of the literature review which allowed the identification of gaps is presented in the Appendix I. A summary is provided below.

- Supply chain: The gap in this topic was identified through a confusion in the definition of the concept itself. Supply chain is often confused with a value chain concept in mining literature (Gap 1). Clear differences between the supply chain and value chain are difficult to identify in general (Gap 2) as well as applied in mining (Gap 3).
- Vulnerability: The information identified in primary and secondary sources of literature was vast, in terms of concept definition and vulnerability assessment however there is a gap in the mining literature (Gap 4). There is also a vast variety of approaches or techniques to assess the vulnerability, however, there is a lack of studies completed for the mining industry (Gap 5).
- Adaptation/Adaptive capacity: There is significant literature related to adaptation strategies but there is a limited number of researchers in the mining area (Gap 8). Furthermore, there limited research associated with the identification of adaptation strategies in mining (Gap 9). There is also a gap in the literature regarding the study of uncertainties and adaptation in mining (Gap 10).
- Evaluation of adaptation strategies: One article was identified that evaluated the impacts of climate change on the mining industry however, the evaluation of adaptation strategies was not completed (Gap 11).

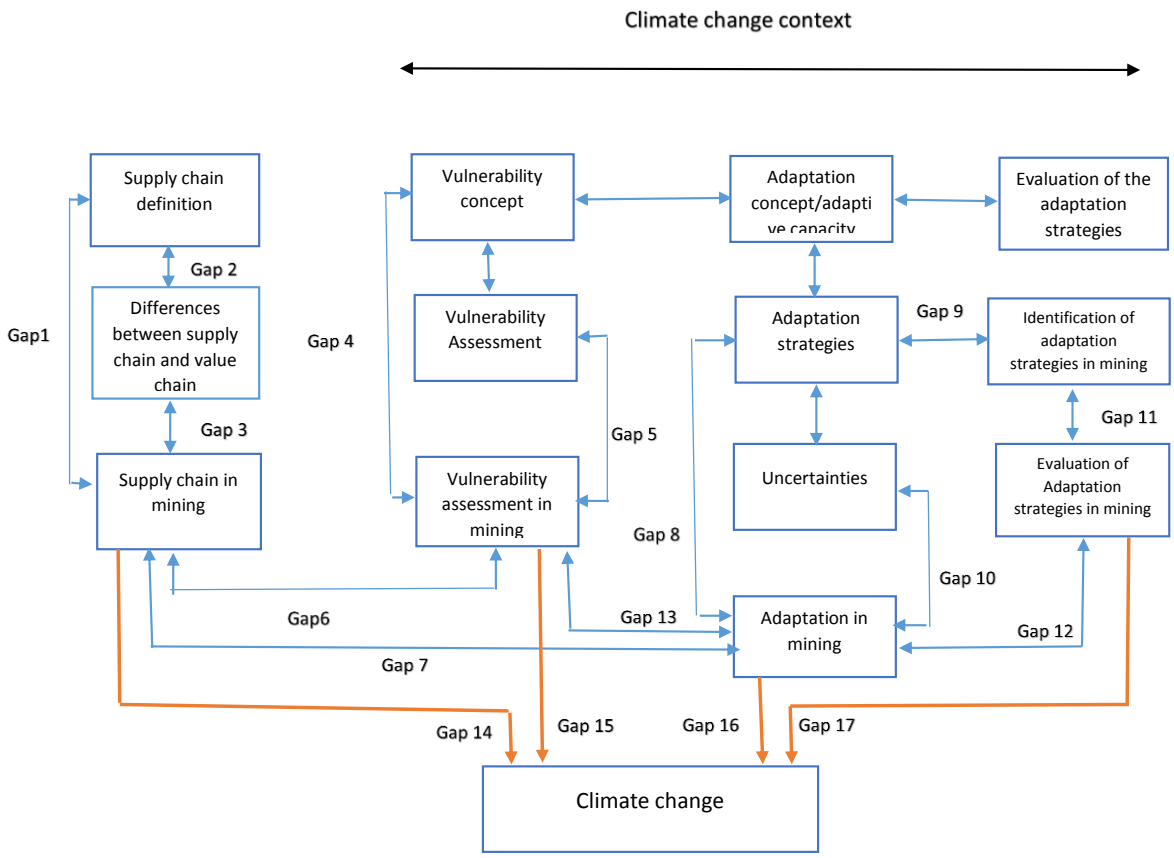

Figure I.1: Identification of gaps in the existing literature

Literature gaps between topics were identified that included : supply chain in mining and vulnerability assessment (Gap 6), supply chain and adaptation in mining (Gap 7), vulnerability assessment and adaptation in mining (Gap 13), adaptation strategies and evaluation of these strategies (Gap 12).

In relation to climate change there signficaint literature on the global and regional scales that are focused on other industries, however, limited literature for the mining industry exisits. Gaps identified included:

Gap 14 : Connection between climate change and supply chain in mining

Gap 15 : Connection between climate change and vulnerability assessment

Gap 16 : Connection between climate change and adaptation in mining

Gap 17 : Connection between climate change and evaluation of adaptation strategies

The last gaps (15, 16 and 17) formed the basis of this research.

Appendix II: Survey Questionnaire

1.What kind of company/organisation do you work for? Please select all that apply.

Answer Options
Mining Company
Mining services (engineering, maintenance, scientific & technical, drilling, labour hire, etc)
Contractor
Consultant
Mining supplies (materials, chemicals or equipment)
Water supply
Energy supply - fuel
Energy supply - gas
Energy supply - electricity
Telecommunications
Transport - roads, trucking
Transport - rail
Transport - air
Transport - ports, shipping
Government - local
Government - state
Government- federal
Community services (health, education, police, emergency, welfare, etc.)
None (member of public/local community)
Other (please specify)

2. Which best describes your role/position in the company/organisation/community?

Answer Options
Management
Engineer
Scientist
Operational worker
Administrative staff
Community member
Other (please specify)

3. How many years of experience do you have in your industry/organisation?

4. If you are a community member near the uranium mine, how many years have you lived there?

5. In which state is your company/organisation or community based/located?

Answer Options
Northern Territory (NT)
Queensland
New South Wales
Victoria

South Australia
Tasmania
Western Australia
Australian Capital Territory (ACT)

6. From your experience, what are the most influential climate conditions that most affect your company/organisation/community? Select one or more.

Answer Options
Droughts
Fires
Heat waves
Storms
Intense rainfall/Flooding
Other (please specify)

7. Based on your own experience or historical knowledge, how often have these climate risks affected your company/organisation/community?

Answer Options
Less than once in 20 years
Once every 20 years
Once every 10 years
Once every 5 years
Once every 3 years
Once a year
Twice a year
Three or more times a year
Other (please specify)

8. On scale of 1 to 10 (where 1 is Low and 10 is High) how would you rate your company/organisation/community risks exposure to climate conditions you selected in question 6?

Answer Options	Low 1	2	3	…	9	High 10
Droughts						
Fires						
Heat waves						
Storms						
Intense rainfall/flooding						
Other						

9. How have the climate events identified in question 6 impacted your company/ organisation/community? Select all that apply.

Answer Options
Financial performance
Loss of revenue
Increased costs
Operational disruption
Delayed production
Quality of production
Supply of essential inputs or services (water, energy, telecommunications, labour, materials etc.)
Transportation of product
Health and safety of workers
Infrastructure/ plant & equipment damage
Other (please specify)

10. What aspects of the mining operation has been most affected by the climate events identified in question 6? Select the main risk areas.

Answer Options
Ore extraction
Processing
Transport within the mine site (e.g. access and haulage roads)
Transport outside the mine site (e.g. road, rail, port)
Tailings/ waste management facilities
Mine planning
Maintenance activities
Exploration
Other (please specify)

11. Have climate events that have impacted other organisations flowed-through to affect the operation of your company in the past? If yes, please specify what type of organisation has impacted you. Select all that apply.

Answer Options
Mining Company
Local community
Mining Services (engineering, maintenance, scientific & technical, drilling, labour hire etc)
Transport company
Utilities company (water, energy, telecommunications etc)
Not Applicable
Other (please specify)

12. If your company/organisation/community is affected by the climate events you selected above, which organisations or sectors (identified below) would be most affected by your situation? Could you rank them (i.e. 1 = most affected to 8= least affected)?

Answer Options
Mining Company
Local community
Construction
Manufacturing
Transport company
Customer company
Mining Services
Surrounding environment

13. If the climate condition/climate risks identified in question 6 become greater in the future (i.e., an increase in frequency, magnitude, duration and/or extent), how would you rate the impact to your company/organisation/community in the future?

Answer Options	Low 1	2	3	…	9	High 10
Droughts						
Fires						
Heat waves						
Storms						
Intense rainfall/flooding						
Other						

14. Which of the following factors would increase the vulnerability to climate conditions/climate risks in the future for your company /organisation/community? Select all that apply.

Answer Options
Age of the assets
Design of the assets
Geographical location
Type of operational process or method used
Frequency of climate events
Intensity and magnitude of climate events
Impact on labour force availability or productivity
Other (please specify)

15. How would an increase in the frequency or severity of climate events identified in question 6 impact your company/ organisation/community? Select all that apply.

Answer Options
Financial performance
Loss of revenue
Increased costs

Operational disruption
Delayed production
Quality of production
Supply of essential inputs or services (water, energy, telecommunications, labour, materials etc.)
Transportation of product
Health and safety of workers
Infrastructure/ plant & equipment damage
Other (please specify)

16. What aspects of your mining operation would be impacted the most if climate events identified in question 6 increase in the future? Select the main risks areas.

Answer Options
Ore extraction
Processing plant
Transport within the mine site (e.g. access and haulage roads)
Transport outside the mine site (e.g. road, rail, port)
Tailings/ waste management facilities
Mine planning
Maintenance activities
Exploration
Other (please specify)

17. Do you think climate change could increase the demand for any resources used by your company/organisation/community? Select all that apply.

Answer Options
Water
Energy
Inputs (materials, equipment, etc.)
Labour
Infrastructure
Technology
Knowledge/expertise
Not applicable
Other (please specify)

18. Which company/organisation/community impacted by future climate conditions/climate events could lead to flow-on impacts that affect your organisation the most? Select the main ones.

Answer Options
Mining company
Local community

Mining services (engineering, maintenance, scientific & technical, drilling, labour hire etc)
Transport company
Utilities company (water, energy, telecommunications etc)
Other (please specify)

19. Regarding the current climate conditions/climate risks identified in question 6, please rate the preparedness of the current risk management plan of your company/organisation/community.

Answer Options	Poor 1	2	...	Excellent 10
How well identified are the key climate-related risks in the Risk Management Plan (RMP)?				
How relevant/specific is the RMP to the actual site or operation?				
How adequate are the current risk mitigation procedures and response/contingency plans?				
How clear are the different positions, roles and responsibilities of the personnel required to respond to the event?				
How clear are the guidelines and procedures to follow in the case of a climate event?				
How well is the RMP communicated to staff?				
How regularly is the RMP updated?				
How effective is the communication between the other companies/organisations related with your company e.g. Energy, Water, and Transport, Communication Company or other?				

20. How would you classify the general approach of your company/organisation/community to dealing with climate related events?

Answer Options
Reactive
Proactive (anticipatory, preventive)
Other (please specify)

21. Has your company/organisation/community performed a climate change vulnerability assessment?

Answer Options
Yes
No

Unsure
If no, why not?

22. Was a risk reduction plan developed to respond to the vulnerability assessment?

Answer Options
Yes
No
Unsure
If no, why not?

23. Were any opportunities from climate change identified?

Answer Options
Yes
No
Unsure
If yes, could you mention some of them.

24. If the climate risks identified in question 6 become greater in the future (i.e., an increase in frequency, magnitude, duration and/or extent), how would you rate your current risk management plan to cope with these changes?

Poor 1	2	3	4	5	6	7	8	9	Excellent10

25. What types of changes do you think are required to improve the adaptive capacity of your company/organisation? Select all that apply.

Answer Options
Management procedures
Administrative procedures
Operational procedures
Work practices
Technical changes
Management approach/leadership
Not applicable
Other (please specify)

Appendix III: Paper Accepted (in press)

Climate change vulnerability assessment for the uranium supply chain in Australia

Climate change vulnerability assessment for the uranium supply chain in Australia

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Abstract

Uranium demand is expected to increase due to the worldwide growth in electricity demand and the shift towards more sustainable and reliable low carbon energy sources. For more than 10 years, the Australian uranium industry production (primarily represented by production from the Ranger and Olympic Dam Mines) has been affected by adverse weather conditions. Since Australia meets 12% of the current world uranium demand, there is a need to study, at depth, any potential threat to this market. This study has included a vulnerability assessment of the impact that climate change currently makes, and potentially might have on the supply chain of the two biggest uranium mines currently operating in Australia. The assessment identified the most vulnerable parts (past and future) of both operational chains, in addition to the chain participants with the greatest and least adaptive capacity.

Key words: Supply chain, uranium mining, climate projections, vulnerability assessment.

1 Introduction

The energy sector has been classified as the greatest worldwide contributor of Greenhouse Gas Emissions (GHGs). In 2010 it contributed 35% of total GHGs (Bruckner *et al*, 2014). Within the energy sector, electricity is the end-use of energy consumption with the greatest utilization occurring in the most recent years (Buckner *et al*, 2014). Together with renewable sources of energy, uranium has been argued as an alternative cleaner source of energy (IPCC, 2014). While it produces a range of hazardous contaminants that require rigorous procedures for containment, it is nevertheless a lesser GHG pollutant compared with other sources (e.g. coal). For example, lifecycle emissions of nuclear power are 29 tonnes CO_2e/GWh compared to 888 tonnes CO_2e/GWh for coal (WNA, 2011). In light of this, worldwide demand for uranium is expected to increase in the future, from 82,000 tonnes in 2017 to 89,600 tonnes in 2019 (NEA and IAEA, 2016; AG, 2017). While Australian exports are expected to decrease by 1.3% during FY 2017-2018 (due to a temporary halt in production at Olympic Dam mine), by FY 2018-2019 an increase of 1.6% is projected (AG, 2017).

Australia has 34% of worldwide uranium resources recoverable at a cost of less than US$130 per kilogram, which is about 1,287,000 tonnes (ASNO, 2017). At the present time (2018) there are three operating uranium mines Ranger Mine (owned by Energy Resources of Australia – ERA), Olympic Dam (owned by BHP Billiton) and the Four Mile Mine (Beverley Mine) (WNA, 2017). Together, the Ranger Mine and Olympic Dam Mine represent more than 80% of the domestic Australian uranium

oxide output in the years 2013 to 2016, and supply 12% of the global demand (WNA, 2017). Their locations are presented in Figure 1.

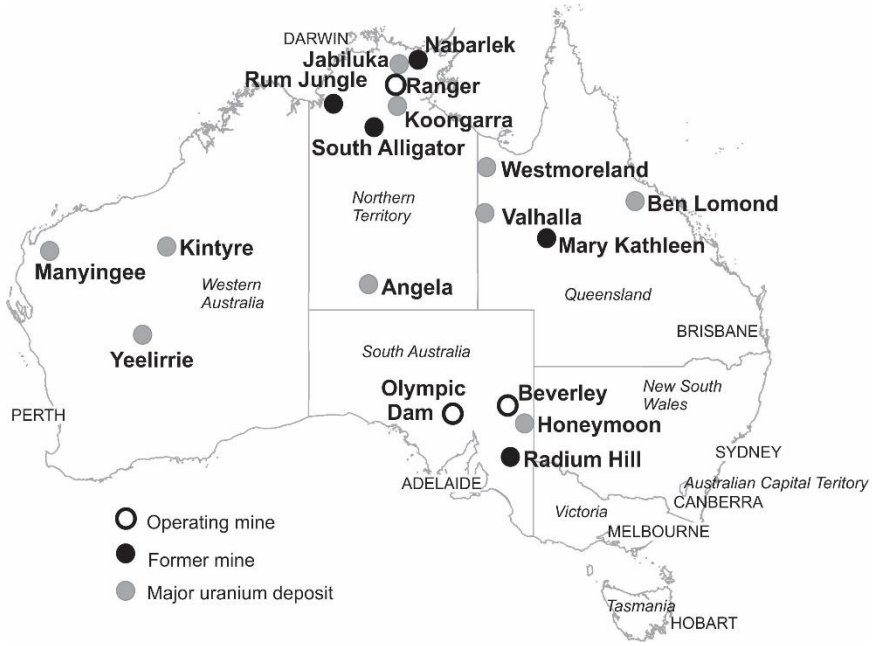

Figure 1: Location of Ranger mine and Olympic Dam in addition to uranium deposits and former uranium mines (Source: after Australian uranium, 2017)

The operational profitability of the two main uranium mines (Ranger Mine and Olympic Dam) in Australia have previously been affected by spot price, production costs and market fluctuations as well as by climate conditions and extreme weather events (more details at Pizarro *et al*, 2017). For example, extreme weather events such as heavy storms, heavy flooding, and cyclones have had significant operational and economic repercussions for Ranger Mine. A review of the company operation reports over 10 years (2006-2016) allowed the identification climate impacts, which are summarised below.

- Mining and the processing plant were halted frequently (ERA, 2007a; ERA, 2008a; ERA, 2011; ERA, 2012).
- Operational pit was flooded several times, this prevented access (total or partially) to the high-grade ore (ERA, 2007a; ERA, 2008a; ERA, 2009; ERA 2010; ERA, 2011; ERA, 2012).
- Tailing storage facilities and/or Pond Water were also flooded (ERA 2007a; ERA 2010; ERA 2011; ERA, 2012).
- The main road access to the mine (Arnhem highway) was closed for most March 2007 (ERA, 2008a).
- Interruptions in power and water services in 2015.

The impacts on the Ranger Mine were associated with loss of production, which led to the need to purchase the mineral elsewhere (at higher costs and increased capital expenditure) in the market to fulfil contract obligations. All in all, this represented an estimated economic loss of A$934.5 million in the 2006-2016 period. It was clear that climate conditions and the extreme weather events also affect the supply chain and the external group of stakeholders. To study in depth how they have been affected and how they likely will be affected in the future, a vulnerability assessment (based on the concept of vulnerability employed by IPCC 2001-2007, summarised by Jurgilevich *et al*, 2017) has previously been performed. The vulnerability assessment characterises the parameters of vulnerability (exposure, sensitivity and adaptive capacity) at each of the mines. This has been completed through a study of supply chain participant responses for each of the mines. This assessment has used the "lessons learned" from past extreme weather events to estimate future vulnerability.

2 Summary of climate projections in mine locations

A simplified review of the historical climate conditions at each the Ranger and Olympic Dam Mines along with climate projections are presented below. Four Representative Concentration Pathways (RCPs) have been considered in this research that include RCP2.6 (Van Veurren *et al*, 2011; Jubb *et al*, 2016), RCP4.5 (Van Veurren *et al*, 2011), RCP6 (Hijioaka *et a*l, 2008), and RCP8.5 (Riahi *et al*,2007).

Due to the uncertainties in the climate projections, the IPCC (2007) developed confidence criteria to qualify the level of certainty of each of the projections. Qualifiers such as '*very high*', '*high*', '*medium*', '*low*' and '*very low*' for each of the RCPs have been defined. The same confidence criteria have been used herein.

2.1 Ranger mine location and climate

The Ranger Mine is located 251.5 km east of Darwin in the Northern Territory. The closest meteorological station to the mine is the Jabiru Airport Station, located 2.7 km away.

In the Darwin region there are three seasons that include a wet season, cyclone season and a dry season (BOM, 2016a; Moise *et al*, 2015). The mean temperatures in this region have increased between 1.0 ^{0}C in the north east and 0.9^{0}C in the north west, for the period 1910-2010 (Moise *et al*, 2015). A warming tendency is expected with *very high confidence* in the future including an increase in minimum and maximum temperatures (Moise *et al*, 2015). In each of the RCP scenarios, increased average rainfall is expected at this location

Extreme high temperature events are expected to increase in magnitude, frequency and duration (Moise *et al*, 2015) with *very high confidence* in all RCPs (Moise *et al*, 2015). Heavy rainfall intensity is expected to increase with *high confidence*, since a warmer atmosphere (in a warmer climate) can retain more moisture (Sherwood *et al*, 2010). However, the magnitude of this change has been estimated with *low confidence* (Moise *et al*, 2015). Cyclone intensity is projected to increase with *medium confidence*, but decrease in frequency (Moise *et al*, 2015). The duration of droughts is projected to increase mainly under RCP 8.5.

2.2 Olympic Dam location and climate

Olympic Dam is situated 15.3 km north of the town of Roxby Downs in South Australia. The closest meteorological station is located at the Olympic Dam Aerodrome 4.4 km from the mine.

Daytime maximum temperatures and overnight minimum temperatures have increased by 0.8^{0}C and 1.0^{0}C respectively since 1910 (Watterson *et al*, 2015). Temperatures are expected to continue to increase at this location, with *high confidence* (Watterson *et al*, 2015). Rainfall projections are highly variable, by 2030 the annual mean variation expected is ± 10% and by 2090 under RCP 8.5 it is expected to decrease 4% (Waterson *et al*, 2015). However, extremes related to rainfall are expected to increase in intensity with *high confidence*, but the magnitude of this change has been estimated with *low confidence (*Waterson *et al*, 2015).

Drought duration is projected to increase with *medium confidence*, however, the change in frequency and intensity has been estimated with *low confidence* under the RCP 8.5. Heat wave frequency, intensity and duration are also projected to increase with a very *high confidence (*Waterson *et al*, 2015*)*.

3 Identification of the Australian Uranium Supply Chain

The literature provides numerous definitions of a modern supply chain (La Londe and Masters; 1994, Mentzer *et al*, 2001; Noémi, 2012; Christopher, 2016). The definitions rely on the physical flow of products from the source (suppliers) to the sink (customer). However, what really provides a competitive advantage is information flow (Sherer, 2005; Walker *et al*, 2007). As a result of this, the approach adopted herein considers the customer as the demand driver (primary source of information) who then passes information to their suppliers (Sherer, 2005; Walker *et al*, 2007). This information

driven approach was used for the identification of the uranium supply chain participants for each of the mines.

3.1 Stakeholders as Supply Chain Participants

In this study, stakeholders have been identified as "people who are adversely or positively impacted by our operations (or) those who have an interest or those who have an influence on what we do" (BHP Billiton, 2009b).

A total of 18 groups of stakeholders for each mine (Olympic Dam and Ranger) have been identified based on historical analysis of company reports (Freeman, 2010), their rights or interests (Walker *et al*, 2007) (including ownership), as well as groups who can be affected or benefit from the activities of the mines (BHP Billiton, 2009b).

It is also important to note that stakeholders' participation and their interests in any supply chain are dynamic and their interests may overlap or be somewhat influenced e.g. a community member may also supply good and services to the mine. For this study, they have been identified based on information available during 2015-2017. The stakeholders identified were categorised after Walker *et al* (2007) and Bessant *et al* (2003).

Mining Group: each of the mines (Ranger and Olympic Dam) have been considered as the leading partner/co-ordinator in each of their supply chains.

Downstream Group: included suppliers, contractors, consultants, and service providers.

External Group: included local community, independent individuals or groups who feel affected by the project, research teams, and invisible stakeholders (e.g. family support network) involved in the delivery project.

Upstream Group: paying customers and end users. These stakeholders were not considered in this study due to a lack of participants responding the survey.

4 Vulnerability Assessment Methodology

Climate vulnerability has been considered a function of exposure, sensitivity and adaptive capacity to climate change (Smit and Wandel, 2006; Füssel and Klein, 2006; Füssel 2007, Pearce *et al*, 2009; Ford *et al*, 2010), which is the approach used by the IPCC 2001-2007. The same conceptual framework for vulnerability assessment that was applied to the Canadian mining industry developed by Pearce *et al* (2009) has been used in this research. This assessment required input from stakeholders which has been collected via survey methods.

4.1 Survey

The survey was designed taking into account similar research in the mining field (Pearce *et al*, 2009; Ford *et al*, 2010). A total of twenty-five questions were prepared (see Annexe A), under five sections: respondents' information, current and future vulnerability, current and future adaptive capacity. Exposure / sensitivity has been assessed through historical parameters such as climate event magnitude, frequency and impacts expected for future parameters based on the RCP scenarios (summarised in Section 2). Scarcity or consumption of resources (e.g. water, energy) and factors that increase vulnerability (e.g. labour market) were considered to estimate the future vulnerability at each of the sites. Adaptive capacity was considered through (a) the evaluation of Risk Management Plans (RMP) and (b) their ability to deal with climate risks both in a reactive and proactive manner, (c) the existence of a vulnerability assessment or a Risk Reduction Plan d) effectiveness of the current RMP to respond to climate change.

A total of 350 persons were contacted to participate in this study and 26 responses were obtained. It should be noted that some participants such as NGO and Services providers belong to both chains. The survey was delivered electronically between February and October of 2016.

4.2 Respondents profile

For the Mining and Downstream groups relevant persons with at least 5 years of experience were identified. In addition, the roles preferred were managers and professional since these individuals were considered the most qualified to provide valuable and reliable input to the study (Delbecq *et al*, 1975; Hsu and Sandford, 2007). In the case of the External Group, the search for relevant persons focused on the service-towns for each mine: Jabiru and Roxby Downs. A summary of the respondents is presented in Table 1.

Table 1: Respondents of the survey

a) Supply chain and External group of stakeholders Ranger Mine

Mining Group	
Management	1
Scientist	1
Total	2
Downstream group	
Mining services	1
Consultant	1
Contractor	1
Total	3
External group	
NGO	1
Community services- education	1
Researcher-Mining	1
Researcher-Animal welfare	1
State Government-Mines and Energy	1
Local Government	1
	6

b) Supply chain and External group of stakeholders of Olympic Dam mine

Mining Group	
Management	1
Management	1
Internal maintenance	1
Engineer	1
Total	4
Downstream group	
Contractor-Transport	1
Contractor	1
Contractor-Electrical	1
Consultant-Environmental	2
Consultant-Project management	1
Consultant-Technical services	1
Mining services	1
Total	8
External group	
Community member-	1
State Government	1
Community services-Local business	1
Community Services- Education	1
NGO	1
Total	5

4.3 Data analysis

The survey data was analysed using the IBM SPSS statistical software (V.22). Fisher's exact test was used to process data for questions containing categorical data values (e.g. types of climate risks, impacts of climate risks or flowed-through impacts), jointly with cross tabulations between the past and future cases. For questions with ordinal data (e.g. rate of exposure or flow-on impacts), the Kruskal-Wallis test was applied. When analysing the data for these tests, values of $p < 0.05$ indicate a significant difference in the distribution of responses between the groups considered (with respect to the rest of the

sample). Values of $p>0.05$ indicate the absence of a significant variation of responses between the groups of participants. Weighted averages of rankings and ratings were used to interpret the responses when the Kruskal-Wallis test did not provide any significant result. A summary of the survey results is provided below.

5 Results

5.1 Consideration of Current Climate Risks

Respondents perceptions of their organisation's current vulnerability to climate events (based on their own experience) was analysed to provide a historical account.

5.1.1 Ranger Mine

The Mining and Downstream groups at the Ranger Mine considered intense rainfall and flooding as the most influential climate events to affect their organisation at the present time, with 100% of respondents in these groups selecting this option. This result is consistent with the data gathered from company reports before conducting the survey. E.g. The supply chain of the Ranger Mine has previously been affected by intense rainfall and flooding. The most serious impacts occurred during 2011 when mining operations were interrupted by flooding for almost five months (ERA, 2012). This event impacted production, decreasing it by 30%, and forced the company to purchase 2126 tonnes of uranium at an estimated cost of AU$253.2 million to meet contract commitments (Pizarro *et al*, 2017).

The External group members most frequently selected storms (66.7%), heat waves, (50.0%) and intense rainfall/flooding (40%) as the most influential climate events. Members of the External group mentioned storms with a higher tendency ($p=0.028$) than members of the other groups in this chain. This may be a result of a reduced capacity to deal with excess water from storms due to their smaller size (compared to the mine), dispersed nature and/or reliance on community infrastructure to complete their business (e.g. roads).

5.1.2 Olympic Dam

The Mining group considered intense rainfall and heat waves (both 75%) and storms (50%) to be the most influential climate events at Olympic Dam. The Downstream group selected intense rainfall/flooding (75%), followed by droughts (37.5%) and heat waves (25%). The External group considered heat waves (80%) to have been the most influential climate event, followed by droughts (40%).

Some differences in responses were detected in this chain. For example, members of the Downstream group did not select storms as a significant climate event ($p=0.048$) unlike other groups of the supply chain. Further, members of the External group did not consider intense rainfall/flooding to have been a relevant climate event, in contrast to other groups in the survey ($p=0.040$). (Annexe A)

Minimal published information associated with the impact of extreme weather events at the Olympic Dam Mine is available. However, BHP Billiton has previously documented that their Olympic Dam mining activities have been adversely affected by weather events (BHP Billiton, 2015). These events have been characterised by variations in water supply and increasing temperatures (BHP Billiton, 2015) that have included extended periods of droughts e.g. the millennium drought and intense rainfall, storms and strong winds (Heavy storm in 2016). These events have caused the temporary closure of the surroundings roads to the mine (Arid Recovery, 2011) impacting the supply chain.

The variation in responses by the participants of the Olympic Dam supply chain seem to support the varied nature and duration of extreme weather events that have occurred and their impact on individual operations.

5.1.3 Discussion

The Mining Group members of both supply chains identified that intense rainfall/flooding is the most influential climate risk that they face, despite the location of both mines being in very different climatic zones – Ranger being tropical and Olympic Dam being arid.

The results of Olympic Dam's supply chain assessment suggest that in arid climates, extreme weather events, such as intense rainfall/flooding have a strong impact on supply chain member's ability to (a) cope with the immediate inundation and (b) project ongoing water reserves for operational activities (e.g. processing). At the Ranger Mine, intense rainfall/flooding results in significant financial impacts due to increased operational cost (pumping) and increased capital costs (increasing the height of tailings storage dams).

On the other hand, heat waves and droughts are common extremes in areas of arid climate (RDA, 2016), particularly relevant for Olympic Dam because of its location in an arid zone, the competitors (e.g. agriculture) for the use of this resource and the future projection of drought duration (section 2.2). Specifically, the mine's location has experienced heat waves, on average, of 94 days per year in the last 30 years, with temperatures over 35°C (Watterson *et al*, 2015).

At either operations, heat waves are perceived to be a health issue by the local government and regulators organisations (Hodgkinson *et al*, 2014; Xiang, 2014; SafeWork SA, 2015). Increased potential for duration and severity of these events, may affect operation production and/or global supply; unless a transition to automation can be made.

5.1.4 Frequency of climate risks

The members of each supply chain estimated different frequencies of climate risks that they had been exposed to. Members of the Ranger Mine supply chain reported a frequency between "twice a year" to "once every 10 years" but the majority (36.4 %) agreed on "once every 3 years". Members of the Olympic Dam supply chain estimated a risk frequency that varied from "three or more times a year" to "less than once climate event in 20 years". However, the majority (23.5%) of the members selected "three or more times a year".

This is a significant frequency of climate-related events at both locations that must be impacting financial performance. Pizarro *et al* (2017) has previously shown that in each of the years, 2007, 2008, 2010, 2011 and 2012, increased capital expenditure at the Ranger Mine can be attributed to costs associated with the impacts of floods and cyclones. Heavy rainfall and cyclone activity intensity are expected to increase with *high confidence* at the Ranger Mine in the future. Heat waves frequency, intensity, and duration are projected to increase with a very *high confidence* at Olympic Dam, increasing the severity of dry climate conditions in the area. As a result of these projections, increased financial impact can be expected that may jeopardise production at these operations and global supply.

5.2 Specific climate impacts at the mine site (present and future)

Mining group respondents of both chains were asked about what aspects of the mining operation were currently (or have been historically) impacted by climate related conditions. The most commonly selected aspects were tailings/waste management facilities (63.6%) and transport within the mine site (54.5%). Ore extraction, processing, and maintenance activities were also identified as having been impacted (45.5%), in contrast with transport outside the mine site (36.4%) and mine planning (9.1%).

A comparison of the historical to the future expectations is not possible due to a lack of survey responses, however, the results can be discussed in isolation. With this in mind, tailings/waste management facilities were most commonly selected as being affected by respondents of the Mining group (66.7%), followed by processing (44.4%), transport within and outside the mine site (44.4%), and ore extraction (33.0%). Respondents were least likely to select maintenance activities (20.0%) and mine planning (11.0%) as being affected in the future. Although there appears to be a difference in both cases (current and future), this may be attributed to the unanswered questions. Nevertheless, it can be

concluded that at each of the mine locations these climate related impacts will continue to affect operational output.

5.3 Exposure (present and future)

Members of each mining supply chain (for Ranger and Olympic Dam) were asked to rate their exposure to the climate risks that they had previously experienced. Respondents were asked to consider several climate risks and estimate their future exposure on a rating scale from 1 (least exposed) to 10 (most exposed).

5.3.1 Ranger Mine

The survey results for the Ranger Mine associated with the rating of exposure to climate risks (current and future) are provided in Table 2.

Table 2: Rating of exposure (present and future) across the supply chain of Ranger mine (qualitative scale of 1 (least exposed) to 10 (most exposed).

	Present n=11					**Future n=11**		
Average rating of exposure	Mining (n=2)			Downstream (n=3)	External (n=6)	Mining (n=2)	Downstream (n=3)	External (n=5)
	Average*	x2 (df=1) #	Asymp. Sig.**	Average*	Average*	Average*	Average*	Average*
Droughts	1.5	0.357	0.55	2.5	2	2	4	3.4
Fires	4.5	0.627	0.428	2.5	2.83	5.5	4	2.75
Heat Waves	4.5	0.004	0.949	3	3.83	5.5	4	4.6
Storms	8	3.22	0.073	5	5.17	7.5	7	4.8
Intense rainfall/flooding	**9.5**	**4.746**	**0.029**	6	4.67	9.5	7.67	4.6
Average score	5.5			4.25	3.33	5.75	5.83	4

* 1: least exposed, to 10: most exposed

#x2 (df=1): Values of the Chi Square Distribution of the Kruskall Wallis Test with 1 degree of freedom.

**Asymp. Sig. = Asymptotic significance

Overall, the members of the Ranger Mine supply chain considered that they are currently are, and expect to become, more exposed to climate-related risks in the future. The greatest risks were considered rainfall/flooding, storms, and heat waves. According to the results shown in Table 2, the Mining group is the most exposed in the present case while in the future it would be the Downstream group.

In the Present, the Mining group had a higher tendency towards rating intense rainfall/flooding the risk than other groups of the chain (Asymp. Sig. =0.029). This is because they have directly faced economic and operational impacts in the past due to climate events (ERA, 2007a; ERA, 2011; ERA, 2012, Pizarro *et al*, 2017). Based on climate projections outlined in Section 2, it is obvious that the mine will be increasingly more exposed (as identified by survey participants) to rainfall/flooding events in the future which may potentially affect operational output and global supply.

5.3.2 Olympic Dam

Results of the average rating of exposure (current and future) across the Olympic Dam supply chain are presented in Table 3. A qualitative scale of 1 (least exposed) to 10 (most exposed) was provided to the respondents to allow an estimation of present and future exposure considering climate change.

Table 3: Average rating of exposure (present and future) across the supply chain of Olympic Dam mine (qualitative scale of 1 (least exposed) to 10 (most exposed)

	Present			**Future**		
Average rating of exposure *	**Mining (n=3)**	**Downstream (n=8)**	**External (n=5)**	**Mining (n=4)**	**Downstream (n=8)**	**External (n=6)**
Droughts	1	3.5	4.2	3	4.43	4.4
Fires	1	3.25	4.2	1.67	5	4.6
Heat Waves	6.33	3.4	5.75	6.5	5.57	6
Storms	5	4.5	3.5	7.67	6.17	4.6
Intense rainfall/ Flooding	4.67	4.75	3.2	8.33	6.75	4.6
Average score	3.6	3.88	4.17	5.67	5.59	4.84

* 1: least exposed, to 10: most exposed

According to the evaluation of respondents, the External group is the most exposed at the present time and Mining group are expected to be the most exposed in the future. The Mining group showed the greatest concern to future climate risks in this study. This coincides with the report by BHP Billiton (2015). The Mining group considered that they are less exposed to droughts (and related fires) than the other two groups, which reflects their confidence in their water management program. The ongoing management of water for the mine will be the main issue to ensure operability since drought conditions are expected to increase at this location in the future (See section 2.2).

5.4 Sensitivity (present and future)

Information was compiled about the general impacts that members of the supply chain have faced due to climate change and how they expect these risks to change in future.

5.4.1 Ranger Mine

Results of a sensitivity (present and future) across the Ranger Mine supply chain are presented in Table 4. A comparison between current versus future results is presented.

Table 4: Climate impacts reported across the Ranger mine supply chain

	Present				**Future**				
Climate impacts	**Mining**	**Downstream**	**External**		**Mining**	**Downstream**		**External**	
	n=2	**n=3**	**n=5**	**p value**	**n=2**	**n=3**	**p value**	**n=6**	**p value**
Financial performance	100.00%	66.70%	0.00%	0.057	100.00%	100.00%	0.141	0.00%	**0.031**
Loss of revenue	100.00%	100.00%	0.00%	**0.015**	100.00%	100.00%	0.225	0.00%	**0.012**
Increased costs	100.00%	66.70%	20.00%	0.136	100.00%	66.70%	0.664	75.00%	0.672
Operational disruption	100.00%	100.00%	60.00%	0.436	100.00%	66.70%	0.521	100.00%	0.365
Delayed production	100.00%	100.00%	20.00%	0.245	100.00%	66.70%	0.5	25.00%	0.295
Quality of production	50.00%	33.30%	0.00%	0.496	50.00%	0.00%	0.761	0.00%	0.688
Supply of essential inputs or services	50.00%	66.70%	0.00%	0.057	50.00%	66.70%	0.371	25.00%	0.437
Transportation of product	50.00%	66.70%	20.00%	0.657	50.00%	33.30%	0.664	0.00%	0.224
Health and safety of workers	50.00%	33.30%	60.00%	0.622	50.00%	0.00%	**0.042**	75.00%	0.514
Infrastructure/ plant & equipment damage	50.00%	33.30%	40.00%	0.699	100.00%	33.30%	0.565	50.00%	0.637
Average	75.00%	66.70%	22.00%		80.00%	53.30%		35.00%	

These results have revealed that the Mining group is the most likely affected by climate risks at the present as well as in the future. Differences between the group responses were detected. For example, in the current case, loss of revenue was not considered a relevant impact (p=0.015) by members of the External group (compared to the other participants). Furthermore, the health and safety of workers was not considered relevant (p=0.042) in the future by members of the Downstream group. Perhaps unsurprisingly, financial performance (p=0.031) together with the loss of revenue (p=0.012) at the mine were not identified as being important to members of the External group. The members of this group are more concerned about the environmental or community damage related to uranium mining operations than they are about economic/operational issues related to climate change as also ECNT (2014) suggested.

5.4.2 Discussion

In this chain, the members of Mining group reported the greatest sensitivity to climate conditions in the past. They also estimated that they would be one of the most sensitive groups to climate change in the future. This result is consistent with the climate projection in the area since heavy rainfall is expected to increase in all RCPs considered. Furthermore, cyclone activity is expected to increase in intensity with *high confidence*. In fact, this group has been severely affected in the past by floods in the operational pit, floods in the Tailings Storage Facilities (TSF), leading to a halt of operations. As a result, planned production has decreased and the financial performance has been affected (ERA, 2007a; ERA, 2011; ERA, 2012, Pizarro *et al*, 2017). However, this group has undertaken adaptation measures such as the commission of a brine concentrator (value at AU$220 million) to improve its water management capability in the wet season.

Downstream group members' responses indicated that they expected the health and safety of workers in the future to be less sensitive than the other groups. This suggests that this group might implement adaptation measures for protecting workers under future climate change such as heat stress training programs. These training programs are expected to ensure operations can continue during climate change.

5.4.3 Olympic Dam

Results of the sensitivity (present and future) across the Olympic Dam supply chain are presented in Table 5.

Table 5: Climate impacts reported across the Olympic Dam mine supply chain

	Present				**Future**			
Climate impacts	**Mining**	**Downstream**	**External**		**Mining**	**Downstream**	**External**	
	n=4	**n=8**	**n=5**	**p value**	**n=4**	**n=8**	**n=4**	**p value**
Financial performance	75.0%	50.0%	0.0%	0.057	75.0%	75.0%	0.0%	**0.031**
Loss of revenue	75.0%	50.0%	40.0%	0.459	75.0%	87.5%	25.0%	0.13
Increased costs	50.0%	62.5%	40.0%	0.459	100.0%	62.5%	50.0%	0.328
Operational disruption	75.0%	87.5%	20.0%	**0.012**	75.0%	87.5%	50.0%	0.179
Delayed production	50.0%	50.0%	0.0%	**0.038**	50.0%	62.5%	25.0%	0.295
Quality of production	0.0%	0.0%	20.0%	0.504	0.0%	12.5%	0.0%	0.688
Supply of essential inputs or services	25.0%	62.5%	40.0%	0.699	50.0%	37.5%	50.0%	0.563
Transportation of product	0.0%	37.5%	0.0%	0.219	25.0%	50.0%	0.0%	0.224
Health and safety of workers	75.0%	37.5%	60.0%	0.622	75.0%	62.5%	75.0%	0.514
Infrastructure/ plant & equipment damage	50.0%	25.0%	40.0%	0.699	50.0%	25.0%	50.0%	0.637
Average score	47.5%	46.3%	26.0%		57.5%	56.3%	32.5%	

The same sequence-rank of groups is repeated in this chain. The Mining group is estimated as the most affected by climate risks in the present and in the future, followed by the Downstream and the External groups. The Mining group considered several items as having been impacted (75%) by climate risks (see Table 5). Regarding the expected future impacts, members of the Mining group agreed that greater climate risks would lead to "increased costs" (100%). They estimate future impacts will be the same as those experienced at present, apart from the supply of essential inputs or services (25% vs 50%) and transportation of product (0% vs 25%).

Operational disruption (87.5%) was the most popular selection in the present by The Downstream group followed by increased costs and supply of essential inputs (62.5%). They reported a varied of increasing tendency towards estimating future likely climate risks, for example, the "quality of production" (impacts on their ability to follow their usual quality-controlled procedures) was considered to be affected in the future (See Table 5). This might be directly related to the water scarcity and droughts which are projected to increase in duration (section 2.2) at the location.

Members of the External group were most likely to select health and safety of workers (60%). In this group, climate-impacts are expected to increase for all cases mentioned except loss of revenue, which decreased from 40% to 25% in future

Differences between group responses were detected e.g. in the current case, members of the External group do not estimate operational disruption ($p=0.012$) and increased costs ($p=0.038$) as relevant climate-related impacts compared with the other two groups. In addition, financial performance ($p=0.031$) was considered to be only of future relevance by the External group**.**

5.4.4 Discussion

Almost all groups reported being sensitive to varying degrees of climate risks in most of the economic and operational impacts. This is particularly relevant if according to climate projections presented in section 2.2, the mean temperature, heat waves and rainfall are expected to increase in all RCPs.

The Mining group was the most sensitive to climate risks at present case. They estimated they would also be the most sensitive out of all the other groups in the future. This group showed more concern about the internal economic impacts such as financial performance, loss of revenue and increased cost in the present and future case compared with the other groups. In contrast, the results discussed by Pearce *et al,* (2009) indicated that uranium mining participants reported to have more concern about external market fluctuations than the internal impacts that can cause the climate change on mining. This included potential impacts to both ore extraction and surface equipment, but it should be noted that the climate in the Canadian uranium mining areas is different to that in Australian uranium mining areas.

The External group of this chain considered there to be lesser impact by climate risks at present than in future. They also showed lower concern over the financial performance and loss of revenue in the present and future case compared with the other two groups. This suggests that the members of this group (mainly community, NGOs and Government representatives) are not concerned about the economic issues related to climate risks, however, they consider health and safety of workers to experience the greatest climate-related in the future.

5.5 Indirect flow-through and flow-on impacts

In order to gather information about indirect climate impacts faced by supply chain members and external stakeholders, respondents were asked about the 'flow-through' and 'flow-on' effects of climate impacts from other organisations. This allowed the identification of which organisations have historically affected their own organisation. In turn, they were likewise asked to identify, under current

climate conditions, what organisations might be affected by 'flow-on' climate events from their own organisation. For this, respondents ranked the alternatives using the scale from 1=most affected to 8 =least affected. The results for each of the chains is presented below.

5.5.1 Ranger Mine

Based on the sum of responses that were "not applicable", "other" and/or "skipped" (45.2%) it was difficult to sort the responses for this chain in a meaningful way. Nevertheless, it was determined that respondents were least likely to select that a Mining company (9.1%) would produce 'flow-through' impacts onto their own organisation under the current climate conditions. Regarding the future conditions, respondents were most likely to select the local community (54.6%) as indirectly affecting their own organisation through climate related risks, followed by Utility companies and the Mining company (both 36.4%). Mining services (27.3%) and Transport companies (18.2%) were least identified as likely to produce flow-through impacts affecting one's own organisation in a future climate event.

The Mining group has been identified as the most affected by flow-on impacts (3.92), followed by the Downstream group. No significant differences between groups were detected in this question. The Ranger Mine has been affected by flow-on impacts in the past, such as flooding of the Arnhem Highway (ERA, 2007a; ERA, 2013c), the Jabiru township (ERA, 2007b) and its surrounding roads throughout Kakadu National Park (ERA, 2008b)

5.5.2 Olympic Dam

External respondents estimated that the most indirect (flow-through) risk affecting their own organisation would be the mining company (70.1 %) and the local community (52.9 %) in the future. Other members of the chain considered their own organisation likely to be affected in the future by transport and utility companies, and mining services, all reporting 41.2%.

The Mining services group was identified as the least affected by flow-through impacts in both the present and future cases. Furthermore, the Mining Company was found to be the most affected by flow-through impacts in the future. This was similarly indicated by Hodgkinson *et al* (2014) where participants of the mining supply chain identified climate impacts on mining infrastructure, transport (ports), and energy (electricity outages). In 2016 Olympic Dam was affected directly and indirectly by a severe storm (extreme rainfall, strong wind, and lighting) (BOM, 2016b), which caused a widespread blackout across the state of South Australia. This storm forced the shutdown of the mine for 15 days and resulted in an economic loss for the mining company of AU$137 million (BHP Billiton, 2017).

The Downstream group of the supply chain of Olympic Dam mine was considered as the most affected (3.03) by flow-on impacts within the chain followed by External group (5.17). Mining services (engineering companies, consulting companies or maintenance companies) belonging to Downstream group have been affected by the increased cost of safety shutdown of critical elements of the mine site, and extra working hours for personnel, when Olympic Dam mine stopped its operations after the severe storm of September 2016 (Burns *et al*, 2016).

Based on the survey results, only one difference in responses between groups was detected to this question. Members of the External group ranked manufacturing as being most likely to be affected (Asymp. Sig. =0.046) by flow-on impacts from their own organisation.

5.6 Factors that can increase future vulnerability

The survey results have revealed that there is concern associated with increasing vulnerability of a range of factors in both of the mine supply chains. These factors include: the age and design of assets, geographical location, type of operation, the frequency of climate events, intensity and magnitude of the events, and impact on labour force availability.

5.6.1 Ranger Mine

The respondents of the three groups within the Ranger Mine's supply chain indicated that geographical location and frequency of climate events were the major factors likely to increase their vulnerability to future climate risk. This is important since both factors cannot to be controlled. For this mine, the design or age of assets was not considered as particularly relevant factors by any group. This may be a result of significant capital investment in the recent years. Some adaptation measures to modify assets have been performed, mainly by the Mining group, including a rise (three times) of the wall of the tailings storage facility, construction of a brine concentrator, and additional pond water storage capacity (ERA, 2012).

5.6.2 Olympic Dam

All of the Olympic Dam supply chain groups identified the frequency of climate events and impact on labour force availability as having the most future vulnerability. Labour force availability can be indirectly affected by an impact of climate change e.g. water scarcity or power outages at the mine site may lead local communities relocating which could cause a deficit in the labour force (Hodgkinson *et al*, 2010) . The design of assets was relevant for members of the Mining group only since this group has already considered the impact of climate change on their infrastructure. For example, the expansion project of Olympic Dam mine considered measures such as additional freeboard in the TSF, levees, and the sea walls in the port facility (BHP Billiton, 2009a).

5.7 Increase of resources required in light of climate change

Respondents were asked to indicate any increase in resources they might expect in the future in response to climate change. Resources were clarified as being water, energy, inputs (materials and equipment), labour, infrastructure, technology, and knowledge and expertise.

5.7.1 Ranger Mine

The Mining group of this chain most frequently indicated that their energy needs would increase (100%), followed by labour, technology, and knowledge/expertise (50% each). In the Downstream group, the most popular resources nominated were water, energy, infrastructure, technology and knowledge/expertise. However, it was not possible to sort these into a descending order as they were all selected an equal number of times (50%). The External group (e.g. community) most commonly selected energy (40%) as the resource most likely to increase in the future as a result of climate change. This may be directly attributed to their personal knowledge of how energy plays an important role in their own lives. E.g. electricity for lighting, cooling; fuel for transportation, heating, and cooking. None of the groups indicated that the demand of Inputs (materials and equipment) would be expected to increase in the future.

5.7.2 Discussion

All the members of the chain agreed that energy is the most likely resource required in the future to increase. However, based on ERA (2013b) there was no forecast variation in energy consumption even when the underground mine expansion was considered. It is expected in this case that Rio Tinto (2016) has committed to energy-efficiency measures e.g. trials of new technology to its operations (Rio Tinto, 2014; Rio Tinto, 2016). Furthermore, as part of the increasing need for knowledge/expertise and understanding about climate change, the Australian Government has prepared adaptation/strategy plans for the surrounding region such as Kakadu National Park (AG, 2010) and the local government has undertaken adaptation plans (2010-2020) for the local community (WASC, 2010).

5.7.3 Olympic Dam

All members of the Olympic Dam supply chain agreed that the need for water, energy, labour, and knowledge/expertise resources may increase in the future. In addition to these, the Downstream group members also considered that improved infrastructure would be required. Overall, members of both

supply chains estimated an increase in demand of almost all resources in the future. Similar to the Ranger Mine results, a potential increase in Inputs (including materials and equipment) was dismissed by all respondents.

5.7.4 Discussion

Water scarcity can impact the productivity of a mine, especially in the case of Olympic Dam where there is little surface water in close proximity to the operations. Considering the mean annual rainfall is expected to decrease in the future at this location, this could have a significant impact on the operations. Both the mine and nearby towns (Roxby Downs, and Andamooka) rely on groundwater extracted from the Great Artesian Basin (Torrisi and Trotta, 2013). Olympic Dam has implemented a plan for sustainable water use, which includes a water efficiency program to reduce water demand (Torrisi and Trotta, 2013). In addition, the local community has been advised on water saving and water sustainability (Roxby Downs Council, 2014).

The most commonly occurring extreme weather event at the mine's location is heat waves during the summer, resulting in an increase (by almost 70%) in electricity consumption (Pilli-Sihvola *et al*, 2010; ESAA, 2015). Heat waves are expected to increase in frequency, intensity and duration in this area (Watterson *et al*, 2015) leading to higher electricity consumption as cooling becomes a priority. Olympic Dam is the largest single client of Electranet (the distribution company in South Australia). Olympic Dam's annual electricity consumption is about 7% of the total electricity consumption in South Australia (BHP, 2009c), having a significant impact on the increase in electricity demand during a heat wave.

Energy and water resource supplies may be affected by extreme weather events in the future, and subsequently, the mine's operations since uranium mining is an energy and water intensive operation (Schneider *et al*, 2013). The survey's results confirm the concern for these two resources (water and energy) that may become stressed in the future as a result of climate change and affect the ability to maintain sustainable uranium mines.

5.8 Current adaptive capacity

The current adaptive capacity of organisations was assessed by asking respondents to rate a range of items in their Risk Management Plan (RMP) with a qualitative scale from 0: low to 10: excellent. In addition, there were questions posed about their organisation's approach (proactive or reactive) to deal with climate risks (results expressed in percentages), whether a vulnerability assessment and a risk reduction plan had been undertaken, and the identification of opportunities from climate change.

5.8.1 Ranger Mine

The results of the evaluation of the RMP across the supply chain of the Ranger Mine are presented in Table 6.

Table 6: Evaluation of the Risk Management Plan across the supply chain of Ranger mine based on a qualitative scale of 1 (poor) to 10 (excellent).

Evaluation of the Risk Management Plan (RMP). Scale of 1 (poor) to 10 (excellent).	**Mining (n=2)**			**Downstream (n=2)**	**External (n=4)**
	Average*	**x2 (df=1)#**	**Asymp. Sig.****	**Average***	**Average***
How well identified are the key climate-related risks in the Risk Management Plan (RMP)?	5	0.85	0.36	6.5	7
How relevant/specific is the RMP to the actual site or operation?	8	0.33	0.56	6.5	8
How adequate are the current risk mitigation procedures and response/contingency plans?	8.5	0.6	0.44	7.00	7.25
How clear are the different positions, roles and responsibilities of the personnel required to respond to the event?	9	1.28	0.26	6.5	8
How clear are the guidelines and procedures to follow in the case of a climate event?	9	0.67	0.41	6	7.75
How well is the RMP communicated to staff?	6.5	0.28	0.6	7	7.25
How regularly is the RMP updated?	7.5	0.12	0.73	7.5	7.5
How effective is the communication between the other companies/organisations related with your company e.g. Energy, Water, and Transport, Communication Company or other?	3.5	**4.16**	**0.04**	5.5	7.75
Average score	7.17			6.56	7.56

* 1 poor, to 10 excellent
#x2 (df=1): Values of the Chi Square Distribution of the Kruskall Wallis Test with 1 degree of freedom.
**Asymp. Sig. = Asymptotic significance

According to these results, the External group gave the highest overall score (7.56) for their RMP, followed by the Mining (7.17) and Downstream (6.56) group. The effective communication between companies related was considered the weakest item in their RMPs by Mining (3.5) and Downstream (5.5) group. In the case of Mining group, ERA has undertaken stakeholder engagement programs for other purposes e.g. expansion plan to mine underground (ERA, 2013a), so the adaptive capacity to communicate with related companies exists - it just needs to be mobilised in this case.

Regarding to the approach to deal with climate-risks, members of the External group stated they have a proactive approach (83.3%), however no members of this group indicated their organisation had conducted a vulnerability assessment or had developed a risk reduction plan. Due to the high percentage of "unsure" responses in the previous questions (60.0% and 66.6% respectively), it may be inferred that there is a lack of knowledge about these two concepts. This group did not identify any opportunities that may arise from climate change for their business.

The Mining group identified that they have a proactive approach when dealing with climate risks (100%) and know about the vulnerability assessment (50%) and risk reduction plans in place (50%). However, similar to the External group, they did not identify any opportunities that may be derived from climate change. Further, members of the Downstream group reported to have mainly a proactive approach (66.66%) to deal with climate risks. However, 66.66% of respondents reported that they did not have a vulnerability assessment and a risk reduction plan within their operations.

5.8.2 Discussion

Taking into account the evaluation of the RMP, the approach to dealing with climate risks and the existence of a vulnerability assessment and a risk reduction plan, it seems that the Mining group of this chain is the best prepared to meet climate change challenges. The Downstream group appears to be the least prepared although the reason for this is not clear. This group consists mainly of contractors and consultants, and while they may be small organisations, they are required to comply with the same requirements in all aspects as the outsourcing companies as was stated by ERA (2007b). In addition, in 2005 ERA undertook a program to upgrade the contractor's management system, which included the assessment of critical risks (ERA, 2007b). The results of this research presented herein, suggest that compliance may have slipped in the decade since this program was undertaken.

5.8.3 Olympic Dam

The results of the evaluation of the Risk Management Plan across the supply chain of the Olympic Dam Mine are presented in Table 7.

Table 7: Evaluation of the Risk Management Plan across the supply chain of Olympic Dam mine based on a qualitative scale of 1 (poor) to 10 (excellent).

Evaluation of the Risk Management Plan (RMP). Scale of 1 (poor) to 10 (excellent).	**Mining (n=4)**	**Downstream (n=8)**			**External (n=4)**
	Average *	**Average ***	**x2 (df=1)#**	**Asymp. Sig.****	**Average***
How well identified are the key climate-related risks in the Risk Management Plan (RMP)?	7.75	5.88	1.21	0.27	7.33
How relevant/specific is the RMP to the actual site or operation?	8.5	**6**	**5.7**	**0.02**	8
How adequate are the current risk mitigation procedures and response/contingency plans?	8.25	7.13	0.27	0.6	7.25
How clear are the different positions, roles and responsibilities of the personnel required to respond to the event?	8.5	7.38	0.11	0.74	7.25
How clear are the guidelines and procedures to follow in the case of a climate event?	8.5	7.13	0.35	0.55	8
How well is the RMP communicated to staff?	7.75	7	0.08	0.78	7.33
How regularly is the RMP updated?	7.5	6.13	1.23	0.27	6.67
How effective is the communication between the other companies/organisations related with your company e.g. Energy, Water, and Transport, Communication Company or other?	6	6.63	0.34	0.56	5.75
Overall average rating	7.84	6.58			7.19

* 1 poor, to 10 excellent
#x2 (df=1): Values of the Chi Square Distribution of the Kruskall Wallis Test with 1 degree of freedom.
**Asymp. Sig. = Asymptotic significance

The highest overall average rating for their RMP (7.84) was provided by the Mining group. They also gave the highest score for individual items identified in the question except for effective communication between related companies, which was the lowest score (the same response as Ranger Mine). Members of the External group gave an overall rating average of 7.19. Communication between companies was once again identified as with the lowest score (5.75) in this group. Downstream group gave the lowest overall rating (6.58) to their RMP and also the lowest rating for any single item of the plan, namely the relevance of the RMP to their situation (6.00).

Respondents of Mining group stated they had a mainly proactive approach (75%) for dealing with climate risks, they have performed a vulnerability assessment (50%), they have a risk reduction plan (50%) and they have identified potential opportunities from climate change (25%). Members of the External group reported a mainly reactive approach (60%) to dealing with climate change, with the highest percentage of "unsure" responses in the chain regarding the existence of a vulnerability assessment, risk reduction plan and identification of opportunities (60%, 80% and 60% respectively).

Members of the Downstream group reported having both a proactive and reactive approach (50% for each). They also provided a strongly negative response to the existence of a vulnerability assessment and a risk reduction plan (both 87.5%). They have not identified operational opportunities from climate change. Further, members of Downstream group reported more concern (Asymp. Sig. =0.02) about the relevancy of their RMP for the site of operation, explaining the lower rating compared to the other groups.

5.8.4 Discussion

Based on the previous results, it seems that the Mining group is the best prepared in this supply chain. This group gave a good rating for their RMP, they have mainly a proactive approach, they have knowledge about a vulnerability assessment and a risk reduction plan and they were the only group that identified opportunities that may arise from climate change although those opportunities were not specified. Some members of this group stated that "climate change is well understood" or "vulnerability assessment will be complete in 2016".

In contrast, the Downstream group appears to be the worst prepared to face climate risks: this group gave the lowest overall score to their current RMP. Members of this group reported a high percentage of "no" answers to the questions relating to the existence of a vulnerability and risk reduction plan. This suggests there may be a lack of knowledge of these concepts driven by poor communication or there may be no plans. This is confirmed by direct comments from respondents such as "have not heard about this". They were unsure in the identification of opportunities, which also supposed a lack of knowledge in this matter.

5.9 Future adaptive capacity

In order to estimate the current supply chain's future adaptive capacity, the respondents were asked to provide an overall rating of their RMP with respect to how well it would cope with greater future climate risks. The comparison between the current cases versus future is presented below.

5.9.1 Ranger Mine

Similar to the previous highest overall rating given by the Ranger Mine, External group members also gave the highest overall rating for the future adaptive capacity. However, the External group's rating of their RMPs for future conditions was lower than for current conditions (7.56 current versus 6.00 future). The Mining group also gave a lower score for their RMP for coping with future events than they did for current conditions (7.17 versus 5.50). This result is in contrast with the estimated by ERA (2012), where the company stated they are confident they will be able to manage future climate events.

The Downstream group again returned the lowest overall score (6.56 vs 4.33). Nevertheless, some members of this group, such as Ports or Rail, present a proactive approach to dealing with climate risks and climate change (Darwin Port Corporation, 2012; ARA, 2012).

5.9.2 Discussion

Based on the previous results, the External group of this supply chain might have the best RMP to face climate change. In fact, members of this group (e.g. Government organisations) have shown increased interest and concern to bring climate change concepts to all communities in an attempt to increase their adaptive capacity. Until a few years ago, indigenous communities showed a lack of, or unclear,

knowledge about climate change (Petheram *et al*, 2010). More recently, programs administered by national and local government have provided climate change adaptation advice such as the climate change action plan NTG (2011), the Flood Mitigation Advisory Committee (NTG, 2015) or the Kakadu National Park: Climate change Strategy (AG, 2010) provided knowledge to communities.

5.9.3 Olympic Dam

For the Olympic Dam mine supply chain, the Mining group again returned the highest RMP score, even though the score given for handling future conditions was lower (current 7.84 vs future 7.00). This was followed by the Downstream group (current 6.58 vs future 6.38) and the External group returned the weakest RMP score for coping with future conditions (current 7.19 vs future 6.00). According to these results, the Mining group may be the best prepared for climate change followed by the Downstream group. In fact, members of Downstream group such as Ports have undertaken several measures to reduce the risks of climate change, including a vulnerability assessment for the region and the identification of adaptation measures such as AdaptWest (2015) and; AdaptWest (2016).

5.10 Changes needed to improve the adaptive capacity

5.10.1 Ranger Mine

The members of the Ranger Mine supply chain considered changes that might be needed to improve adaptive capacity. The results are provided in Table 8.

Table 8: Changes posed across the supply chain of Ranger mine

Changes posed in the question	**Mining**	**Downstream**	**External**	**P**
	n=2	**n=3**	**n=4**	**Value**
Management procedures	50.00%	0.00%	75.00%	0.233
Administrative procedures	0.00%	0.00%	75.00%	**0.04**
Operational procedures*	100.00%	33.30%	100.00%	0.224
Work practices	0.00%	0.00%	75.00%	0.178
Technical changes	100.00%	33.30%	25.00%	0.672
Management approach/leadership	50.00%	33.30%	25.00%	0.593
Not applicable	0.00%	33.30%	0.00%	0.563
Other (please specify)	0.00%	0.00%	0.00%	0.833
Average score	37.50%	16.70%	46.90%	

* Operational procedures include mechanical, extraction and processing operations of the mine, contractors and consultants in addition to those of local organisations procedures required to operate.

The Mining group were most likely to select operational procedures and technical changes as needed to improve adaptive capacity. The Downstream group selected operational procedures, technical changes, and management approach with equal frequency (33.3%). The External group identified operational procedures with greatest frequency (100%), followed by management procedures, administrative procedures and work practices (all 75%). Further, members of the External group selected administrative procedures in a higher proportion (p=0.04) than the other groups. They also enumerated the highest number of changes required to improve the future adaptive capacity.

5.10.2 Discussion

All members of this chain selected operational procedures as the most important change required to improve their adaptive capacity. Operational procedures include mechanical, extraction and processing operations of the mine, contractors and consultants in addition to those of local organisations procedures required to operate. It was suggested that this change can be achieved by modifying the current risk identification processes, considering the cumulative impact of climate risks over the infrastructure, implementing measures that address the risks identified, monitoring the risks and identifying measures to ensure they are suitable and developing local climate projections to evaluate potential risks as Mason and Giurco (2013) suggested. Further, Rio Tinto has recognised the value of integrating climate change factors into its business management and planning (C2ES, 2013), which can facilitate this operational change.

For members of the External group (mainly NGOs, Government organisations and communities) administrative and management procedures are a matter of concern if they do not change in the future. This is because administrative procedures can facilitate or impede adaptation to climate change (Productivity Commission, 2012; Hussey *et al*, 2013). In addition, local government has already discussed the high vulnerability to climate change and that it is important to adapt at all levels (government, business, communities and individuals) (WASC, 2010). As a result of this national, state and local government organisations have been preparing adaption plans and engagement activities with community members (e.g. BMT WBM, 2010; Darwin City Council, 2011).

5.10.3 Olympic Dam

The members of the Olympic Dam supply chain and the External group estimated that changes in all aspects posed in the question are required (in different percentages) as can be seen in Table 9. However, operational procedures were selected by the three groups with the highest percentage in each group.

Table 9: Changes mentioned across the supply chain of Olympic Dam mine

Changes posed in the question	**Mining**	**Downstream**	**External**
	n=4	**n=8**	**n=4**
Management procedures	50.00%	37.50%	50.00%
Administrative procedures	25.00%	25.00%	25.00%
Operational procedures*	75.00%	75.00%	50.00%
Work practices	75.00%	37.50%	25.00%
Technical changes	25.00%	12.50%	25.00%
Management approach/leadership	25.00%	37.50%	25.00%
Not applicable	0.00%	12.50%	25.00%
Other (please specify)	25.00%	0.00%	0.00%
Average	**37.50%**	**29.70%**	**28.10%**

* Operational procedures include mechanical, extraction and processing operations of the mine, contractors and consultants in addition to those of local organisations procedures required to operate.

5.10.4 Discussion

Some members of this chain have already taken action to trigger changes to their operational procedures. For example, BHP Billiton integrated climate change into its expansion planning process for the Olympic Dam mine (although expansion planning was postponed in 2012), including analysis of the climate projections for the project location and how they can affect the operational procedures and the physical impacts of the operations (BHP Billiton, 2009a; BHP Billiton, 2015). Furthermore,

they have analysed and assessed how to increase the business resilience in response to climate change. Changes have been made to operational procedures (BHP Billiton, 2015) such as a sustainable water usage (Torrisi and Trotta, 2013), energy efficiency use, low emission technologies, and training (BHP Billiton, 2015). The local government of South Australia has prepared vulnerability assessment and adaptation planning reports, which included members of this supply chain such as Mining, Roxby Downs community, and Transport (Port Augusta, Roads and Railways) (Hodgkinson *et al*, 2014; RDA, 2016).

6 Conclusions

This research has analysed the vulnerability that the uranium supply chains in Australia have to climate change. This study has shown that both supply chains have the capacity to respond to current climate risks. However, the capacity to anticipate future climate risks, including a vulnerability assessment or risk reduction plan appears to be very limited. The vulnerability assessment revealed the different aspects of sensitivity (direct and indirect) to climate change in both supply chains with a special focus on the impacts on mining companies. It was shown that vulnerabilities are location-specific. The most vulnerable group for the future was identified as the Mining group in both chains. They were also identified with the greatest capacity to adapt. At both locations, the least prepared group is the Downstream group suggesting that these groups may require the most assistance to reduce their vulnerability.

Based on the RCP scenarios, it likely that in all scenarios that there should be an expected increase in rainfall intensity at the Ranger Mine and decrease in rainfall at Olympic Dam. Based on the results of the survey, it is evident that both of these locations have been impacted by severe storms and drought in the past resulting in increased operating costs and lost revenue. This study has revealed that the adaptive capacity across the uranium supply chain might require some changes at different levels (operational and administrative), especially in administrative procedures which are perceived as a constraint to be better prepared to face climate change. It was shown that the chains are strongly connected and weaknesses within any of the links can have flow-on impacts to others that may negatively impact the whole chain. It has been revealed that the communication between companies is the weakest item within the Risk Management Plans and this is certainly an easy area to improve. There is a need for a more in-depth study to identify specific adaptation needs and options that can be implemented across the chains.

The requirement to identify and implement adaptation options at these locations (Ranger Mine and Olympic Dam) is imperative to secure the global uranium demand. With these mines currently supplying 12% of the world demand, and an expected increased potential in the future, the impacts of climate change on daily operations are required to be considered to avoid / revert to reliance on more polluting energy sources around the globe.

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ANNEXE A

Survey questionnaire

1.What kind of company/organisation do you work for? Please select all that apply.

Answer Options
Mining Company
Mining services (engineering, maintenance, scientific & technical, drilling, labour hire, etc)
Contractor
Consultant
Mining supplies (materials, chemicals or equipment)
Water supply
Energy supply - fuel
Energy supply - gas
Energy supply - electricity
Telecommunications
Transport - roads, trucking
Transport - rail
Transport - air
Transport - ports, shipping
Government - local
Government - state
Government- federal
Community services (health, education, police, emergency, welfare, etc.)
None (member of public/local community)
Other (please specify)

2. Which best describes your role/position in the company/organisation/community?

Answer Options
Management
Engineer
Scientist
Operational worker
Administrative staff
Community member
Other (please specify)

3. How many years of experience do you have in your industry/organisation?

4. If you are a community member near the uranium mine, how many years have you lived there?

5. In which state is your company/organisation or community based/located?

Answer Options
Northern Territory (NT)

Queensland
New South Wales
Victoria
South Australia
Tasmania
Western Australia
Australian Capital Territory (ACT)

6. From your experience, what are the most influential climate conditions that most affect your company/organisation/community? Select one or more.

Answer Options
Droughts
Fires
Heat waves
Storms
Intense rainfall/Flooding
Other (please specify)

7. Based on your own experience or historical knowledge, how often have these climate risks affected your company/organisation/community?

Answer Options
Less than once in 20 years
Once every 20 years
Once every 10 years
Once every 5 years
Once every 3 years
Once a year
Twice a year
Three or more times a year
Other (please specify)

8. On scale of 1 to 10 (where 1 is Low and 10 is High) how would you rate your company/organisation/community risks exposure to climate conditions you selected in question 6?

Answer Options	Low 1	2	3	…	9	High 10
Droughts						
Fires						
Heat waves						
Storms						
Intense rainfall/flooding						
Other						

9. How have the climate events identified in question 6 impacted your company/ organisation/community? Select all that apply.

Answer Options
Financial performance
Loss of revenue
Increased costs
Operational disruption
Delayed production
Quality of production
Supply of essential inputs or services (water, energy, telecommunications, labour, materials etc.)
Transportation of product
Health and safety of workers
Infrastructure/ plant & equipment damage
Other (please specify)

10. What aspects of the mining operation has been most affected by the climate events identified in question 6? Select the main risk areas.

Answer Options
Ore extraction
Processing
Transport within the mine site (e.g. access and haulage roads)
Transport outside the mine site (e.g. road, rail, port)
Tailings/ waste management facilities
Mine planning
Maintenance activities
Exploration
Other (please specify)

11. Have climate events that have impacted other organisations flowed-through to affect the operation of your company in the past? If yes, please specify what type of organisation has impacted you. Select all that apply.

Answer Options
Mining Company
Local community
Mining Services (engineering, maintenance, scientific & technical, drilling, labour hire etc)
Transport company
Utilities company (water, energy, telecommunications etc)
Not Applicable
Other (please specify)

12. If your company/organisation/community is affected by the climate events you selected above, which organisations or sectors (identified below) would be most affected by your situation? Could you rank them (i.e. 1 = most affected to 8= least affected)?

Answer Options
Mining Company
Local community
Construction
Manufacturing
Transport company
Customer company
Mining Services
Surrounding environment

13. If the climate condition/climate risks identified in question 6 become greater in the future (i.e., an increase in frequency, magnitude, duration and/or extent), how would you rate the impact to your company/organisation/community in the future?

Answer Options	Low 1	2	3	…	9	High 10
Droughts						
Fires						
Heat waves						
Storms						
Intense rainfall/flooding						
Other						

14. Which of the following factors would increase the vulnerability to climate conditions/climate risks in the future for your company /organisation/community? Select all that apply.

Answer Options
Age of the assets
Design of the assets
Geographical location
Type of operational process or method used
Frequency of climate events
Intensity and magnitude of climate events
Impact on labour force availability or productivity
Other (please specify)

15. How would an increase in the frequency or severity of climate events identified in question 6 impact your company/ organisation/community? Select all that apply.

Answer Options
Financial performance
Loss of revenue
Increased costs

Operational disruption
Delayed production
Quality of production
Supply of essential inputs or services (water, energy, telecommunications, labour, materials etc.)
Transportation of product
Health and safety of workers
Infrastructure/ plant & equipment damage
Other (please specify)

16. What aspects of your mining operation would be impacted the most if climate events identified in question 6 increase in the future? Select the main risks areas.

Answer Options
Ore extraction
Processing plant
Transport within the mine site (e.g. access and haulage roads)
Transport outside the mine site (e.g. road, rail, port)
Tailings/ waste management facilities
Mine planning
Maintenance activities
Exploration
Other (please specify)

17. Do you think climate change could increase the demand for any resources used by your company/organisation/community? Select all that apply.

Answer Options
Water
Energy
Inputs (materials, equipment, etc.)
Labour
Infrastructure
Technology
Knowledge/expertise
Not applicable
Other (please specify)

18. Which company/organisation/community impacted by future climate conditions/climate events could lead to flow-on impacts that affect your organisation the most? Select the main ones.

Answer Options
Mining company
Local community
Mining services (engineering, maintenance, scientific & technical, drilling, labour hire etc)

Transport company Utilities company (water, energy, telecommunications etc) Other (please specify)

19. Regarding the current climate conditions/climate risks identified in question 6, please rate the preparedness of the current risk management plan of your company/organisation/community.

Answer Options	Poor 1	2	...	Excellent 10
How well identified are the key climate-related risks in the Risk Management Plan (RMP)?				
How relevant/specific is the RMP to the actual site or operation?				
How adequate are the current risk mitigation procedures and response/contingency plans?				
How clear are the different positions, roles and responsibilities of the personnel required to respond to the event?				
How clear are the guidelines and procedures to follow in the case of a climate event?				
How well is the RMP communicated to staff?				
How regularly is the RMP updated?				
How effective is the communication between the other companies/organisations related with your company e.g. Energy, Water, and Transport, Communication Company or other?				

20. How would you classify the general approach of your company/organisation/community to dealing with climate related events?

Answer Options
Reactive Proactive (anticipatory, preventive) Other (please specify)

21. Has your company/organisation/community performed a climate change vulnerability assessment?

Answer Options
Yes No Unsure If no, why not?

22. Was a risk reduction plan developed to respond to the vulnerability assessment?

Answer Options
Yes No Unsure If no, why not?

23. Were any opportunities from climate change identified?

Answer Options
Yes No Unsure If yes, could you mention some of them.

24. If the climate risks identified in question 6 become greater in the future (i.e., an increase in frequency, magnitude, duration and/or extent), how would you rate your current risk management plan to cope with these changes?

Poor 1	2	3	4	5	6	7	8	9	Excellent10

25. What types of changes do you think are required to improve the adaptive capacity of your company/organisation? Select all that apply.

Answer Options
Management procedures Administrative procedures Operational procedures Work practices Technical changes Management approach/leadership Not applicable Other (please specify)

Appendix IV: Published Paper

Australian uranium industry climate change vulnerability assessment

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Australian uranium industry climate change vulnerability assessment☆

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ABSTRACT

Australia holds 31% of the global uranium resources and currently supplies 12% of the worldwide market. Based on the expected increase in global energy consumption, the demand for uranium is projected to increase, and Australia is well positioned to ensure it remains a significant supplier in the market. However, due to future climate change, the local uranium industry may be impacted as more intense and more frequent extreme weather events are expected, leading to potential disruption to operations and damage to mining infrastructure. Therefore, Australia's reputation as a reliable industry supplier may be at risk in the future. This paper conducts a review of the vulnerability of the Australian uranium industry to climate related impacts, based on surveys conducted around currently operating uranium mines. Operational disruptions, loss of revenue and increased costs have all been reported as existing impacts by major climatic events. Survey respondents identified tailings/waste storage facilities, ore extraction, processing, transport within the mine site and maintenance activities as the most affected. Through this research, critical aspects to improve the adaptive capacity of the industry have been revealed.

1. Introduction

1.1. The australian uranium industry

The mining industry's contribution to the Australian economy has historically been high: for example in 2015 it represented 46% of the total value of Australian exports (ABS, 2016). As a source of energy, uranium is a small part of this trade comprising just .8% of the total value of exports; however it represents 16.5% of the total energy exported from Australia in 2014–2015 (AG, 2016). Australia is the world's third largest producer, behind Kazakhstan and Canada (World Nuclear Association, 2016a). Australia has 31% of the world's known uranium reserves, and supplies 12% of world uranium demand (MCA, 2016). At the present time, all of Australia's uranium output is exported to Asia, Europe and North America. Australia's volume of uranium exports is expected to increase by 9.9% during 2017–2018, in line with demand. This comes after a decrease of 6.8% in 2016–2017 (AG, 2017). The expected nuclear energy demand has been recently impacted by:

- The devastating earthquake and tsunami in 2011 that resulted in the Fukushima Daiichi incident. This incident contributed to reducing uranium demand worldwide and increased the costs of construction of power plants due to increased safety requirements

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Fig. 1. Current, former, and prospective uranium mines in Australia. (Source: WNA, 2016a).

and higher discount rates for investments in nuclear energy (Hayashi and Hughes, 2013)

- Higher costs of initial investment, technical/knowledge expertise in nuclear plant operations and more stringent market and regulatory requirements with local governments and worldwide agreements (IEA, 2011)
- A lack of worldwide agreement regarding the long term storage and treatment of nuclear waste (Bruckner et al., 2014)
- A trend of declining uranium spot prices in the last 6 years, with possible increases in future prices still dampened by the accumulation of inventories and abundant supply (AG, 2017).

Nevertheless, there are currently 66 reactors under construction, 160 planned and 300 in the proposal stages (WNA, 2016b). While Australia does not produce nuclear energy itself, the worldwide increase in nuclear power facilities offers a significant opportunity for the Australian uranium mining industry.

Uranium has been mined in Australia since 1954. During 2016, there were three Australian uranium mines operating: Energy Resources of Australia's (ERA) Ranger mine located in the Northern Territory, BHP Billiton's Olympic Dam and Four Mile mines, located in South Australia (WNA, 2016a). Their locations are presented in Fig. 1.

In 2015–2016, the majority of Australian uranium production (80.27%) was from the Ranger and Olympic Dam mines. Historically, these mining operations have been impacted differently by climatic conditions in both direct and indirect ways due to the nature of their operations (open pit and underground respectively).

At the Ranger mine, production and safety have been directly influenced by extreme rainfall. Olympic Dam has been indirectly affected through energy interruptions during heat waves and scarcity of water during prolonged periods of drought (BHP Billiton, 2009b, 2012; Torrisi and Trotta, 2013; Toledano and Roorda, 2014). For example, during 2016, an unusually heavy storm impacted operations at Olympic Dam mine that caused shutdown of the mine for 15 days due to energy supply issues (BHP Billiton, 2016).

Both mines have documented the financial impact of extreme weather events to their operations in recent years (BHP Billiton, 2009b, 2012, 2015; Rio Tinto, 2012; ERA, 2013b) and they have considered climate change in their expansion plans (BHP Billiton, 2009a; ERA, 2013b).

1.2. Climate change adaptation in mining

Climate change scientists suggest that extreme weather events (primarily heat waves) would increase in frequency in South Australia and cyclones will increase in intensity in the Northern Territory by 2030 (Watterson et al., 2015a, 2015b; Moise et al., 2015; Reisinger et al., 2014). Loechel et al. (2013a, b) have previously documented the disruption to the Australian mining industry caused

by extreme weather events including drought, heat waves, and heavy rainfall. They also report that only a limited number of mining industry survey participants recorded that they were concerned about future climate change and the potential impact on their operations. At the time, mines were more concerned with developing mitigation measures to reduce their emissions (Loechel et al., 2013b).

Three years on, in 2016, some mining companies have accepted climate change as being a significant risk to their operations (Rio Tinto, 2015; BHP Billiton, 2015). This suggests that proactive adaptation measures may be necessary in order to ensure business continuity in the light of climate change (Hodgkinson et al., 2010; BSR, 2011) within mine operations plans. Without climate change adaption strategies in place, production may be adversely affected, impacting on the world uranium supply chain. Therefore, there is a growing need to assess how climate conditions and climate risks have impacted the industry to date and how they may impact it in the future. For this purpose, a vulnerability assessment of the industry has been performed focusing on the current uranium operations at the Ranger and Olympic Dam mines.

Analysis of public domain company reports (full annual reports and sustainability reports) from both the Olympic Dam, and Ranger mine was conducted in order to identify how they have been affected by climate risks and if they have taken any approach to deal with future climate risks.

1.3. The concept of vulnerability assessment

Vulnerability to climate change, as conceptualised by Ford and Smit (2004), Smit and Wandel (2006), Ford et al. (2009), Pearce et al. (2009), and Pearce et al. (2011) can be considered a function of exposure/sensitivity and adaptive capacity. Pearce et al. (2009) have defined components of vulnerability for the mining industry that have been applied in this study. They are provided below:

Exposure/sensitivity: the tendency of mining operations to be affected by climate conditions assessed by parameters including frequency, magnitude, location and impacts.

Adaptive capacity: the ability of the mining company to plan towards changing their operations to suit climate conditions. This involves the identification and characterisation of the current risk management plan's ability to cope with climate risks.

Nelitz et al. (2013) have defined a vulnerability assessment as the process of measuring or characterising exposure, sensitivity and adaptive capacity of a system (natural or human) to any disturbance. Two approaches used to assess vulnerability include a top-down approach and a bottom-up approach (Nelitz et al., 2013). The top-down approach is focused on global climate models and their downscaling of projections that are used as inputs to project regional climate impacts and to evaluate the physical vulnerability (Nelitz et al., 2013). The bottom-up approach focuses on understanding the past and present vulnerability that is used to estimate future vulnerability and adaption options in order to reduce the future vulnerability (Nelitz et al., 2013). Both approaches have different emphasis or perspectives but are complementary (Dessai and Hulme, 2004).

In this study the bottom-up approach has been applied based on the input of stakeholders to evaluate both social and physical vulnerabilities (Nelitz et al., 2013). Predictive biophysical models have been replaced by stakeholder feedback that has been collected via survey methods.

2. Historical impacts of climate and extreme weather events

This section describes the climate characteristics and historical record of the main climate events that have affected the region where each mine is located. It also reviews expected future climate conditions, based on downscaled projection provided by the Intergovernmental Panel on Climate Change and Reisinger et al. (2014). These projections are based on the downscaling of Global Climate Model (GCM) simulations for each RCP scenario to the particular conditions of each area. A confidence language has been specified by IPCC (2007) for climate projections, that employs the follows qualifiers '*very high*', '*high*', '*medium*', '*low*' and '*very low*' for confidence of projections.

2.1. Ranger mine

Based on the division of Australia into Natural Resource Management (ANRM) regions, the Ranger mine is located in the area described as the Monsoonal North West sub-cluster[1] (Moise et al., 2015; CCA, 2015).

There are two well-defined seasons in this area that include a wet season, from October to April and a dry season, from May to September. The wet season has historically caused water management issues at the Ranger mine (ERA, 2012a, 2012b). During 1910–2013, the temperature in this area has increased by .9–1.0 °C, in minimum and maximum respectively (Moise et al., 2015).

Since 2006 a number of extreme weather events (intense rainfall/flooding and cyclone activity) and their associated impacts have been documented at the Ranger mine. They include:

- Halt of mining and processing for periods of one day to four and a half months during 2011 (ERA, 2011, 2012a, 2012b);

[1] For the purpose of projecting future climate conditions, Australia has been subdivided into geographical 'clusters' or areas, which correspond to regions with very broadly similar climate and morphological conditions. Some of these 'clusters' are divided further into 'sub-clusters'. 'Sub-clusters' represent regions of minor variances in climate attributes within the broader 'cluster' area.

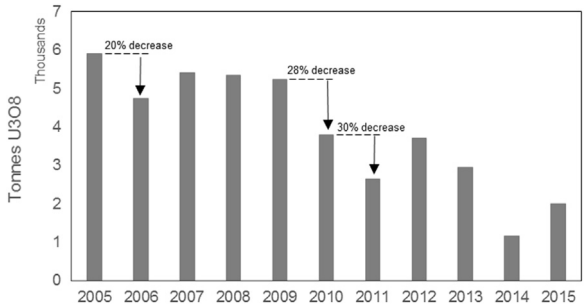

Fig. 2. Production rates at the Ranger mine 2005 – 2015 (ERA, 2008a, 2009, 2010, 2011, 2012a, 2013a, 2014, 2015, 2012b).

- Flooding of the operational pit in 2006, 2007, 2011, and 2012 (ERA, 2007a, 2008a, 2012a, 2013a, 2012b);
- Flooding of the tailings facilities in 2007 and 2010 (ERA, 2008a, 2011);
- Blocked access to the high grade ore in 2006, 2007a, 2010, 2011, and 2012

(ERA, 2007a, 2011, 2012a, 2013a; ERA, 2008b, 2012b).

These events can be linked to documented financial and operational impacts that include:

1. Restriction of exploration activities (capacity to increase ore reserves) to the dry season only (ERA, 2013a, 2014);
2. Decreased production (actual versus planned). Fig. 2 presents historical production rates from 2005 to 2015 that clearly show the downwards trend in production over this time. In addition to the climate event impacts (detailed below) production at the Ranger mine was also negatively impacted by lower milling rates in 2013 and the closure of the mine for 6 months in 2014 due to the accidental spill of slurry from a leach tank (ERA, 2014, 2015).
   a) Production in 2006 decreased 20% to 4748 t equating to AU$64 million loss in revenue (calculation based on average commodity price of AU $24.98 lb in 2006). This also resulted in the purchase of 316 t of uranium oxide to fulfil contract commitments in 2007 (ERA, 2008a).
   b) In 2010, the interruption of mining operations caused a decrease in production of 28%, (1447 t) resulting in a calculated loss of AU$196 million in revenue (ERA, 2011).
   c) Disruptions in 2011 led to 30% decrease in production and forced the company to purchase 2126 t of uranium at an estimated cost of AU$253.2 million in the market to meet contract commitments (calculation based on the average spot price during 2011).

3. Damage to capital infrastructure. A review of annual reports provides costs associated with expenditure for each year (ERA, 2008a, 2009, 2011, 2012a, 2013a, 2012b). The historical trend of capital expenditure at the Ranger mine for the period 2006–2015 is provided in Fig. 3. In each of the years, 2007, 2008, 2010, 2011 and 2012, the increase of capital expenditure can be attributed to costs associated with the impacts of extreme weather events that included flooding and cyclones. The 2012 costs can be directly attributed to the construction of a brine concentrator that is used to reduce the process water inventories, especially in wet season to avoid flooding or discharge of process water to the environment (ERA, 2013a). The total cost of the brine concentrator was AU$220 million (ERA, 2011).

Climate impacts at the Ranger mine also implied additional capital and operating costs associated with:

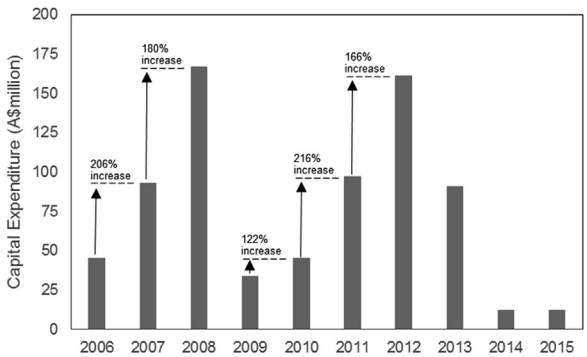

Fig. 3. Capital expenditure at Ranger mine, 2006–2015. (ERA, 2008a, 2009, 2010, 2011, 2012a, 2013a, 2014, 2015, 2012b).

- removal of temporary excess water from the pit (ERA, 2007a)
- raising the height of the tailings storage facility three times for a total cost of AU$72 million (ERA, 2008a, 2009; ERA, 2013a).
- installation of a new water treatment facility to treat contaminated flood water at the site (ERA, 2009).
- access and service impacts to the local town of Jabiru, which is situated approximately 8 km east of the mine and provides accommodation for the workforce. Jabiru has been affected by extreme weather events, with documented negative impacts on power, water and communication services, and damage to houses and local businesses as a result of flooding (AECOM, 2010). In addition, local access roads and bridges were damaged due to cyclone activity in 2011–2012 requiring extra funding for repair (WASC, 2011, 2012).

Based on this summary, ERA have spent an estimated AU$514.5 on climate related impacts over the 10 years from 2005 to 2015. Over this time, a total of AU$403 million in lost revenue has been estimated due to production issues and/or the need to purchase ore to fulfil contract agreements.

Climate projections to 2030 suggest with *high confidence* that the temperature will continue to increase at the historical rate (.9 °C – 1.0 °C, in minimum and maximum respectively) coupled with an increase in days over 35 °C and heat waves. The frequency and the duration of extreme weather events are also expected to increase (Moise et al., 2015).

Rainfall variations in all seasons are projected with *low confidence* for this area with variations ranging from a reduction of 7 mm to an increase of 49 mm (Moise et al., 2015). Extreme weather events such as heavy rainfall are projected to increase in frequency in the coming years. The frequency of tropical cyclones is projected to decrease but each event is expected to increase in magnitude (Moise et al., 2015).

2.2. Olympic dam mine

According to the ANRM map of Australia (Watterson et al., 2015a, 2015b; CCA, 2015), the Olympic Dam mine is located in the area referred to as the Rangelands-South sub-cluster. Over the past century, rainfall in this area can be characterised by very dry periods to periods of heavy rainfall (Watterson et al., 2015a, 2015b).

The pattern of rainfall during the last century has shown a slight increasing trend, with recurrent cycles of wetter and drier conditions with respect to the baseline average (established 1986–2005). Over this time, very dry periods (2002–2009) usually followed periods of heavy rainfall such as 2011, being also the highest level of rainfall in history (Watterson et al., 2015a, 2015b). In terms of seasonal rain patterns, the slight upward trend can be attributed to a higher magnitude of rainfall during the summer in the northwest portion of the area, matched partially by slight decreases of rainfall during the autumn and winter in the southern region of the area. Further, mean temperature in the vicinity of Olympic Dam has risen by .9 °C over the past 100 years.

On the other hand, minimal published information associated with the impact of extreme weather events at the Olympic Dam mine is available. BHP Billiton has previously documented that their Olympic Dam mining activities have been adversely affected by weather events (BHP Billiton, 2015). These events have been characterised by variations in water supply and increasing temperatures (BHP Billiton, 2012) that have included extended periods of droughts (2002–2009) and intense rainfall, storms and strong winds (2010–2011). These events have caused the temporary closure of the surroundings roads to the mine (Arid Recovery, 2011) impacting on the supply chain. Recently an extreme storm event, that included intense rainfall (with total precipitation more than double the average for the month), thunderstorms, lightning strikes and strong winds of 95 km/h, caused flooding and a state-wide energy blackout in South Australia that lasted several days (BOM, 2016b); AEMO (2016)). As a consequence, Olympic Dam had to halt operations for 15 days during September 2016. Estimates of economic losses have not yet been calculated but the event is expected to have impacted production capacity (BHP, 2016). In contrast to the Ranger mine, Olympic Dam has undertaken water management programs in response to water scarcity issues (RepRisk, 2009; ICMM, 2012). This includes a water saving project implemented in 2004 (ICMM, 2012).

Projected rainfall up to 2030 will strongly reflect natural variations, with average annual rainfall oscillating around ± 10% from the baseline average of the period (1986–2005) and seasonal rainfall variances predicted to be around ± 20% from the average (Watterson et al., 2015a, 2015b). Mean temperature is projected to rise by approximately .6 °C to 1.5 °C by 2030 (with *very high confidence*) in all future emission scenarios.

3. Vulnerability assessment

A vulnerability assessment of the industry has been undertaken based on stakeholder feedback collected via survey methods. The survey focused on sampling the opinions of uranium mining chain participants that include mining and service provider employees, consultants, contractors, government organisations, local communities and non-governmental (not-for-profit) organisations (NGOs). The survey was designed with questions based on historical climate impacts documented at the Ranger mine and at Olympic Dam; and the consideration of climate risks that are expected to increase at these sites in the future. Existing vulnerability was measured by asking participants to indicate the most influential climate risks, their frequency and impact they may have had on their company's operations or their immediate environment e.g. "From your experience, what are the most influential climate conditions that most affected your company/organisation or community"? Additionally, participants were asked about the possible indirect impacts they have experienced. Future vulnerability was assessed by asking participants to provide an estimate, based on present vulnerability, of the future vulnerability e.g. "If the climate risks identified become greater how would you rate the impact to your company/organisation/community"?

Adaptive capacity was qualitatively assessed through the evaluation of the current site risk management plans against known climate risks. Participants were asked to self-assess their sites ability to deal with the effects of climate risks through the implementation of current policies and procedures documented in their vulnerability assessment and risk reduction plan/s. Future adaptive capacity was assessed based on the perception of present adaptive capacity e.g. Participants were asked what types of changes do you think are required to improve the adaptive capacity of your company/organisation?

This survey was delivered via the internet to uranium mining stakeholders in Australia between the end of February and June 2016. Respondent data was analysed in IBM SPSS statistics software (V.22) using several tests. Due to the small number of responses (250 persons were contacted but just 21 of them completed the survey), an analysis of independence was conducted using the Fisher's exact test only.

To run a Fisher's test, 96 cross tabulations between responses and categories were performed. These associations were generated for all multiple choice responses and respondent categories classified by:

a) geographical location (whether they are located in the Northern Territory or South Australia);
b) position or role in the company; and
c) level of experience 0–10, 11–19 and 20 or more years).

These categories provided an assessment of significant variation in survey responses. Values of $p < .05$ indicate that the distribution of responses is significantly different between the category test groups. Values of $p \geq .05$ suggest that there is no significant difference between groups of respondents.

Weighted averages of rating and ranking responses were also used to interpret (and rank) the survey responses. To do this, respondents were asked to rate or rank several statements regarding their organisation's experience or capacity through a grading scale. The scores were weighted by the proportion of respondents who selected each grade, to arrive at one average rate or rank.

3.1. Profile of respondents

The selection of the participants for this survey was based on having a background and experience related to uranium mining and/or the uranium industry (including nearby communities) at either of the Olympic Dam or Ranger mine sites.

There were a total of 21 survey respondents across a broad cross section of the community that included past and present mine employees, contractor and consultant companies, transport companies, state government, community services, community members and NGOs. Their roles varied greatly from professional management positions, engineers and scientists to administrative staff and community members. The majority of respondents had more than 20 years of experience in the uranium industry. A summary of the respondents' profile is provided in Table 1.

3.2. Present vulnerability assessment

The following sections describe the results of the survey conducted to evaluate the historical and estimated vulnerability and adaptive capacity of the uranium mining industry to climate change risks within Australia.

Respondents were questioned on climate conditions that most affected their companies/organisations/communities both in terms of how influential the nominated climate event was and how frequently it occurred. Respondents were also asked to rate their organisation's overall risk exposure to climate conditions. The majority of respondents (65%) indicated that intense rainfall/flooding have been the most influential weather event/s in the past. This is despite the two mines being located in different climate zones. Respondents from South Australia listed "heat waves" as an influential climate risk, with a much higher tendency ($p = .04$) than those in the Northern Territory. Respondents with at least ten years of experience were also more likely to cite "heat waves" as an

Table 1
Profile of survey respondents.

Organisation type	Responses	Role/Position	Responses
Mining company	3	Management	14
Mining services	1	Engineer	1
Contractor	3	Scientist	1
Consultant	5	Administrative staff	2
Transport-roads trucking	1	Community member	1
Government-State	3	NGOs	1
Community Services	1	Coordinator	1
		Location	
None (member public/local community)	2	Northern Territory	5
Other (not specified)	2	Queensland	1
		New South Wales	1
		Victoria	2
Total	**21**	South Australia	12

Table 2
Rate of exposure to climate risks.

	N	Average Score	p value location SA	p value location NT	p value years of experience 0 −10	p value years of experience 11–19	p value years of experience 20 or more	p value management
Droughts	15	3.20	.154	.286	.882	.193	.197	.197
Fires	14	3.93	.793	.815	.389	.285	.804	**.021**
Heat waves	16	4.75	.211	.522	.000	.052	.239	.935
Storms	14	5.07	.762	.249	.515	.168	.501	.762
Intense rainfall/ flooding	20	4.90	.876	.077	.604	.088	.354	.295
Other	3	3.67	.667	.667	NULL	NULL	NULL	NULL

p-values for the null hypothesis of equal means between the nominated group and the rest of the sample

influential climate risk (p = .05) and respondents with 20 or more years of experience reported heavy rainfall and flooding as the most common climate risk (p = .03). Surprisingly, these results suggest the occurrence of heat waves has been more common in South Australia than the Northern Territory in the last 10 years. Over a broader period of time (more than 20 years), heavy rainfall and flooding appears to be the most influential climate risk at both locations.

According to the respondents of the Northern Territory, the frequency of climate risks varied from “once a year” to “once every 10 years” for climate risks such as intense rainfall/flooding, heat waves, storms, fires and droughts. In the case of South Australia, the frequency of climate risks varied from “once a year” to “less than once in 20 years” for risks that included intense rainfall/flooding, heat waves, droughts and storms. In addition, state government representatives indicated that extreme weather events caused issues every year and consultants documented that climate risks are a constant issue when companies undertake environmental impact assessments.

The last question in this section was to rate the exposure of their companies/organisations/communities to climate risks, from a scale of 1–10 where 1 was low exposure and 10 high exposure (Table 2).

In contrast to the earlier question, where those with *at least ten years* of experience cited “heat waves” as the most influential climate risk, for this question it was respondents with *10 or fewer years* of experience who rated the risk of exposure to “heat waves” higher than the rest of the sample with the difference being statistically significant. This suggests, that in the last 10 years the industry has been more exposed to heat waves than any other climatic event. In addition, from a management perspective the industry is more exposed to fires (P = .02).

Respondents were asked to identify the main impacts to their company/organisation/community that climate events have had, with the possibility to identify more than one response. The results are provided in Table 3.

The majority of respondents (70%) identified operational disruption as the main climate related impact followed by loss of revenue and increased costs, health and safety of workers, delay in production, financial performance, and damage to infrastructure/ plant and equipment. A less significant impact was the supply of essential inputs and services (e.g. water, energy, and telecommunications), infrastructure, plant and equipment damage, transportation of products and quality of production.

Respondents from South Australia showed a higher tendency to single out the “supply of essential inputs or services” (p = .05) and the “health and safety of workers” (p = .04) as impacts to their organisations. Respondents with 11–19 years of experience were more likely to discount the loss of revenue as a relevant impact to their organisation, compared to the other respondents (p = .049).

The comparison between mine locations has shown that the South Australian respondents reported greater sensitivity to “supply

Table 3
Impacts caused by climate risks.

	% (n = 21)	p value location SA	p value location NT	p value years of experience 0 −10	p value years of experience 11–19	p value years of experience 20 or more	p value management
Financial performance	45.0%	.465	.625	.604	.145	.157	.426
Loss of revenue	60.0%	.388	.535	.693	**.049**	.113	.545
Increased costs	60.0%	.113	.465	.307	.344	.612	.187
Operational disruption	70.0%	.455	.657	.483	.681	.455	.613
Delayed production	45.0%	.205	.217	.604	.145	.157	.574
Quality of production	10.0%	.653	.368	.447	.716	.653	.521
Supply of essentials (water, energy, telecommunications, labour or materials)	40.0%	**.054**	.465	.704	.656	.612	.545
Transportation of the product	20.0%	.153	.162	.282	.491	.102	.343
Health and safety of workers	55.0%	**.040**	.625	.221	.421	.465	.574
Infrastructure and equipment damage	40.0%	.612	.153	.307	.344	.612	.545
Other (specified)	10.0%	.147	.632	.553	.716	.347	.521

p-values for the null hypothesis of equal percentage of agreement between the nominated group and the rest of the sample

Table 4
Climate impacts on mining operations.

	% (n = 20)	p value location SA	p value location NT	p value years of experience 0 −10	p value years of experience 11–19	p value years of experience 20 or more	p value management
Ore extraction	50.0%	.103	**.024**	.778	.778	.738	.083
Processing	40.0%	.738	.548	.667	.667	.548	.667
Transport within the mine site (access and haulage)	50.0%	.500	.738	.222	.222	**.024**	.500
Transport outside the mine site (road, rail, and port)	30.0%	.500	.167	.467	.467	.167	.708
Tailings/waste management facilities	60.0%	.262	.071	.667	.667	.548	.167
Mine planning	10.0%	.500	.400	.800	.800	.600	.300
Maintenance activities	50.0%	.103	.262	.778	.222	.262	.083
Exploration	.0%	1.00	1.00	1.00	1.00	1.00	1.00
Other (Specified)	.0%	1.00	1.00	1.00	1.00	1.00	1.00

p-values for the null hypothesis of equal percentage of agreement between the nominated group and the rest of the sample

of essential inputs or services" as well as "health and safety of workers" than respondents from the Northern Territory. This result might be due to the fact that Olympic Dam (577 km from Adelaide) is located further from a city compared to Ranger mine (230 km from Darwin), making the former more vulnerable to disruptions in the supply chain due to limited options for site access. Access to Olympic Dam has previously been impacted by extreme weather events such as flooding and storms, which caused road closures – affecting the normal supply of materials, equipment and resources. In fact, Olympic Dam was closed 15 days in early October 2016 due to failure of electricity transmission after a major storm (BHP, 2016).

The impacts of climate change were further explored exclusively for mining company employees. The responses are presented in Table 4. The majority of respondents (60%) identified tailings and waste management facilities as being the most impacted by extreme weather events, followed by ore extraction, processing and transport within the mine (access and haulage) and maintenance activities. Processing and transporting outside the mine were also mentioned (road, rail, and port) but were not rated highly. The personal assessment provided by mining company employees suggests that their companies are sensitive to climate risks especially when tailings/waste management facilities are considered.

By location, the Northern Territory respondents reported more sensitivity ($p = .024$) to climate events in the ore extraction area. This suggests that Ranger has faced more issues associated with production when extreme weather events are considered. In fact, pit operations have been halted at least 4 times in 10 years due to flooding (ERA, 2007; ERA, 2008a; ERA, 2012a, 2012b, ERA, 2013a). Dividing respondents by years of experience, those with more than 20 years identified that the most sensitive area to climate risks is "transport within the mine site". This suggests that haulage roads within the mine site have been affected by flooding in the last 20 years, leading to impacts on production.

Indirect impacts were examined through an assessment of the influence of external companies/organisations affected by climate events and their flow-on effects at the respondents' own company/organisation. The results are provided in Table 5.

Based on the survey results, 30% of the respondents considered that climate related impacts on a mining company had flowed-through to produce secondary impacts on the respondent's own organisation in some way. Of the respondents, 25% indicated that the local community, utility companies and transport companies had impacted upon them in some way and 15% indicated that direct impacts on mining services had affected them. Respondents from South Australia showed a higher tendency to mention "utility company" (water energy, and telecommunications) as particularly affecting them ($p = .05$). There was a high proportion (35%) of respondents who considered this question as being "not applicable". This could suggest that the respondents consider the mining

Table 5
Types of external companies/organisations affected by climate events that have affected the respondents' own company/organisation.

	% (n = 20)	p value location SA	p value location NT	p value years of experience 0 −10	p value years of experience 11–19	p value years of experience 20 or more	p value management
Mining company	30.0%	.455	.657	.517	.681	.545	.387
Local community	25.0%	.307	.751	.073	.399	.296	.517
Mining services (engineering, maintenance, drilling, labour)	15.0%	.656	.509	.399	.404	.656	.319
Transport company	25.0%	.693	.751	.634	.601	.693	.517
Utility company (water, energy, telecommunication)	25.0%	**.051**	.282	.634	.601	.693	.517
Not applicable	35.0%	.608	.439	.594	.270	.251	.664
Other (please specify)	5.0%	.400	.800	.750	.850	.600	.300

p-values for the null hypothesis of equal percentage of agreement between the nominated group and the rest of the sample

Table 6
Factors that can increase the vulnerability to future climate conditions.

	% (n = 19)	p value location SA	p value location NT	p value years of experience 0 − 10	p value years of experience 11–19	p value years of experience 20 or more	p value management
Age of assets	52.6%	.430	.333	.556	.124	.115	.444
Design of assets	57.9%	.337	.574	.336	.624	.449	.071
Geographical location	73.7%	.366	.258	.084	.376	.336	.172
Operational process / method used	21.1%	.525	.648	.258	.470	.085	.272
Frequency of climate events	84.2%	.296	.530	.376	.422	.624	.376
Intensity and magnitude of climate events	73.7%	.634	.728	.603	.624	.664	.603
Impact on labour availability/ productivity	52.6%	**.017**	**.033**	.184	.542	.115	.119
Other (please specify)	.0%	1.00	1.00	1.00	1.00	1.00	1.00

p-values for the null hypothesis of equal percentage of agreement between the nominated group and the rest of the sample

company is the most influential participant in the supply chain.

Participants were further questioned in regards to the impacts their own company/organisation can generate on others when affected by climate events. The ranking obtained were mining company most affected (3.20), following by surrounding environment (3.73), local community (3.83), and transport company (4.23). The least affected in the industry were manufacturing (6.18), the customer's company (4.92), mining services (4.64) and construction (4.30).

These results show how the uranium mining industry can be affected both directly and indirectly by climatic conditions and weather extremes. In addition, other members of the regional supply chain such as upstream, downstream and regional stakeholders can also be affected if the mining company is affected by climate conditions e.g. water consumption by Olympic Dam mine in a water competitive environment (Mudd, 2008). This suggests that the participants are linked as members of a chain of activities or a network with several nodes as CIPS (2013) suggested.

3.3. Future vulnerability assessment

As part of a future exposure assessment, respondents were asked to rate exposure of their company/organisation or community to risks if there was an increase in the frequency, magnitude, duration and/or extent of climate events in the future. The majority of respondents considered that the exposure would increase if intense rainfall is more frequent in the future, followed by, in order of importance, storms, heat waves, fires, and droughts. Compared to the evaluation of present vulnerability, it seems that intense rainfall/flooding will continue to be the most influential climate risk for future vulnerability. On the other hand, storms are considered to become a greater risk than heat waves in the future.

A question was posed about factors that could increase the vulnerability of the respondents' company/organisation or community to climate conditions. The results are presented in Table 6.

In response, the most (84.2%) cited factor that will increase vulnerability to climate conditions is the change in frequency of extreme climatic events. This was followed by the intensity and magnitude of these events and geographical location. Design of assets was also a significant factor cited by respondents, followed by age of assets and impact on labour force availability or productivity. The impact on labour force availability or productivity was considered to be the most critical factor for respondents from South Australia ($p = .017$). Conversely, respondents from Northern Territory did not rate this factor as being critical ($p = .033$). Overall, this suggests that future vulnerability of the industry would be climate dependent if no steps are taken to increase the adaptive capacity of operations through re-design or renewal of assets or by securing the labour force availability and productivity. The selection of the critical factors differed in both locations and are considered site specific.

Respondents were also asked to identify new impacts to their companies/organisations that may occur should the climate risks identified previously increase in the future. Respondents could select more than one option. Operational disruption was identified as the area with highest impact (84.2%), followed by an increase in costs (78.9%) and loss of revenue and health and safety of workers (both 68.4%). Respondents from South Australia reported higher concern about the health and safety of workers if climate risks are greater in the future ($p = .01$). Other significant factors identified were financial performance (63.2%), delays in production (57.9%), and infrastructure/plant and equipment (47.4%). Compared to the present vulnerability assessment, "operational disruption" remains as the main impact for future vulnerability, however, it is expected to be more prevalent in the future (84.2% vs 70%). Higher response rates were also shown between future and current impacts for loss of revenue (68.4% vs 60%), increased costs (78.9% vs 60%) and health and safety (68.4% vs 55%). This means respondents anticipate for the future a greater degree of climate impacts. The "quality of production" was not considered at risk for the future and the "transportation of the product" has remained at the same level of impact (26.3%).

With regards to which aspects of mining operations were identified as being most at risk in the future, tailings and waste management facilities received the highest rating (66.7%), followed by the processing plant, transport within the mine site, and

Table 7
Impacts from other organisation/company to their own business or community.

	% (n = 19)	p value location SA	p value location NT	p value years of experience 0 −10	p value years of experience 11–19	p value years of experience 20 or more	p value management
Mining company	68.4%	.472	.656	.656	.502	.528	**.041**
Local community	52.6%	.056	.550	.126	.256	**.024**	.221
Mining services (engineering, maintenance, drilling, labour)	42.1%	.201	.656	.262	.498	.166	.133
Transport company	36.8%	.324	.443	.557	.593	.676	.210
Utility company (water, energy, telecommunication)	47.4%	.377	.647	.258	.586	.377	.676
Other (Specified)	.0%	1.00	1.00	1.00	1.00	1.00	1.00

transport outside the mine site (all at 44.4%). In this question the comparison with the present vulnerability assessment is difficult to interpret due to the lack of data. However, the general perspective of the respondents between the present and future impacts on the mine site and associated infrastructure did not change significantly.

Respondents were asked to comment on the potential for an increased need for resources such as water, energy, telecommunication, labour, technology, and knowledge as a result of climate change. Half of the respondents (52.6%) estimated that the demand for water and energy would increase. Other significant resources that would be in demand would be knowledge/expertise (42.1%) and labour (31.6%). This result coincides with the key elements (water and energy) used currently by the mining industry and continue to be a critical part of the operational efficiency of a mine. Participants indicated that "knowledge or expertise" in these fields would be required to face the future climate changes.

The flow-on impacts from another company/organisation to their own company/organisation in the future were considered. For this question, respondents were able to choose more than one option. The results are presented in Table 7.

Most of the respondents indicated that flow-on impacts from mining companies could affect their operation, followed by those from the local community, utility companies, mining services and transport companies. Respondents in management positions had a higher likelihood to mention mining companies as a source of future risks for their organisation ($p = .041$). Respondents with more than 20 years of experience did not consider the local community as a particularly significant source of future vulnerability ($p = .024$). This suggests that the mining company is considered the most influential in transferring impacts to others in the industry supply chain. The future impact is expected to be higher compared with the present vulnerability assessment (68.4% vs 30%). Another significant difference is local community, which is considered to be almost 100% more influential than in the assessment of present vulnerabilities (52.6% vs 25%) as well as utility companies (47.5% vs 15%) and mining services (42.1% vs 15%). This suggests that in the future, the industry would be more prone to be indirectly affected. However, from a management perspective ($p = .041$) the mining company is the most influential in the supply chain. According to Walker et al. (2008) there is a coordinator member or leader partner in a chain which is the most important part of the chain, in this case is mining company.

3.4. Present adaptive capacity

The survey queried adaptive capacity in terms of the plans (mainly through the Risk Management Plan, RMP) and preparedness (nature of the approach, existence of vulnerability assessment and a risk assessment plan) employed by the uranium mining industry to face with climate risks. The survey asked respondents to rate their organisation's current RMP on a range of characteristics on a scale from 1 (poor) to 10 (excellent).

Overall, respondents gave the highest rating (8) to the quality of their organisation's RMP in terms of "the clarity of the guidelines and procedures to follow in the case of a climate event", followed by the "the clarity in the different positions, roles and responsibilities of the personnel required to respond to the event" with a rating average of 7.78. The adequacy of current risk mitigation procedures and response contingency plans (7.56) and communication within the company/organisation (7.35) also rated well, suggesting the RMPs were considered well prepared in these four aspects. The lowest rated items were the revision of the RMP to cope with the dynamic changes in the future (7.00), the clear identification of climate risks in the current risk management plan (6.65), and the level of communication between the company and other related organisations (e.g. energy, water, transport, and communication company) which was rated at 6.22. Overall, the results show that all RMP characteristics received a rating above 5, which suggests a reasonable level of adaptive capacity is present in the industry at the present time. Nevertheless, some areas must be improved to ensure the changing climate is considered.

Most of the respondents (61.9%) indicated that they considered the approach of their company/organisation to dealing with climate events was proactive (anticipatory or preventative). Even though short and long term were not considered in the question, respondents from mining companies pointed out that they have a proactive approach in the short term but there is a lack of long term planning. In the case of local communities, it was indicated that there is not a proactive approach (i.e. without having been suitably prepared in advance) when it comes to community services, contractors or community members. This suggests these organisations could be the most vulnerable part of the industry at the present time, as they lack preparedness and/or information to face extreme weather events, especially in remote communities in the Northern Territory (Veland et al., 2010; Boon, 2015).

3.5. Future adaptive capacity

Respondents were asked to rate their current RMP against its overall ability to cope with more frequent or more extreme climate risks on a scale from 1 (poor) to 10 (excellent). The responses were varied with 38% rating their RMP at a score 4–5. This is below the mid-point of the scale (5), so it could be inferred that most RMPs would not cope well with future climate risks. Approximately 20% scored their plan between 6 and 7, and the remainder of the respondents (33% – who were mainly from government organisations) scored their RMP between 8 and 10. This suggests that just one portion of the industry is currently well prepared for future climate risks.

As part of the future adaptive capacity evaluation, respondents were asked about the existence of a vulnerability assessment and a risk reduction plan at their location. Most responded "no" (45.8%), a significative percentage were 'unsure" (33.3%) and a small percentage (8.3%) stated having a vulnerability assessment plan. Some respondents pointed out that "they don't know what a vulnerability assessment is" or that "they are a small consultancy" and "they have reduce budget". In regards to the existence of a risk reduction plan, most of the respondents (80%) stated they "don't have one" or were unsure of the existence of such a plan. Only 12% confirmed they had one.

Respondents were asked to select preferred options from a list of proposed changes to improve the adaptive capacity of their organisation for future climate conditions. The majority of respondents (73.7%) indicated that operational procedures were a measure to improve the adaptive capacity, followed by management procedures (52.6%), work practices (42.1%) and administrative procedures and management approach/leadership (both 31.6%). These results suggest that respondents of the uranium industry are aware that their adaptive capacity can be improved by making changes to their operational and management procedures.

4. Discussion of the results

This study provides a review and assessment of the past impacts related to climate conditions and climate risks for the Australian uranium industry (focused on the Ranger and Olympic Dam mines) and a future vulnerability assessment (based on past experience and future expected conditions) of the industry for climate change. The uranium industry was considered to be composed of a broad set of participants: not just the mining companies per se, but also contractors, consultants, mining services, government agencies (state and local), non- government agencies, community members and community services.

In a first section, a detailed review of the annual activity and sustainability reports of the mining holding companies was conducted for the period 2005–2015. As an example, in the case of Ranger mine, this review allowed the identification of climate impacts on business performance (in terms of decrease of production, loss of revenue, forced purchase of uranium in the spot market, increase of costs and additional capital expenditures) and in field operations (e.g. operational pit flooding, tailings storage facilities flooding, partially/full halt of mine operations, blocked access to the high-grade ore by flooding and infrastructure damage). The identification of past impacts at Ranger mine allowed an estimation of the economic cost of AU$514.5 million in additional investment (reactive measures) and loss of revenue over 10 years of AU$403 million. Given this analysis is confined to one mining operation, it is easy to infer that this represents a lower bound in the estimation of costs for the industry.

The results of our survey provided data to evaluate the climate vulnerability of the industry to assess the depth that climate impacts the industry in the past and will face in the future.

4.1. Climate change perceptions

In general, the results of the survey suggests that the uranium mining industry in Australia may have differing perceptions about climate change or climate risks compared to the broader mining industry. This study was limited to uranium mining supply chain participants, and the sample is therefore too small to infer a significant requirement across the whole mining industry in Australia. However, these results may signify an important positive change has occurred.

In a previous study undertaken by Loechel et al. (2013b) that included a significant cross section of the mining industry as well as local government representatives, the mining company respondents reported "less concern" about past and future climate risks. In contrast, most of the respondents of this study (> 95%) reported climate risks as an influential impact to their company/organisation or community both in the past and expected in the future. In fact, they reported increased percentages in all climate impacts. The results of the present survey are in contrast to the study by Loechel et al. (2013b), where the mining respondents didn't consider the risk of climate change an important concern, neither in the present nor in the future. The authors suggest that this may be due to low belief/scepticism about the issue in the past. Another explanation for the difference may be that the industry has been negatively influenced by more climatic impacts since 2013. Furthermore, this result could be attributed to the fact that uranium has been proposed as a potential substitute for other energy sources to produce electricity (e.g. coal) (WNA, 2012) thus, might be more in tune to the impacts that climate change might have on them based on experiences to date.

4.2. Present vulnerability

Regarding the present vulnerability assessment, intense rainfall/flooding and heat waves were identified as the most influential climate risks for the industry. Responses varied in intensity among participants, especially according to location (respondents from South Australia tended to mention heat waves with higher frequency than other groups), and years of experience (respondents with up to 10 years of experience mentioned heat waves whereas respondents with more than 20 years of experience mentioned intense

rainfall/flooding).

There is a similarity between the climate risks mentioned by the participants in this research and the results from Loechel et al. (2013b), Mason and Giurco (2013) and Hodgkinson et al. (2014). In both this study and Loechel et al. (2013b), the most frequently mentioned climate risk by respondents was intense rainfall/flooding, even though this research includes the Olympic Dam mine located in an arid region. This suggests the great influence of intense rainfall that leads to flooding in South Australian mining (Hodgkinson et al., 2014).

Regarding exposure to climate risks, respondents in the industry identified storms, intense rainfall/flooding and heat waves as the main events. The trend of this response also varied according to years of experience: respondents with up to 10 years of experience considered the exposure to heat waves with higher concern than other respondents. In both locations, storms and intense rainfall/flooding have caused issues such as flooding in the operational pit at Ranger mine and tailings storage facilities (ERA, 2008a, 2011, 2012a;, 2012b) or the blackout at Olympic Dam mine during September 2016 (AEMO, 2016). Meanwhile, heat waves involve risks to the health (fainting, cramps, exhaustion, fatigue and heat stroke) and safety of workers whether the mine operation is on the surface or underground (Hunt, 2011; Maurya et al., 2015) and also negatively influence work performance (ERA, 2007b; Hodgkinson et al., 2014). More specifically, ERA (2007b,2008b) developed a program to avoid the deterioration in workers' health from heat stress. In a similar vein, BHP Billiton (2009b) developed a plan for heat management. In addition to this, in the light of recent heat waves, the Government of South Australia has developed a strategic plan to prepare for intense heat waves that focuses on the wellbeing of local workers (GSA, 2016).

Climate impacts previously identified, such as operational disruption, increased costs, financial performance, delays of production, health and safety of workers, and loss of revenue were highlighted by the survey results and additional climate impacts over business performance were identified, such as delays in production, supply of essentials (water, energy, telecommunications and labour availability) transportation of the product, health and safety of workers, and quality of production. These climate-related impacts coincide with the results of previous studies (Mason and Giurco, 2013; Loechel et al. 2013a, b, Hodgkinson et al., 2014) undertaken in mining generally, in Australia.

Some differences in responses between locations were identified. South Australian respondents presented more sensitivity to supply of essential inputs than respondents from Northern Territory. Moreover, additional sensitives in the mine site were identified such as transport within and out of the mine site, processing, planning, and maintenance activities.

In this survey, Australian uranium industry respondents categorised tailings/waste management facilities at the greatest at risk, followed by ore extraction, processing, transport within the mine site (access and haulage), and maintenance activities with the same level of negative influence in their businesses. By location, respondents from Northern Territory reported more sensitivity to ore extraction area, this is confirmed by the initial results of historical climate impacts that have affected Ranger mine.

In contrast with these results, the Canadian study undertaken by Pearce et al. (2009) uranium mining respondents reported low sensitivity to climate risks. They considered climate risks to their operations were not climate dependent because the mines were underground and the damage to infrastructure and equipment damage at the surface were estimated as less significant (Pearce et al., 2009).

Respondents in this study identified the company/organisation or community that can cause indirect impacts (flow-on) in the own company. Mining companies were found to be most affected followed by local community, utility companies, and transport companies with the same level of impact. Differences in responses according to location were also detected e.g. utility company was selected by South Australian respondents in higher tendency than other respondents. The remote location of Olympic Dam was emphasised by the massive blackout in September 2016. In that occasion, it took 15 days to restore the supply of electricity, since the need for visual inspection and reparations took longer in that isolated location (AEMO, 2016). Conversely, mining companies and the surrounding environments were established as being the most influential for causing impacts on other members of the industry. These results show that the uranium mining industry is sensitive both directly and indirectly to climate risks and also that the participants of the industry are connected to each other as nodes (CIPS, 2013). In addition, only a minority (17%) of the local government representative participants in the study undertaken by Loechel et al. (2013b) indicated that their organisations had experienced indirect effects (flow-on) from other sectors in the past. This contrast***s*** with the majority (95%) of respondents in this study who reported indirect (flow-on) effects from other companies/organisations.

4.3. Present adaptive capacity

The adaptive capacity assessment (by means of evaluating the effectiveness of current RMPs) found a reasonable level of adaptive capacity in the industry. This was because some items of the RMP were well evaluated by the respondents such as clarity of guidelines, procedures, roles/responsibilities in the case of a climate event, adequacy of the RMP, and communication within the organisation. Conversely, other items such as regular update of the plan, clear identification of the climate risks, and the level of communication with related companies/organisations (water, energy, transportation, and communication companies) were rated lower. In addition, it was found that more than half (61.9%) of the industry respondents had a proactive approach in the short term but they had no long term planning to face climate risks.

In the current study, the collaboration between organisations for adaptation planning through the RMP was perceived to be negatively impacted by poor communication. This is in contrast with the results of Loechel et al. (2013b) where the participants (mainly from government organisations) stated that there were good relationships (92%) with related organisations for working on climate adaptation planning. The difference in results could be attributed to the significant loss of employees in the industry over the past few years, in fact, employment in the mining industry has decreased in the last 5 years by 4.9% (LMIP, 2016) and/or lack of

continuity in employment organisations with the mean time spent at a mining company less than 3 years.

Half of the participants in this study stated that they are aware of a proactive approach in their organisation to deal with extreme weather events. Specifically, most of them (85.71%) indicated there is some type of risk management plan in place to deal with the current climate. However, the perceived effectiveness of the plans varied. Therefore, the previous study by Loechel et al. (2013b) found only 13% of mining company, and 46% of local government respondents indicated their organisation had any plan or policy in place to deal with climate risks.

4.4. Future vulnerability

This study also explored the future vulnerability to climate change of the uranium industry, using an estimation of the future exposure and sensitivity provided by the respondents of the survey. The future estimations were taking as reference the past climate risks faced by respondents, and showed greater exposure to intense rainfall/flooding and storms and less exposure to heat waves in both locations were expected. This result contrasts with the results of Pearce et al. (2009) and Loechel et al. (2013b) where respondents dismissed an increase of vulnerability due to climate change in their operations. However, in part the exposure estimation to these climate risks coincided with the estimations of BHP Billiton (2011), C2ES (2013), and Lacey (2013).

The results of this study also suggest an increase of impacts across the business operations (financial performance, loss of revenue, increased costs, operational disruptions, delayed production, supply of essential inputs, transport of product, health/safety of workers, and infrastructure plant & equipment damage) if the climate risks are greater in the future. Differences in responses according to the location were detected, e.g. respondents from South Australia were more concerned about the labour force availability and productivity. This result coincides with the potential climate change impacts projected by BHP Billiton (2011). Regarding mine sites, tailings/waste management facilities were selected as the greatest at risk followed by transport, maintenance activities and ore extraction with the same level of negative influence in their businesses. In contrast, results obtained by Pearce et al. (2009) suggest surface infrastructure damage by climate conditions were irregular and insignificant.

Factors that play a key role in the increase of future vulnerability were explored in the survey, including change in the frequency, intensity, and magnitude of the climate risks. In addition, the geographical location, the age and design of the assets, labour force availability and productivity were also identified as key factors for future vulnerability. Differences between results from each location were detected in the data analysis: South Australian respondents were more likely to consider labour force availability and the productivity as critical factors for future vulnerability than respondents from Northern Territory. These results highlight the future vulnerability and climate dependence of the industry and the need to plan adaptation strategies to increase the adaptive capacity. It was also emphasised that the vulnerability to climate change is a specific condition of a location and the nature of mining operation as was suggested by Smit and Wandel (2006), this can presents different future needs to improve the adaptive capacity.

The potential increase in the requirement of resources (water, energy, telecommunication, labour, technology and knowledge) due to climate change was highlighted by this study. Water, energy and knowledge/expertise about climate change, were found to be independent of location. The increasing demand of these resources, especially in water, energy and labour have been anticipated in other literature (Mudd, 2008; Torrisi and Trotta, 2013; Hodgkinson et al., 2014).

Regarding indirect impacts, mining companies were stated as being the most influential to transfer impacts to others in the industry supply chain with a higher impact expected in the future (68.4 vs 30). Another remarkable difference between the present vulnerability assessment, is that local community was considered highly more influential in the future (52.6 vs 25) in transferring climate impacts to others. These results suggest the industry would be more sensitive to indirect impacts in the future.

4.5. Adaptive capacity

Regarding the ability of the uranium industry to be resilient to climate change, this study found that the 38% of industry respondents indicated their organisation is not currently ready for greater climate risks in the future if employing the same RMP. In contrast, the 33% of the industry respondents (mainly government organisations) would be able to successfully deal with influences brought by climate change.

Regarding the existence of a vulnerability assessment or a risk reduction plan, just a very small proportion of the participants in this study indicated that they know of a climate change-related vulnerability assessment or a risk reduction plan in their businesses. In addition, an apparent poor level of knowledge in climate change concepts was highlighted by respondents because of the high percentage of “no” or “unsure” responses when queried about these themes.

Finally, this study found that the adaptive capacity of the industry to climate change could be improved by changes in the operations in the mine site, as well as their management procedures, work practices, administrative procedures, and management approach/leadership. Some of these proposed changes (administrative procedures, management or leadership approach) have been seen as barriers to the climate adaptation process (Productivity Commission, 2012).

5. Conclusions

This study reveals the most influential climate risks for the uranium mining industry and how these have affected operations in the past, as well as the likely future impacts in South Australia and Northern Territory. Past-exposure was based on a review of company reports supplemented with the responses to the survey. Both factors were used to pose further questions to respondents regarding their estimate of future vulnerability. Furthermore, past direct and indirect climate-related impacts to organisations

involved in the uranium supply chain have been revealed, as well as possible future impacts together with information that outlines the factors that could increase the vulnerability of these operations in the future. The results of this study suggest that the impacts (financial performance, loss of revenue, increased costs, operational disruption and delayed production) of climate risks will be greater in the future, further increasing the vulnerability of the industry to extreme weather events. An increase of stress upon resources such as water, energy and telecommunications, labour, technology and knowledge in the light of future climate change and key factors that can increase the vulnerability were highlighted with the results of the survey. Despite most of the participants in this study claiming that their company/organisation has a risk management plan to deal with current climate conditions, there were significant weaknesses identified in these plans. Further, few companies appear to have performed a vulnerability assessment or have developed a climate change related risk reduction plan. This outlines a need of knowledge about each of these procedures within the industry. It was clear that the adaptive capacity of the industry can be further improved by strategic changes to operational procedures and management practices. Finally, a further study is necessary to explore the links (as nodes) between the companies related (supply chain) in mining.

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