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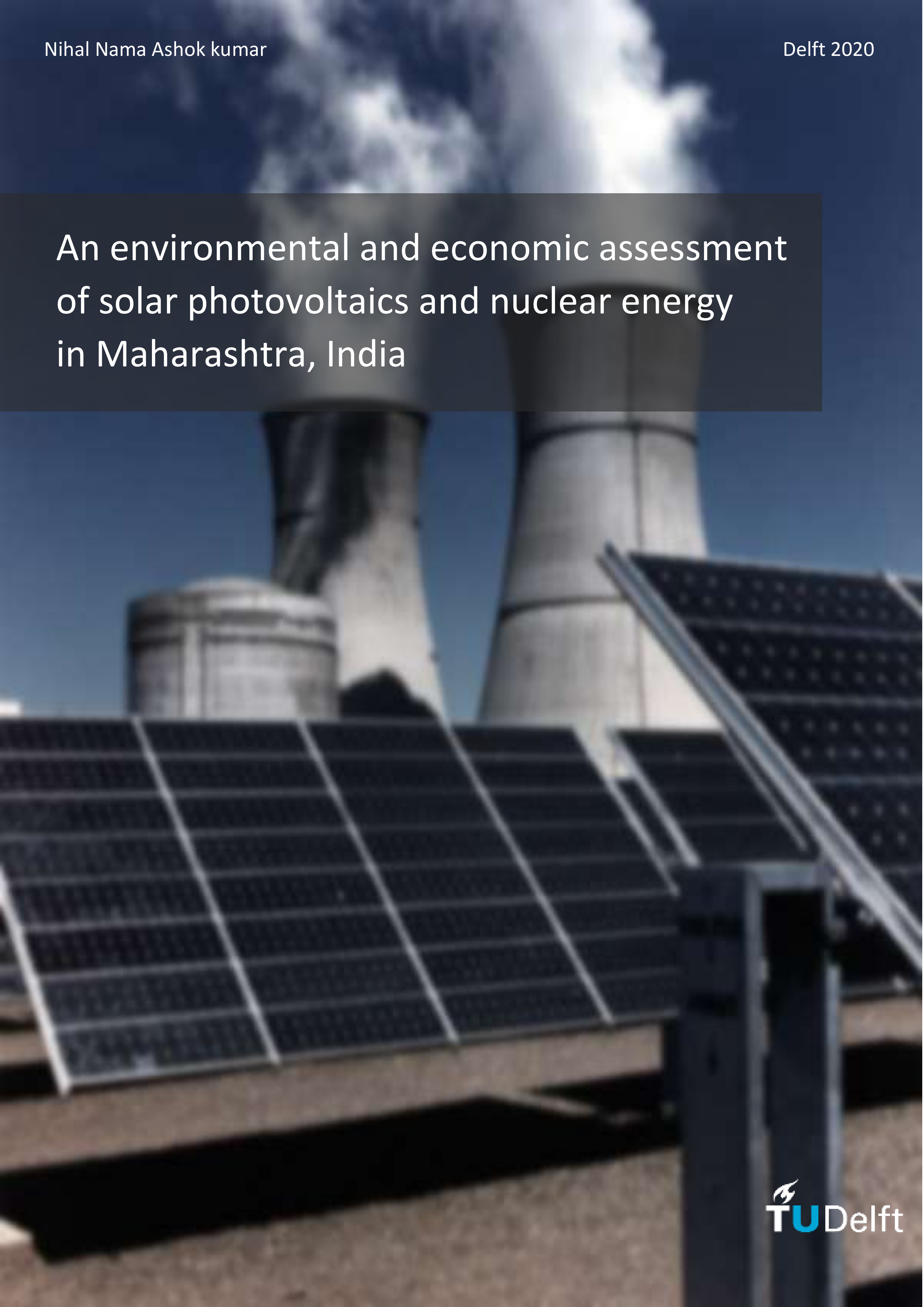
Delft 2020

An environmental and economic assessment of solar photovoltaics and nuclear energy in Maharashtra, India



TU Delft

An environmental and economic assessment of solar photovoltaics and nuclear energy in Maharashtra, India

Master thesis submitted to Delft University of Technology

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MASTER OF SCIENCE

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by

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Preface

First and foremost, I would like to thank my parents and my sister, who supported me at every point of my life in pursuing my dreams. I am highly indebted to them for their unconditional love and their confidence in my abilities even during the difficult times.

Secondly, I would like to express my heartfelt gratitude to the committee for their continuous support in guiding me through every phase of the thesis. Firstly, I would like to thank Dr.ir.G.Korevaar for giving me this tremendous opportunity to work on this project. His constructive feedback has helped me during the uncertain times of the research and has also helped me contemplate how I could improve the quality of the research at every stage. Further, I would like to especially thank Dr.ir.G.A.Tsalidis for taking out his precious time and helping me from the time we started discussions in October 2019. His approachable nature and his valuable feedback have played a crucial role in completion of my thesis. Furthermore, I would also like to express my gratitude for Prof.dr.ir.Z.Lukszo and Dr.E.Schröder for their expert comments and hard questions which made me go beyond my capabilities. It was a pleasure working with the committee and I will truly treasure the experience.

Lastly, the complete journey towards my graduation would not be possible without the support of special ones especially during the pandemic. I would like to thank my friends Sachin Hiremath, Sachin Malagavi and Vignesh Kommarlu who have always been there for me through ups and downs in the last ten years. I would also like to thank my flatmates and friends in Delft who made Delft feel like home. I am very glad to share my masters experience in the same space with them. At last, I would thank my cousins group with whom I had amazing discussions about various topics outside of this research.

Nihal N A.

Delft, August 2020.

Executive summary

Maharashtra, the second largest state in India in terms of population and area, is a fast-developing economy and meeting its electricity demand is crucial for its economic growth. Currently, power production is causing severe environmental and security issues mainly because of the reliance on coal plants in the state. In order to meet SDG 7 "affordable and clean energy" proposed by UN, a government think tank called NITI Aayog helps set polices and targets for sustainable development of electricity production in states of India. However, the stakeholders are hindered to address the problems of sustainability dimensions due to a significant knowledge gap causing discrepancies in power policies. There is a need for a comprehensive approach which involves life cycle thinking and integration of the sustainability dimensions. Hence, this study adopts an integrated approach of environmental and economic dimensions of power sector in Maharashtra for suggesting NITI Aayog on policies and framework which can be used in the expansion of electricity generation capacity. This leads us to the research question:

How can the combination of LCA and MCDA help Maharashtra's policy makers in deciding alternative electricity generating technologies that can contribute to a sustainable development of electricity production?

The framework followed in this study consisted of the four steps, indicator selection, environmental performance evaluation, economic performance evaluation, integration and policy implications. For this work, solar PV and nuclear technologies were selected and then the dimensions of technologies were integrated with respect to the predominant technology, coal.

Firstly, in order select indicators which relevant to SDG 7 and our case study, a literature study was conducted based on several criteria. After the analysis on the studies selected, GWP and LCOE indicators for environmental and economic dimensions were selected.

Furthermore, for evaluating the environmental performance of the technologies, LCA studies were used to quantify GHG emissions and to identify hotspots in life cycle stages. A methodology was followed to harmonise the published results of the selected studies to reflect the current status of Maharashtra conditions. The GHG emissions of solar PV was found to be 39 g CO_2 eq/kWh of which 89% was contributed from manufacturing phase of the modules whereas GHG emissions of nuclear energy was estimated to be 12.5 CO_2 eq/kWh in which 75% of the emissions is during HW production. The emissions of both technologies can be reduced drastically by importing input materials from countries that have low carbon intensity energy mix and by improvements in the technology used and the energy consumed. Over time, solar PV emissions tend to decrease because of the improvements in the system efficiency while nuclear energy emissions tend to increase because of decreasing uranium ore grades.

Thirdly, evaluation of economic performance of both technologies was carried out by using LCOE tool. DCF method was used to bring the future costs to NPV and after calculating LCOE, a sensitivity analysis was performed to know the influential parameters. Under the defined system boundaries, LCOE of solar PV was estimated to be 0.045 USD/kWh in which 85% of the costs are capital costs. whereas LCOE of nuclear energy was calculated to be 0.055 USD/kWh in which capital costs and O&M costs account to 50 and 37% respectively. Nuclear energy involves long lasting construction times and fluctuating and increasing fuel costs whereas solar PV has short installation time, capital intensive, high upfront costs and negligible costs thereafter. Over time, the LCOE of solar energy tends to decrease with improvements in technology while LCOE of nuclear tend to increase because of the increasing safety standards and inflation.

Lastly, an MCDA method, weighted sum approach was chosen for integration of two aspects as it provides platform for stakeholder participation and provides a transparent, inclusive and organised framework. Three scenarios were considered in which even extreme weights were considered for calculation of sustainability scores and the overall ranking of technologies remained same in the given scenarios. Clearly, solar energy is the winner in the range of the assumed extreme weights and is followed by nuclear and coal energy.

Based on the outcomes of LCA and MCDA of this study, policy implications were discussed. On economic front, electricity bundling of solar and nuclear energy is recommended to reduce the overall cost and to solve the issue of intermittency of solar energy. Other suggestions included easing liquidity and de risking for low cost financing needed for capital-intensive technologies. On the environmental front, GHG hotspot phases in both solar PV and nuclear energy were identified and policy recommendations were discussed. Overall, policies should be aimed at lowering or phasing out the fossil fuels and at providing enabling environment for increasing the low carbon technologies into the energy mix.

As far as LCA and MCDA framework in this research is concerned, the sustainability scores of the technologies help ranking the technologies. More than ranking the technologies, the deliberative process makes stakeholders come together on a platform to formulate problem, discuss trade-offs and come up with unique solutions to reduce the impacts. NITI Aayog can use the framework not only for the case of Maharashtra, but also for different states. The framework allows to arrive at a customised solution according to the preferences of all stakeholders while still be able to measure and compare the improvements in the sustainability aspect.

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List of Abbreviations

AHP	Analytic Hierarchy Process.
BOS	Balance of System.
CEA	Central Electricity Authority.
CBA	Cost Benefit Analysis.
DAE	Department of Atomic Energy.
DCF	Discount Cash Flow.
GWP	global warming potential.
GOI	Government of India.
GHGs	Green House Gases.
HW	Heavy Water.
IAEA	International Atomic Energy Agency.
IEA	International Energy Agency.
IRENA	International Renewable Energy Agency.
KAPS	Kakrapar Atomic Power Station.
LCOE	Levelized Costs of Electricity.
LCA	Life Cycle Assessment.
LCC	Life Cycle Costing.
LCIA	Life Cycle Impact Assessment.
LCI	Life Cycle Inventory.
LCSA	life cycle sustainability assessment.
MNRE	Ministry of New and Renewable Energy.
MAVT	Multi attribute value tree analysis.
MCDA	Multi Criteria Decision Aid.
NITI Aayog	National Institution for Transforming India Aayog.
NPCIL	Nuclear Power Corporation of India.
NPT	Nuclear Proliferation Treaty.
NSG	Nuclear Supply group.
PHWR	Pressurised Heavy Water.
PWR	Pressurised Water Reactor.
RAPS	Rajasthan Atomic Power Station.
RETs	Renewable Energy Technologies.
sLCA	Social LCA.
PV	Solar Photovoltaics.
SDGs	Sustainable Development Goals.
TAPP	Tarapur Atomic Power Plant.
UN	United Nations.

1. Introduction

1.1 Problem description

1.1.1 Energy Sector emissions

Energy sector has a prominent part in politics, security and economy. Along with increasing world population and economic growth, the demand and consumption of energy has significantly soared. Every society need services of energy to satisfy basic human needs such as cooking, lighting, health, mobility, space comfort, and communication. Energy consumption from fossil fuels has increased from 6632 million tons of oil to 11296 tons of oil in the time period of 1980-2008 and it is predicted that mean depletion time for global fossil fuel reserves such as oil, gas and coal are 35, 37 and 108 years respectively (Nejat et al., 2013). Additionally, the issue with increased energy generated from fossil fuel causes air pollution and Co2 emissions (see figure 1) which increases the risk of extreme heat, floods, drought and poverty. The continuous build-up of congregation of Green House Gases (GHGs) in the earth's atmosphere will lead to climate change which in turn results in enormous changes of ecosystem, steering towards catastrophic disruptions in living conditions, livelihoods, human health and economy (Field et al., 2014).

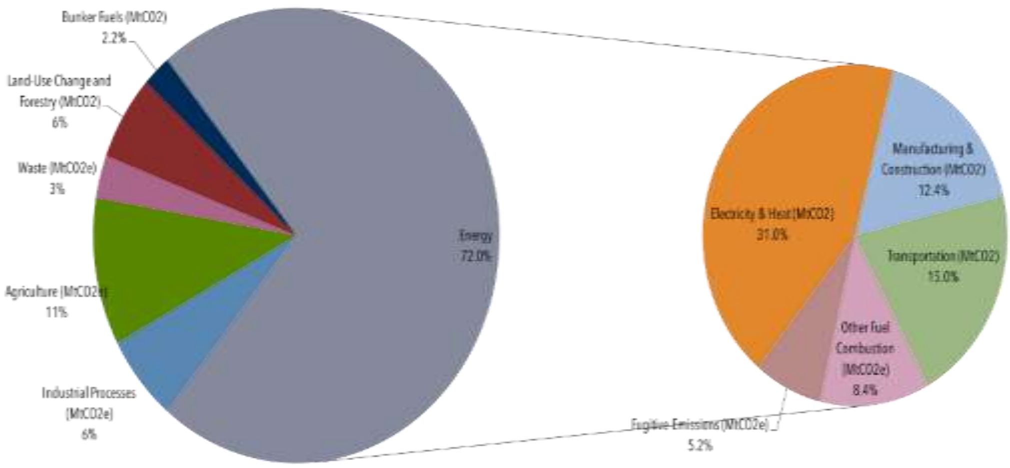


Figure 1. Global GHG Emissions by Sector in 2013.

1.1.2 Climate change agreement and Maharashtra, India

The new UN climate accord which was approved in 2015 in Paris, has set an ambitious goal to reduce global warming to less than 2 degree Celsius with a clear target of 1.5 degree Celsius. The principal goal of the Climate Agreement, namely the reduction of greenhouse gas emissions, will affect everyday life(Field et al., 2014). India is a developing country and is the fourth largest in terms of emissions and is estimated to take the third position in the short future. India's energy demand has been growing rapidly in the last two decades and most of the current electricity generated is from fossil fuels. Being a signatory of UN resolution, India has committed to execution of sustainable development goals (SDGs). The National Institute for Transforming India, popularly known as NITI Aayog, will provide the technical advice and coordinate the execution of SDGs in both Centre and States. The SDG 7 is to ensure access to affordable, reliable, sustainable and modern energy for all and the SDG 7.2 target is to increase drastically(40%) the share of non-fossil fuel sources in the world energy mix in terms of percentage of installed capacity by 2030(*Government of India ,Ministry of Power* , 2019).

Since the scope of India is too big and the targets are given to individual states, the state of Maharashtra in India which has the highest installed capacity of electricity generation and consumes about 12% of India's electricity (Kale & Pohekar, 2012) is selected for the study. Maharashtra has a total installed capacity of 43.6 GW with coal having a share of around 61% and renewable energy 30%. Figure 2 shows the portfolio of installed capacity in the state of Maharashtra in the year 2019 (*Policies | Ministry of New and Renewable Energy | Government of India*, 2019). It has 9.3 GW renewable energy installed capacity (excluding Hydro) and Ministry of New and Renewable Energy (MNRE) has given a target of 22GW by 2022 in order to achieve SDGs. However, to satisfy the growing demand and reduce coal import dependency, Maharashtra also aims to expand coal power capacity using the domestic coal which is of poor quality and creates high pollution.

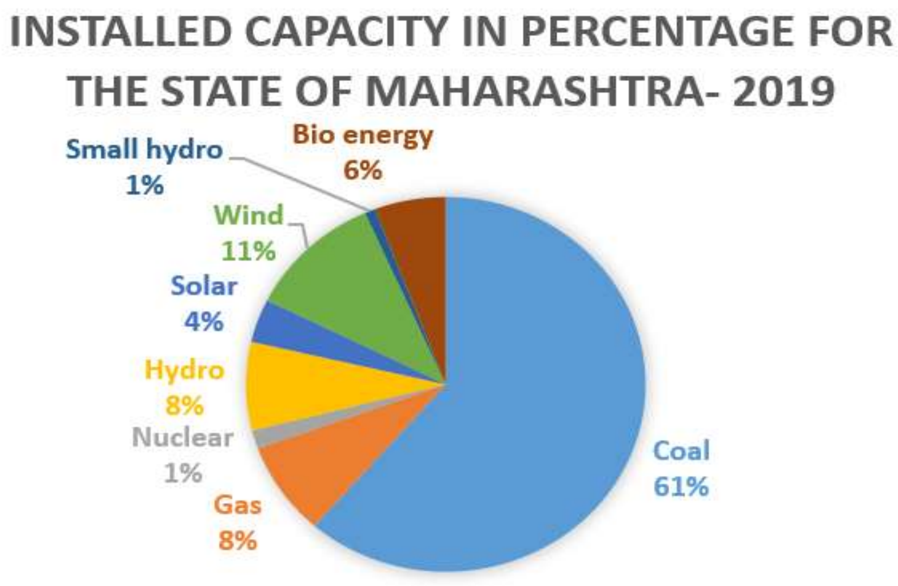


Figure 2. Maharashtra's electricity mix.

1.1.3 Energy transition

Energy transition aims to transform world's energy sector from fossil fuel based to zero carbon by 2050(Escamilla et al., 2019). It is indicative from literature that transiting from fossil fuel-based energy sources with low carbon technologies which includes solar energy, wind energy, geothermal energy, bioenergy, nuclear energy, ocean energy, hydropower would eventually help in achieving better environmental performances. It becomes crucial to evaluate the complete environmental footprint along with trade-offs between pros and cons of different renewable sources. The important global policies have the objectives of energy supply security, alleviating of climate change effects and economic growth. All over the world, researchers and policy makers have been conducting studies on analysing technologies figure out alternative investments that contribute to sustainability (de Paula do Rosário et al., 2020). For choosing the most sustainable technology, conflicting elements like environmental, social, economic and technical criteria in a given area have to be taken into account. For example, pros can be a reduction in CO2 emissions and less dependence on fossil fuels, but at the same time, the renewable energy technology might be expensive and can have effects on habitats or landscapes. Most of the energy policies are based mainly on cost of electricity and global warming potential aspects ignoring other environmental and social aspects. Other issues such as air pollution, water pollution, employment is also important. Hence, it is necessary to contemplate and integrate all three aspects of sustainability, environment, economic and social aspects in the comparison of technologies in Maharashtra, India.

1.2 Research methods

1.2.1 Life Cycle Sustainability Assessment

Life Cycle Assessment (LCA) is one of the most extensive method which can be used to any process, product or systems. It is basically a tool to measure a product's environmental impacts and resources used throughout its lifecycle. LCA in energy sector can be used to generate an analysis of the effect or impact that a power plant can have over its lifetime. However, sustainability assessment of energy technology has three aspects and on all three, life cycle perspective is relevant in avoiding problem shifting. This is basically required to avoid shifting problems between the impacts. In addition to that, when impacts are related with production processes, the problem shifting has to be avoided from one phase of the life cycle to other. it can also be considered in terms of spatial and temporal factors; like shifting problems from inside a region to the outside or from present generations to future generations. The extensive scope of LCA can be used to circumvent problem shifting from one environmental impact to other, from one phase of life cycle to other and from one geographic location to other (Finnveden et al., 2009). Many studies have performed LCA for different electricity generating technologies. In this study, data from literature which are relevant to Maharashtra conditions will be gathered and they are based on utility factor, capacity and boundary condition assumptions which are then used for analysis. For economic and social aspects, Life Cycle Costing (LCC) and Social LCA (sLCA) are developed. To integrate the social and economic aspects, a methodology called life cycle sustainability assessment (LCSA), based on LCA, was proposed and it provides analysis including all aspects.

1.2.2 Integration of aspects

Life cycle approach is used to measure or quantify indicators that represent the technology's impact or performance on different aspects. The indicators such as global warming potential, levelized costs are used to assess environmental and economic. The measurement units for these indicators are different making it difficult for their integration and comparison of these technologies. for minimizing the variation among the indicators and translate and integrate the indicators into a single unit, various techniques are used (de Paula do Rosário et al., 2020).

Cost Benefit Analysis (CBA) and Multi Criteria Decision Aid (MCDA) are most frequently used tools for translation of different measurement units of the indicators into same unit. The combined use of LCA and MCDA in the assessment of electricity technologies have been receiving contributions for various parts of the world. In energy sector, many studies (as shown in table 1) have used the combination of LCA and MCDA. While CBA enumerates all environment impacts in money terms, MCDA quantifies them with scores and relative importance of different criteria without requiring monetization. Even though MCDA brings in question of reliability of weights and subjectivity, it can be acquired by data, involving stakeholders, expert analysis and it seems to bring inclusive results as it involves both stakeholders and decision makers. CBA can be criticised on basis of 'rule by experts' who can be alternated by involvement of big set of public and stakeholders along with policy makers and academic experts. It basically helps in overcoming hardships in CBA related to equity and distribution of individual incomes. While CBA can make use of only quantitative data, MCDA can use both qualitative and quantitative data and can be applied to wider range of problems and indicators (Bhagtani, 2008). MCDA instead of making actual decisions, it aims to help policy makers organise and synthesize different kinds of criteria in from of indicators. Policy makers feel comfortable and confident in their decisions as they would have considered and evaluated various complex criteria. CBA would be an ideal option when considering economic performance, but in this case of integrating environmental and economic aspects of electricity generating technologies which affects and involves various stakeholders, CBA would not be as inclusive and robust as it will not be able to monetise all kinds of benefits (Bhagtani, 2008). Hence, MCDA is dominantly used to normalize the given data and to analyse various alternative technologies giving various weights to every indicator, leading to integrated life cycle assessment and comparison of technologies.

MCDA process is a context specific process and does not have a universal understanding like monetization of CBA. This means that weights in the MCDA process are limited to the context and do not have meaning externally. In solving case study, for developing the context, it becomes important to consider existing predominant technology in the system. Maharashtra has coal as a major source of electricity production and the environmental and economic performances has been well established in the literature. Hence in this case study we take the environmental and economic performances of coal power plant directly from literature and use it in the integration process along with the other low carbon technologies performances that we analyse in this study. The whole outcome enables us to compare technologies and develop policy implications.

1.3 Main research question and sub-questions

Among the low carbon technologies, solar energy has a huge potential for power generation in Maharashtra and the state is already in the process to boost this enormous resource. Also, India has one of the world's largest uranium reserve for producing nuclear energy and Tarapur plant in Maharashtra was started as early as 1969. Therefore, *solar Photovoltaics (PV) and nuclear energy* will be considered for the study.

For the 25-week Master thesis to be pursued, the following broad research questions are to be answered.

How can the combination of LCA and MCDA help Maharashtra's policy makers in deciding alternative electricity generating technologies that can contribute to a sustainable development of electricity production?

- What are the most considered environmental and economic indicators in the literature?
- What is the environmental performance of the solar PV and nuclear energy technologies in Maharashtra, India?
- What is the economic performance of the solar PV and nuclear energy technologies in Maharashtra, India?
- What are the policy implications based on the LCA and MCDA outcomes of alternative technologies?

1.4 Objective and deliverable

The main objective is to evaluate low carbon technology alternatives for Maharashtra, India considering at least two among environmental, economic and social aspects. Main focus is to evaluate technology's performance, assess their pros and cons under Maharashtra boundary conditions and seek preferences in which the technologies perform better compared to other options. The indicators of environmental aspects are quantified through data gathering from existing LCA studies. The economic indicators such as levelized costs are calculated based on secondary sources. For translating different measurement units of these indicators to same units, one of the integration methods are used. During the integration process, the indicators are normalised considering the performances of predominantly available coal power plants. Then, based on the integrated performances of economic and environmental aspects, evaluation and comparison of alternative options will be performed.

1.5 Scientific contribution

For the state of Maharashtra, India, several studies have focused only on one electricity technology and considered only one aspect of sustainability mainly, global warming potential. Some studies have considered only economic perspective and have not included other sustainability criteria. Very few studies have considered more than one technology and included one or two aspects of sustainability. None of the studies have integrated the aspects in order to help the policy making.

This study will contribute in the following aspects:

- The study will consider one indicator each from environmental and economic aspects for the case of Maharashtra, India.
- The study will also use integration methods to know the overall performance of the technologies which can help in comparison of technologies.
- The outcomes of the study are used to understand and discuss the policy implications for the case.

1.6 Visualization of the research design with research methods and activities (flow diagram)

The following (see figure 3) is the research design and framework that will be followed in thesis to find the optimised scenario for Maharashtra, India. One indicator from environmental, economic aspects will be considered for evaluating solar and nuclear energy.

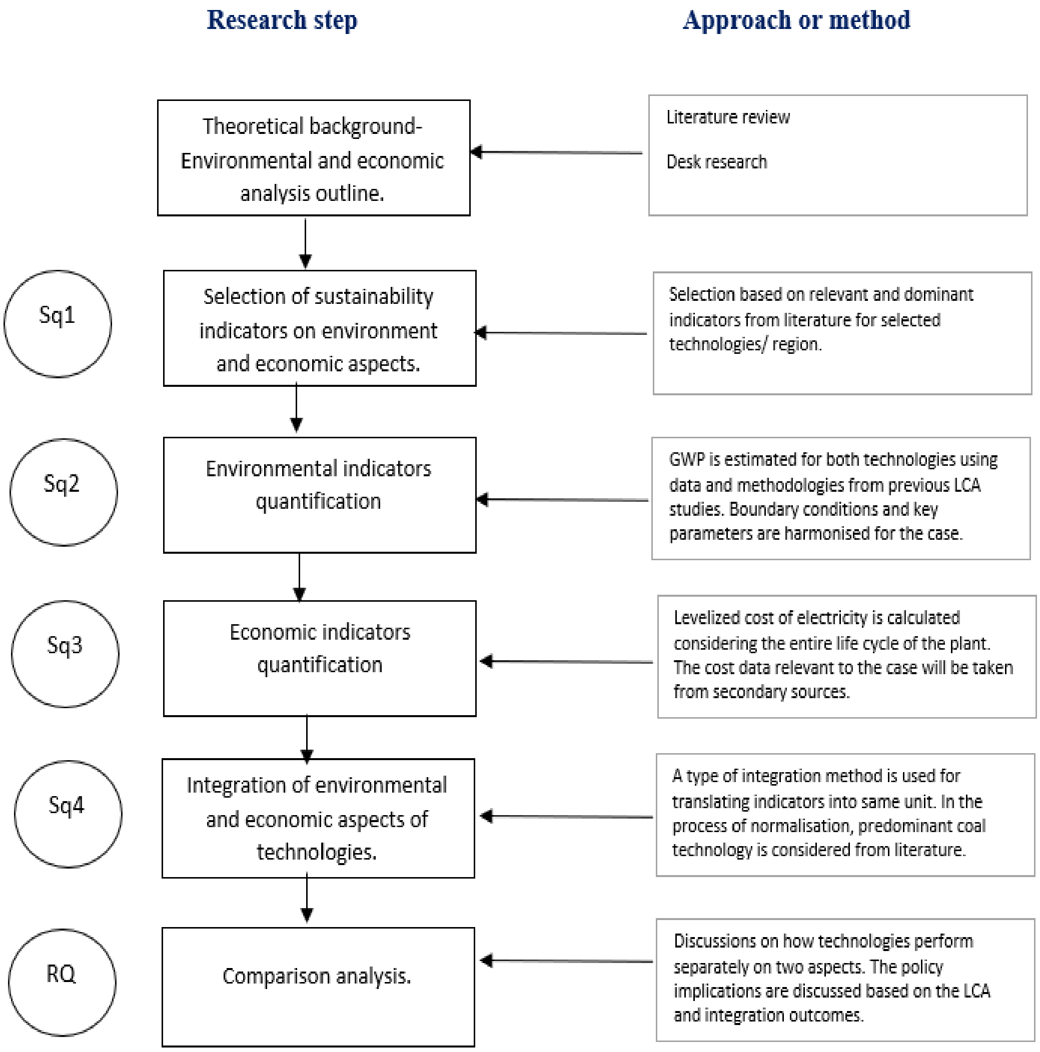


Figure 3. Flow diagram of research methods and activities.

2. Indicator selection

2.1 Search methodology

The search started with simple keywords "life cycle assessment AND energy" and A plethora of studies appeared. This was done as a part of exploratory search to analyse the keywords utilized in the studies. A lot of studies which consisted of only environmental aspects appeared. Four categories of studies could be identified in the field of energy issues: Electricity production technologies evaluation, Energy policy and Management, other energy sources evaluation and regional electricity planning. With the notion of how big environmental and economic aspects influence policy making in a Nation's electricity mix, the objective of the work was established.

From the previous search, the keywords in the category energy policy and management category were noted and are mentioned below.

"LCA" OR "LCIA" OR "LCI" OR "LIFE CYCLE ASSESSMENT" OR "LIFE CYCLE SUSTAINABILITY ASSESSMENT"

"ELECTRICITY GENERATION" OR "POWER GENERATION" OR "ELECTRICITY PRODUCTION" OR "ELECTRICITY MIX"

These keywords were used separately and in combinations with a filter of 'Article title, Abstract, Keywords'. The keywords with Boolean operators like "AND" and "OR", was helpful in narrowing down the exploration. The selection was based on the following criteria.

1. The work should include all the three aspects and indicators, environment, economic and social or more.

2. Any integration method should have been used for these indicators.

To further narrow down the vast research area, the articles before 2013 were excluded. The relevant filtered articles were imported to Mendeley where it was possible to exclude duplicates and categorise the literature. In these filtered articles, the selected articles for this study are based on the number of citations, the application, location and LCA methods. Further when the articles were interesting and highly cited, the bibliography and the cited sources were explored to further add some studies. This, a sum of ten papers or studies lasted for complete analysis. These studies are mentioned in the table 1 below.

Table 1. Studies that use the combination of LCA and an integration method.

Study	Aim and Scope	Technologies considered	Sustainability indicators (LCA)	Integration Methods
(Santoyo-Castelazo & Azapagic, 2014)	Sustainability assessment of energy systems in mexico: integrating environmental, economic and social aspects	Total:13 LCT[a]: geothermal, hydro, nuclear, ocean, solar thermal, solar pv, biomass	Total: 17 Environment:10 Economic:3 Social 4	MCDA
(Atilgan & Azapagic, 2016)	An integrated life cycle sustainability assessment of electricity generation in Turkey	Total: 8 LCT: Wind, Geothermal, Large reservoir, small reservoir, Run of river	Total: 20 Environment:11 Economic:3 Social:6	MCDA
(Volkart et al., 2017)	Multi-criteria decision analysis of energy system transformation pathways: A case study for Switzerland	Total:9 LCT: Solar PV, wind, Biomass CHP, Hydro, Nuclear	Total: 17 Environment: 5 Economic:4 Social: 8	MCDA
(Maxim, 2014)	Sustainability assessment of electricity generation technologies using weighted multi-criteria decision analysis-global	Total: 14 LCT: Nuclear, Hydro, Geothermal, PV, Wind, Solar thermal	Total: 11 Environment:2 Economic:2 Social:4 Technical:3	MCDA
(Klein & Whalley, 2015)	Sustainability assessment of electricity generation technologies using weighted multi-criteria decision analysis	Total:13 LCT: Solar PV, Solar CSP offshore wind, onshore wind, bio power, Nuclear, geothermal, Hydro,	Total: 8 Environment:4 Economic:1 Social:2 Technical:1	MCDA
(Stamford & Azapagic, 2014)	Life cycle sustainability assessment of UK electricity scenarios to 2070	Total: 6 LCT: Nuclear, Solar PV, Wind, Biomass	Total: 36 Environment:10 Techno-Economic:12 Social:14	MCDA
(Troldborg et al., 2014)	Assessing the sustainability of	Total:11	Total: 9 Environment:3	MCDA

	renewable energy technologies using multi-criteria analysis in scotland: Suitability of approach for national-scale assessments and associated uncertainties	LCT: onshore, offshore wind, Hydro, wave, Tidal, Geotharmal, PV, Solar thermal,	Economic-Social: 3 Technical:3	
(Hong et al., 2014)	Nuclear power can reduce emissions and maintain a strong economy: Rating Australia's optimal future electricity-generation mix by technologies and policies	Total:18 LCT:rooftop PV, Large PV,onshore, offshore wind, geothermal, biomass, biogas, ocean, Nuclear, Hydro.	Total: 8 Environment:6 Economic:1 Social:1	MCDA
(Khan, 2020)	Sustainability challenges for the south Asia growth quadrangle: A regional electricity generation sustainability assessment (India, Bangladesh, Bhutan, Nepal)	Total: 8 LCT: Nuclear, Solar, Wind, Hydro.	Total: Varied Environment:4 Economic:4 Social: Varied	MCDA

* Low Carbon Technologies

2.2 Technologies selection

The first step in performing LCA is to select technologies to be ranked and generally the selection is formed on the current scenarios of a country or a region. The technology selection can be categorised into the selection based on (i) current electrical mix technologies that the region already has (ii) the potential technologies that can be incorporated in future. Studies like (Hong et al., 2014; Maxim, 2014; Troldborg et al., 2014; Volkart et al., 2016) consider wide range of technology options, present and future possibilities and objectively select technologies among them. It might be through interactions with experts in industry or a government policy for future or even based on technically feasibility. It is interesting to note that (Hong et al., 2014) considers nuclear energy in the studies despite Australia's prohibition of building or operation of a nuclear power plant. Also,(Volkart et al., 2016) included geothermal and carbon capture storage in spite of technology maturity variation and the need to be demonstrated yet. Subjective assumptions like, the technology will be mature from a future date will be made in these scenarios. Future political decisions and technology development can change or affect future electricity mix and full mix of energy options must be transparently and objectively selected and compared with methods using quantitative data. However (Klein & Whalley, 2015; Santoyo-Castelazo & Azapagic, 2014; Stamford & Azapagic, 2014; Volkart et al., 2017) consider current scenario's electricity mix and do not consider the other alternatives which make the scenarios limited and impractical.

2.3 Indicator selection

Selecting a group of sustainability indicators is a crucial step in the assessment. The literature on indicators is continuously evolving and has hundreds of indicators that can be combined and customised to match with author's scope and objectives(*Indicators of Sustainable Development: Guidelines and Methodologies*, 2007). The indicators are well known for interpreting and monitoring complex energy systems and to help decision makers to make decision with this information. They have the following purposes. 1. They are helpful in knowing the current performances or conditions of a system(magnitude) 2. They measure the efficacy of the policies and actions to push the energy system towards sustainability. 3. They allow us to unearth changes in social, economic and environment systems(McCool & Stankey, 2004).

The Indicators are in the selected studies are considered and selected based on the subjective perception. A big list can result in extensive and overwhelming details for both readers and researchers. The confused priorities can be avoided by following a stringent criterion. After the analysis on the documents selected, the indicators which are used more frequently were recognised. In the economic dimension, not only operation or implementation costs are considered, but also the costs throughout the whole project. The most used indicator for economic dimension is Levelized costs. When it comes to environment dimension, Global warming potential which measures Greenhouse gases (GHGs) emission was the most used. And finally, in social aspect, total employment (direct+ indirect) was prominent.

To avoid confusion, The European Union integrated project New Energy Externalities Developments for Sustainability (NEEDS) rooted a set of important or dominant criteria and indicators which can be used for analysing energy technologies (refer appendix 1). This was based on a comprehensive survey of all the sustainability initiatives and proposals of criteria and indicator groups by national and international organisations which includes United Nations (UN), OECD/NEA, OECD, and International Atomic Energy Agency (IAEA) (NEEDS, 2009). The established indicators include 36 indicators comprising 9 economical, 16 social and 11 environmental indicators. This group of indicators are suited for MCDA analysis with an objective of comparing technology alternatives. However, for decision or policy making purposes, a small set of few dominant indicators with less complex frameworks have more promise.

In our case study, Government of India(GOI)'s think tank, National Institution for Transforming India Aayog (NITI Aayog), has the responsibility of looking after the implementation of 2030 plan of sustainable development of the states in India. According to India's federal structure, the states like Maharashtra are responsible for Sustainable Development Goals (SDGs) and NITI Aayog has made prominent contributions by sensitizing stakeholders, regularly reviewing the progress, providing support, facilitating and sharing of knowledge between states. Among several SDGs, SDG7 aims to make the energy clean and affordable(A. K. Jain & Mishra, 2019). The SDGs are commitments by world nations which sets out a universal agenda to achieve environmental, economic and social dimensions of wellbeing of societies. India formulated its national development plan which is in line with

SDGs and it has 17 goals. In the SDG India index dashboard, an overview of all SDGs is provided and SDG7 is related to energy which has a goal of providing 'affordable' and 'clean' energy to all. The goal ensures access to affordable, reliable, sustainable and modern energy for all. However, it is stated that defining and measuring the success of these goals is a major challenge across the world(Aayog, 2020). Hence in this study we try to select the indicators based on the SDG 7 and dominantly used indicators in the literature.

For decision making purposes, a small set of indicators with less complex frameworks are more promising(Aayog, 2017). Hence, we try to translate the important goals into indicators. SDG 7 goal is to provide access to clean and affordable energy to all. Here the keywords clean and affordable can be translated to environmental and economic aspects. Clean energy means to reduce greenhouse gases from energy sector and among the 36 indicators established by NEEDs project, the relevant indicator to measure this would be global warming potential (GWP) or GHGs. Another key term, affordable energy is directly related to the price of the unit electricity a consumer pays and it depends on the total costs of the plant and the electricity produced over the lifetime. The Levelized Costs of Electricity (LCOE) is an indicator represents the costs per unit over its lifetime and hence it is a good indicator of economic aspects. In the literature study conducted here, the same indicators are found to be dominant environmental and economic indicators. They are defined as follows.

Global warming potential (GWP): GWP expresses the potential of various GHGs to cause climate change. The reference GHG for this indicator is CO2. It can be calculated with following equation. Once the total GWP (in grams) over the lifetime of a plant is calculated, it is divided with electricity produced (in kWh) over its lifetime to get the final output in terms of g CO_2-eq/ kwh.

$$GWP = \sum_{j}^{J} GWP_j \times B_j$$

where:
GWP - global warming potential (kg CO_2-eq.)
GWP_j - GWP factor for GHG j (kg CO_2-eq./kg)
B_j - emission of GHG j (kg)
J - total number of GHGs.

Levelized Cost of Electricity: The indicator considers the total lifetime power generation and complete costs to estimate a price per kwh (USD/kWh) energy generated.

$$LC = \frac{T_{AC}}{A_E}$$

where:
LC - levelised costs (US$/kWh)
T_{AC} - total annualised costs of electricity generation (US$/year)
A_E - annual electricity generation (kWh/year)

Hence, we use these indicators in our study for measuring environmental and economic performance of solar and nuclear energy in Maharashtra, India.

3. Environmental performance of technologies

All around the world, there has been an increased apprehension about environmental issues. The impacts of electricity production technologies on environment is a critical issue in regard to sustainability and hence it is a pivotal research topic in several countries. Renewable & non-renewable energy technologies are subjects of research and policy making aimed towards the development of clean energy ways. On these grounds, for sustainable development of electricity generating technologies, low carbon technologies are gaining prominence for being cleaner.

In this study, two prominent energy sources solar PV and nuclear has been chosen for analysing the impacts. Hence, for the knowledge of potential environmental impacts from each technology, the need of LCA arises. It is an environmental tool which accesses and accounts the environmental aspects and potential impacts associated to processes, products or services. It helps measuring and analysing possible environmental impacts of the selected power generating technologies and it is a prominent mechanism in modern industrial environmental management.

Among various methods used for analysing environmental impacts, the comprehensive and most abundantly used is LCA. This method can be utilized for wide range of arenas and this approach can be very useful in energy systems as it points out areas with prominent impact for the environment taking relevant factors into consideration which allows comparing of various technologies. This is a tool used for robust analysis of the indicators and impacts created through the life cycle of the activity. LCA has been emerging over recent few years. The prominence of this tool is depicted by its standardization from the international standardisation organisation. It can help in various strategies which varies from adoption of strategies to reduce GHGs, hence decreasing the carbon footprint, to broader assessments, like comprehensive impacts of different electricity generating technologies.

In this regard, many cases, reviews and inventories are already found in the literature. This study utilizes the existing state of the art literature for solving the case study of Maharashtra. However, technologies cannot exist independent of the society. The features and configurations of technology depend on the characteristics of society of the place where they exist. LCAs employ parameters or configurations that do not necessarily reflect electricity production system in Maharashtra's current status. The existing studies publish a range of GHG emissions and have considered various performance parameters or configurations depending on the case. Hence, it is required to clearly define the scope with regard to space and time of any technology.

A simple and straightforward methodology is used in this study to harmonize the LCA outcomes of greenhouse gases on the grounds of important key parameters on which the power yield of each electricity generating plant is based on. This can be fuel availability factor, capacity factor, system efficiency and system lifetime. The goal is to apply a methodology to carry out harmonisation on the previous published LCA studies which has a span of results and inflict approximates of performance parameters which are relevant to the case study of Maharashtra, India.

The goal is to understand the characteristics of GHGs from different life phases of the solar PV and nuclear energy only. Once the outcomes are estimated, we compare the GWP of solar PV and nuclear energy with GWP of predominant technology, coal in chapter 5. Many studies have calculated the GWP of coal power plant and since the technology is old and saturated, many studies are available in literature. (Singh et al., n.d.) published that GWP of coal plant is estimated to to be 886 g CO2/ kwh and we use the same during the integration of the aspects. The goal of coal's GWP is not to analyse different life phases and hotspots, but to use as a reference for Low carbon technology estimates in MCDA as the technology is predominant in Maharashtra, India.

3.1 Life cycle analysis

LCA is a mechanism for analysing the energy needs and environmental burden for a product, process or a service, performed by recognising energy needs and materials consumed and waste emitted to the environment. This analysis basically analyses the complete life phases of the product, process or service, which typically includes mining and processing of the raw materials extracted from nature, manufacturing activities, shipping, supply chain activities, utilization phase, reuse, recycle and discarding.

It can be split into following parts (see figure 4).

- Goal and scope defining: This part of selected product, process or technology deals with boundaries of the system, data sources of the impacts and functional unit utilised for the assessment are described.
- Life Cycle Inventory (LCI): LCI is a comprehensive inventory of inputs and outputs with respect to a defined system. It includes clusters of data required for achieving study's goal, quantifying air emissions, energy, raw material needs, emissions to air and water, solid waste and various kinds of environmental emissions that occurs throughout the life phases of the product, process or a service.
- Life Cycle Impact Assessment (LCIA): This part's aim is to analyse the potential environmental impacts using the results of LCI. The data from LCI corresponds to specific impact categories and indicators.
- Life Cycle Interpretation: In this last part of LCA methodology, outcomes of LCI or LCIA are discussed and summarised for developing conclusions, recommendations and policy making with respect to goal and scope definition(Anon, 1998).

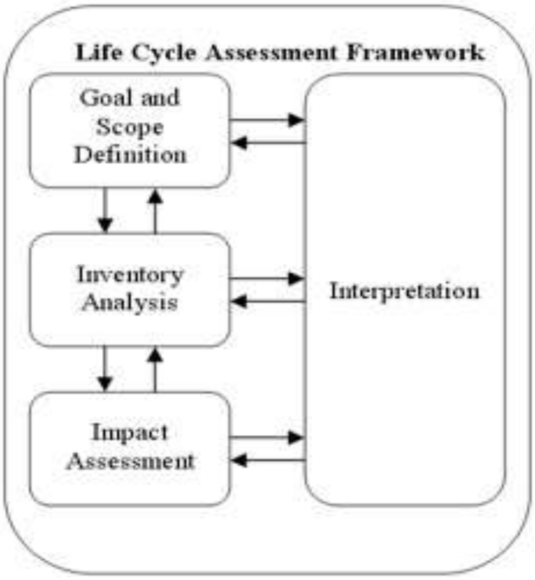


Figure 4. Life cycle assessment framework.

3.2 Environmental performance of solar PV

Solar PV is one among the most sought-after renewable energy sources and has an environmentally friendly approach. PV panels emit no pollutants during the generation of electricity as it directly converts the light from sun to electricity without any heat engine or moving parts (Wu et al., 2017). The study uses GWP as an indicator for environmental performances of the solar PV system. They are robust and flat in design and need limited maintenance. It could be setup as standalone systems which can give outputs varying from micro to megawatts. These are the factors for a vast range of applications. However, many studies claim that solar PV need not be a clean technology in the view of the fact of its high-level consumption of energy & heavy emissions of GHGs during its manufacturing. Nevertheless, while considering complete life cycle from quartz mining, silicon ingot process, cell and module manufacturing and decommissioning of PV systems, the greenhouse gas emissions should not be ignored. Hence it becomes hard for predicting appropriate and valid outcomes if only few life phases are analysed. Even though a considerable amount of energy is consumed during production, it would be much lesser than the energy output over the lifetime of system. Hence it is necessary to quantify greenhouse gases from LC perspective to analyse the environmental performance.

Maharashtra has a target of installing 11.96 GW of capacity by 2022 according to the sustainable development goals of the country. In the year of 2019, the installed capacity of solar PV was 1.63 GW. Crystalline silicon-based PV has a majority market in India and 90% of the solar cells/modules are imported from China (Smiti, 2020). To assess the renewable energy supply in Maharashtra, it is required to examine environmental impacts of poly crystalline silicon PV technology and to approximate potential phase is in China and the plant location is in Maharashtra, India. At first, GHG gas emissions depend on various factors which includes cell technology, annual solar irradiation, type of installation, cell efficiency, installation type, capacity factor, lifetime, carbon intensity of primary energy mix etc. These factors depend on the manufacturing location and plant location. Secondly, different system boundaries are applied in different studies. For example, some studies consider only the module emissions, other studies consider the complete lifecycle of the technology contributing to the variance in the outputs of different studies. Hence these factors have to be considered while estimating the greenhouse gas emissions of the technology in Maharashtra. In this study, relevant LCA studies were harmonised to examine GHG gas emissions when the PV module is produced by china and solar plant is implemented in India.

This study has two advantages. First, the final estimates are based on reliable and robust studies which rely on credible data sources. Second, the estimates reflect the current status in Maharashtra, India. To achieve this, the following methodology is performed. First, the boundaries of the technology or the system is defined. For example, type of solar panel, type of installation, life cycle phases included in the study, functional unit etc. In this study, we are considering ground mounted, utility scale poly crystalline solar PV systems as they are abundantly or dominantly used in the state. Second, a stringent methodology is applied to filter out irrelevant studies and consider studies which are recent and relevant to the technology and type of installation defined in the system boundaries. The screening process is mentioned in detail in the upcoming sections. Third, once the relevant studies are selected, factors including system configurations, key parameters, data sources and data assumptions are carefully assessed. These are helpful in analysing the variance in different study outcomes. The key performance parameters and configurations are different for various studies resulting a range of outcomes. Fourth, to reduce variability, outcomes are harmonised with parameters configurations which are applicable to the case of Maharashtra, India. The harmonisation factors are mentioned previously. Fifth, for selecting a final outcome(study) among the various studies which are harmonised based on the parameters relevant to the state of Maharashtra, 5-point criteria are applied. The five criteria are transparency, latest data, completeness, relevance of manufacturing location and relevance of plant location. Sixth, the characteristics of the different life phases of the system from the perspective of global warming is discussed. The impacts of technology improvement on GHGs in different life phases in the future were discussed. Furthermore, a sensitivity analysis would be carried out to know the important parameters which affect the GHG emissions and to what extent.

3.2.1 System Boundaries

The goal of the study is to analyse the life-cycle environmental performance of solar PV from different studies and facilitate a scientific rooting for making policies concerning the sustainable development in Maharashtra, India. As we discussed earlier, technology cannot be independent of society and when dealing with multiple LCAs, there should be a fair and correct comparison. Hence clearly defining the system boundaries is important. The boundaries of the system of this study considered are depicted in figure 5 and it includes upstream processes, spanning from extraction of silica to the growth of silicon bar and ingot, and midstream processes that involves cell and module manufacturing in addition to aluminium frame fabrication. Ground mounted large-scale PV systems studies are considered here and they need extra equipment and materials, like grid connections, concrete for mounting and office space.

Because poly- Si PV systems accounts for most of the India's PV products, this study focuses on utility scale, ground mounted, poly-Si PV system as a representation of the Maharashtra's solar PV system. Usually, the life cycle of a product includes the stretch ranging from its fabrication, utilisation, and maintenance to its last discarding process and we include the same in this study. The selection of studies procedure for analysing the life cycle study is mentioned in the section search methodology. The functional unit in most of the LCA studies in literature is 1 kWh and it is kept same in this study for maintaining cohesiveness and comparability.

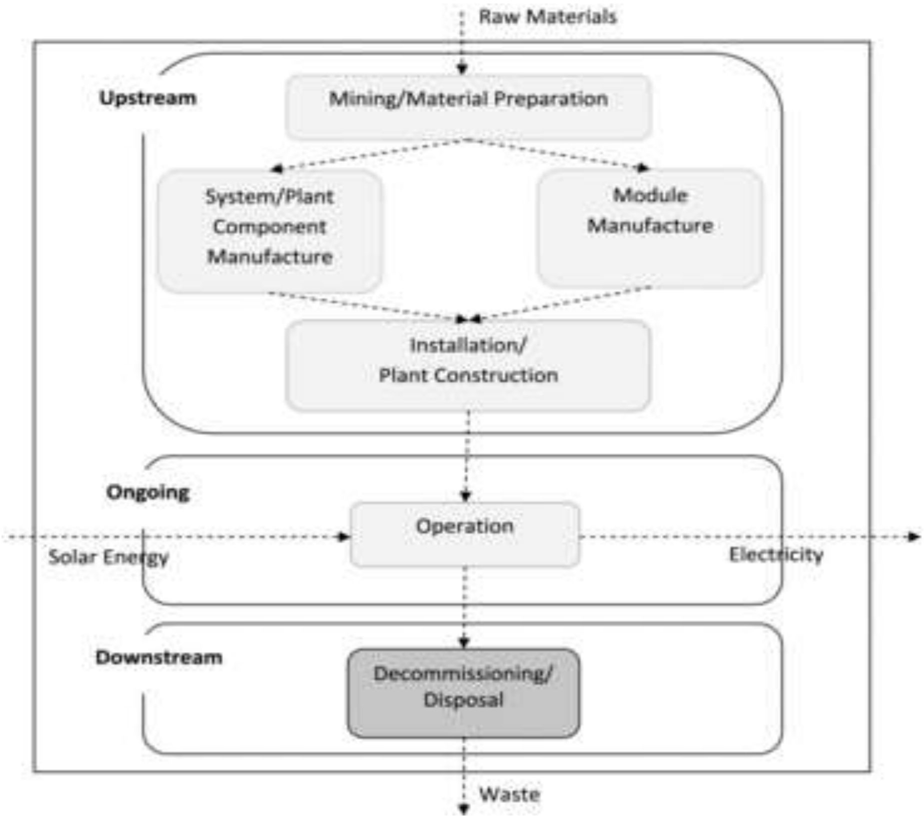


Figure 5. System boundaries of solar polycrystalline PV system.

3.2.1.1 Manufacturing or fabrication of PV station

PV station manufacture is the complicated and energy consuming process. First part of the production is related to the PV systems, which involves mining of quartz, extracting UMG-Si, SoG Si phase, ingot growth, slicing of wafers, cell production, solar module manufacturing, supplementary materials like packing glass, adhesive films of EVA, and various electrical items.

The other section will be building of the utility scale PV plant, and material shipping to the place, with the Balance of System (BOS), which has aluminium structures, cables and inter-connection products, and inverters.

3.2.1.2 O&M of PV station

The process of electricity generation from sunlight by the PV modules is completely a physical one and there is no reaction of chemicals or there is any moving part. Therefore, no emissions of pollutants are made and also there is no consumption of energy. Nevertheless, with time, small proportion of replacement of PV modules or other auxiliary components is possible. Also, PV panel cleansing is necessary for electricity decreases for the reason of the dust accumulation on the panel. Hence, a fixed amount of energy expenditure and GHG emissions do occur while the practical activities of solar PV station O&M are carried out.

3.2.1.3 Decommissioning of PV station

When the PV panels in the plant reached their end of lifetime, they will be decommissioned. The last phase of the LC includes deconstruction, recycling & disposal. Recycling of aluminium structures for module, steel structures, cabling and inverters can slightly vary GHG emissions. But the recycle method takes huge amounts of energy which indirectly contributes to GHGs. Other activities like concrete dismantling will also contribute to GHG (Hsu et al., 2012).

3.2.2 Search Methodology

As mentioned in the system boundaries, the study is limited to polycrystalline silicon PVs. The study began with a literature search using the following search keywords on web of science, Scopus and google scholar. By using the three set of key words as mentioned in table 2, the search results were filtered to 366 papers. As solar PV technology is improving at a tremendous pace in terms of manufacturing and the efficiency of the panels, the old studies become outdated and it is necessary that only recent studies are chosen. Considering this, studies before 2014 are not taken into account.

Table 2. Search methodology for solar PV.

Filter type	Selection	Papers
Keyword	LCA OR LCIA OR LCI OR Life cycle assessment OR life cycle sustainability assessment	44354
Keyword	Solar PV	479
Keyword	Electricity OR Power	366
Year	2014- 2020	263
screening 1		33
screening 2		4

3.2.2.1 Screening 1

The studies which lacked sufficient documentation for the harmonisation process are removed. For example, Conference papers, presentations less than 3 pages are filtered out.

References which were not available in English were not included. Even though, system boundaries consider technology's life phases from fabrication to disposal, solar LCA studies need not consider every stage as the manufacturing emissions are heavily weighted toward the upstream activities like material manufacturing processes and module manufacturing. Many studies make assumptions in some of the life cycle phases and hence the studies which have made some assumptions were not filtered from consideration in this study. This process leads to outcome of 33 studies.

3.2.2.2 Screening 2

The second screening process consists of four important criteria:

- The studies were further filtered based on the type of panel (polycrystalline silicon panel), type of installation (ground mounted utility scale panel).
- The study must have considered life cycle phases from materials mining and manufacturing of the panels as they are biggest contributors to the GHGs for polycrystalline silicon PV panels.
- The study should have minimum described methods, values of inputs, sources, performance parameters and the LCA outcomes.
- The study must be relevant to current state of polycrystalline silicon PV panels.

The second screening process limited the number of studies to 4 from which this analysis is conducted.

3.2.3 Data sources and Data assumptions

Polycrystalline PV LCA studies which qualified every screening are presented in the table 3, with parameter values and characteristics from those studies. Table 4 describes the data sources and the assumptions made in the study.

Table 3. Selected studies and performance characteristics for solar PV.

Author	Year	Location	Irradiation	PR	Efficiency	Lifetime	GHG
(Fu et al., 2015)	2015	China	1300	0.8	16	25	50.9
(Hou et al., 2016)	2016	Northwest china	1600	0.75	17.5	25	60.13
(Miller et al., 2019)	2019	Mumbai, India	2086	0.8	16	30	38
(Kim et al., 2014)	2014	South Korea	1310	0.8	14.9	30	31.5

Table 4. Data sources and data assumption of selected studies.

Author	Data source	Assumptions
(Fu et al., 2015)	Companies that represent Multi Si industry Secondary sources 2012, 2008 Calculation: Gabi4, Eco invent database	• Data assumptions: Some simplifications and assumptions had been made for processes that were not in the database, which were substituted by other similar processes included in the GaBi4 or Eco invent data- base. • Transportation effects were not taken into account in the above analysis. • Didn't consider the balance of system (BOS) • End of life data is not available and is slightly underestimated (1.9% in other studies) • The use and maintenance of PV systems was not taken into account
(Hou et al., 2016)	Latest data was collected by combining and balancing data from published literatures, field visits of key PV enterprises, expert and professional engineer interviews and questionnaire surveys. (2013)	• Energy consumption and GHG emissions during this process thus include the processing of BOS materials and fossil fuels burned in transportation and assembly of the system. • During operation, it is assumed that 0.1 % is the replacement ratio. • For convenience, only road transportation which uses is considered here. • Assume that GHG emission during PV station operation is 0.1% of the GHG emission during PV manufacturing • In this process, recycle and reuse of cable, inverters and metal frames, etc. can partly offset GHG emissions. Since no first-hand data is available for this process, this value is not taken into account here
(Miller et al., 2019)	primary source for this data is the Eco invent V3 database. For the Chinese mc-Si LCIs, approximately half the data are from 2014 and half from 2011.	• Does not account for emissions from EOL processes • In this analysis, transport is treated as a background process that contributes to multiple foreground stages.
(Kim et al., 2014)	Simapro 7.1 Pre manufacturing-Ecoinvent, 2000–	• The recycling and disposal of quantities of materials contained were calculated based on

	2007a, Korean national LCI D/Ba Others- primary and secondary sources (2009-2011). field data, but literature and pilot plant data were also incorporated	each material's recycling and disposal ratios provided by pilot processes • Power conditioning and BOS system included • Transport is not mentioned

3.2.4 Harmonisation – key parameters

The selected studies outcomes vary over a range of values from 31.5 to 60.13. Apart from the differences in data sources and data assumptions, there are two main reasons. First being that the key performance parameters as mentioned in table are different for various studies. The important key parameters which affect the GHG gas emissions are efficiency, performance ratio, annual solar irradiation, lifetime, primary energy mix carbon intensity. Second reason for GHG variance is that the boundary conditions are different for the studies considered. In our case study, the solar panels are majorly imported from china which means that manufacturing location is China and plant location is Maharashtra India. Many of the key performance characteristics depend on the power plant location and manufacturing location and It is important to categorize the key performance parameters based on location. Parameters like Annual solar irradiation, performance ratio and lifetime are dependent on plant location and parameters like primary energy mix from which energy is consumed for manufacturing of panels is dependent on manufacturing country. Hence, for reducing the variance and estimating the greenhouse gases for the case of Maharashtra, harmonisation process needs to be carried out.

This method harmonizes the filtered literature published estimations of LC GHGs at a broad stage. This can be performed by changing few influential key performance parameters to the relevant data of the case & applying same system boundaries. A study conducted by (Hsu et al.coal 2012) used the following equation for harmonising key performance characteristics of the GHG gas emissions to produce comparable and consistent results. In this study, we use the following equation to harmonise different performance characteristics to make it compatible to the case study of Maharashtra.

$$GHG = \frac{W}{I \times \eta \times PR \times LT \times A},$$

(Hsu et al., 2012)

GHG: is the GWP per unit of power generated (g CO2-eq/kWh).

W: is the weighted mass of GHG emissions over complete lifetime of the PV system(g CO2-eq)

I: irradiation of the sun over a location (kWh/m2/yr).

η: is the module efficiency of the system (%).

PR: is the performance ratio of the system.

LT: is the lifetime of the system in years (yr).

A: is the area of the PV module selected(m2).

The estimation utilized in many research studies, has two parameters of the solar PV system. The numerator variable totals most of the GHGs deduced from all material and stages of lifecycle and gives weightage for each GHGs by GWP. The denominator estimates the electricity production throughout the lifetime of the PV module. In this method, various parameters influencing the denominator are customised to the case, and GHGs are estimated again based on the new parameters, giving a harmonized outcome for the case of Maharashtra, India.

3.2.4.1 Annual irradiation- 2086 kWh/m²/yr

Annual irradiation determines the power output from solar module and it depends on location. The total electricity generation per watt increases with the increase in annual irradiation factor. From the above equation, it is known that the GWP is inversely proportional to annual irradiation. Different studies use different irradiation values and in this harmonisation process, we use the value of 2086 kWh/m²/yr, which corresponds to the state's capital Mumbai(Miller et al., 2019). Even though the data in the published LCA studies are applicable only to a specific location, the outcomes are harmonised to Maharashtra because the modules are manufactured in China and could be installed and operated in the Maharashtra state. Hence, the following equation is used to calculate the harmonised GWP (see table 5) for making it compatible with the case study.

GWP published * Annual Irradiation of the study= GWP harmonised * 2086.

Table 5. GWP harmonised based on annual irradiation.

Author	Annual irradiation kWh/m²/yr	GHG	Harmonised GHG
(Fu et al., 2015)	1300	50.9	33.1
(Hou et al., 2016)	1600	60.13	48.1
(Miller et al., 2019)	2086	38	39.6
(Kim et al., 2014)	1310	31.5	20.6

3.2.4.2 Performance ratio

In the studies considered, two performance ratios are assumed 0.75 and 0.8 and It depends on kind of installation (refer table 6). It generally increases with decrease in temperature, monitoring advance identification of defects. So it can be said that well ventilated and utility scale systems have higher performance ratio. (Alsema et al., 2009) is an International Energy Agency (IEA) guidelines document which was developed to provide guidance for solar PV LCAs and it recommends to use the default value of 0.8 for ground mounted installations. Since we set the boundary condition for ground mounted utility scale PV systems, we harmonise results with 0.8.

Table 6. GWP harmonised based on performance ratio.

Author	PR	GHG	Harmonised GHG
(Fu et al., 2015)	0.8	50.9	50.9
(Hou et al., 2016)	0.75	60.13	56.4
(Miller et al., 2019)	0.8	38	38
(Kim et al., 2014)	0.8	31.5	31.5

3.2.4.3 System boundary harmonisation

In the previous section, we discussed about the system boundary assumed in the study. It includes all the upstream, ongoing and downstream activities of entire poly crystalline silicon PV system. The four considered studies have different system boundaries and It influences the GHG emission results. To align the study's results to common, gross system boundaries, incomplete life cycle stages which can prominently contribute to GHGs are added according to the detailed study of (Hou et al., 2016) as shown in table 7.

Table 7. GWP harmonised based on defined system boundary.

Author	GHG	Harmonised GHG
(Fu et al., 2015)	50.9	55.9
(Hou et al., 2016)	60.13	54.87
(Miller et al., 2019)	38	43.86
(Kim et al., 2014)	31.5	31.5

3.2.4.4 Efficiency- 18%

The annual electricity production is equal to the product of irradiation, performance ratio, and module efficiency. The module or conversion efficiency is improving continuously. Presently the PV manufacturing industry efficiency in china varies from 15% to 21% and average efficiency is around 18%(Energy sage, 2020). From the above equation, it is known that the GWP is inversely proportional efficiency of the panel. Hence the following equation is used to calculate the harmonised GWP (table 8) by using the efficiency value of 18% for making it compatible with the case study.

GWP published * efficiency considered in the study= GWP harmonised * 18%.

Table 8. GWP harmonised based on annual efficiency.

Study	Efficiency	GHG	Harmonised GHG
(Fu et al., 2015)	16	50.9	33.085
(Hou et al., 2016)	17.5	60.13	48.104
(Miller et al., 2019)	16	38	39.634
(Kim et al., 2014)	14.9	31.5	20.6325

3.2.4.5 Lifetime of plant- 25 years

From the above equation, it is known that the GWP is inversely proportional to the lifetime of the plant. hence the following equation is used to calculate the harmonised GWP (table 9) by using the assuming the lifetime of 25 years for making it compatible with the case study.

GWP published * lifetime considered in the study= GWP harmonised * 25.

Table 9. GWP harmonised based on plant lifetime.

Study	Lifetime published	GHG	Harmonised Lifetime GHG
(Fu et al., 2015)	25	50.9	50.9
(Hou et al., 2016)	25	60.13	60.13
(Miller et al., 2019)	30	38	45.6
(Kim et al., 2014)	30	31.5	37.8

3.2.4.6 Total harmonisation

A total harmonisation was performed considering all the aspects. The range reduced drastically from 28.63 to 8.3. The estimates from two studies tends to be around 31 g CO_2 eq/kWh and two studies estimate around 39 g CO_2 eq/kWh (table 10). The complete process reduced the variations and improved the accuracy of earlier published GHGs by methodologically making changing the key system characteristics for different studies to a values data set which are relevant for the case study. For our final estimate, instead of taking average or median of these values, the studies are further analysed qualitatively on 5-point criteria to select a final estimate.

Table 10. GWP harmonised based on all the above parameters.

Author	Irradiation	PR	Efficiency	Carbon intensity energy mix	Published GHG	Harmonised System boundaries	Total harmonisation
(Fu et al., 2015)	1300	0.8	16	930	50.9	55.9	31.0
(Hou et al., 2016)	1600	0.75	17.5	930	60.13	54.87	38.4
(Miller et al., 2019)	2086	0.8	16	930	38	43.86	39.0
(Kim et al., 2014)	1310	0.8	14.9	494.9	31.5	31.5	30.7

3.2.5 Selection of the GHG emission paper

In the previous section, the process of harmonisation has reduced the range difference from 28.63 to 8.3. Now the estimated range of GHG emissions for solar PV for the case of Maharashtra, vary from 30.7 to 39. For further detailed analysis and for decision or policy making, an estimate of greenhouse gases is required. Generally, an average or median value is taken from the considered studies and the same is used for further analysis or decision-making process. In this study, a rational choice of one study which performs well on 5-point criteria is made. The four studies are evaluated on the basis of five parameters. Latest data, completeness of the study, transparency, relevance of place of manufacture and relevance of plant location are these parameters. The outcome is qualitatively assessed to put into three colour codes, green, orange and red. as shown in table 11.

Latest data- For a technology like solar PV, the improvements are at a fast pace. An initial filter was applied in the search methodology to remove the old studies. Among the four studies selected, the data were collected from different sources and years as mentioned in the previous table. The studies which has data sources dated before 2011 are marked as orange and data sources which are dated after 2011 are marked as green.

Completeness of the study- As mentioned, LCA needs to be performed for all the phases from cradle to grave. For simplicity and convenience, studies such as (Fu et al., 2015), (Miller et al., 2019) and (Kim et al., 2014), assume one or more of the phases (transport, maintenance or end of life) as negligible and hence they are colour coded orange. (Hou et al., 2016) has considered all the phases of life cycle in the assessment with some assumptions and hence it is coded green.

Transparency and detailedness of the study- Transparency of the process is very crucial in life cycle assessment of Greenhouse gas emissions. While this is already a criteria in selection procedure, more detailed analysis is expected in the study to accept or criticize the analysis. (Miller et al., 2019) being a parametric study, focuses on different variables and locations for analysis. The details and transparency are much lower relative to other studies in terms of emissions presented in different life stages. Study conducted by (Hou et al., 2016) is very detailed for example, if the data sources are more than one, it mentions the range of the values and also why a particular data value is taken and it mentions the emissions in different life cycle stages. Considering these parameters, it is coded red or green.

Relevance of the place of manufacture of panels- The major proportion of greenhouse gas emissions do happen in materials extraction and panel manufacturing stage. Hence the carbon intensity of primary energy supply of the national grid and the manufacturing technologies used in the country plays an important role in the total emissions. India imports majority of the solar panels from China. Three studies are marked green in which China is considered as the manufacturing location and (Kim et al., 2014) has South Korea as manufacturing location and the technologies used and carbon intensity of the primary energy supply of the national grid varies. This is marked as red.

Relevance of plant location- The greenhouse gas emissions vary greatly depending on the plant location and this is mainly due to the performance characteristics as mentioned in the harmonisation section. This can be harmonised based on the performance characteristics and hence if the plant location is not in India, the colour is orange. If the plant location is considered in Maharashtra, it is coded green.

Table 11. Qualitative analysis of studies based on five parameters.

Paper	Latest Data	Completeness of study	Transparency and detailedness in the study	Relevance of place of manufacture	Relevance of plant location
(Fu et al., 2015)					
(Hou et al., 2016)					
(Miller et al., 2019)					
(Kim et al., 2014)					

Based on the above analysis, it is found that (Hou et al., 2016) study is more compatible and reliable for the case study of Maharashtra. However, in this study, relevance of plant location is not favourable. Therefore, we use the harmonised value from the previous section for making it more compatible with the case study of Maharashtra.

3.2.6 Analysis

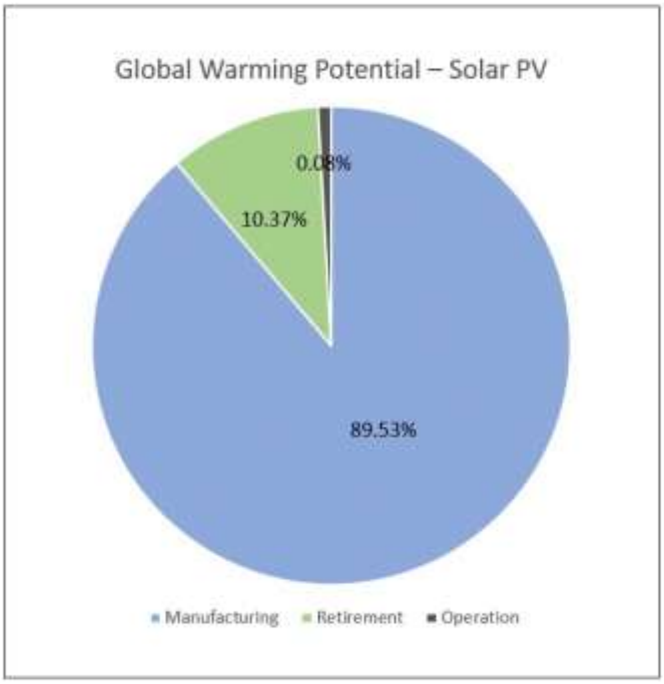


Figure 6. GWP solar PV.

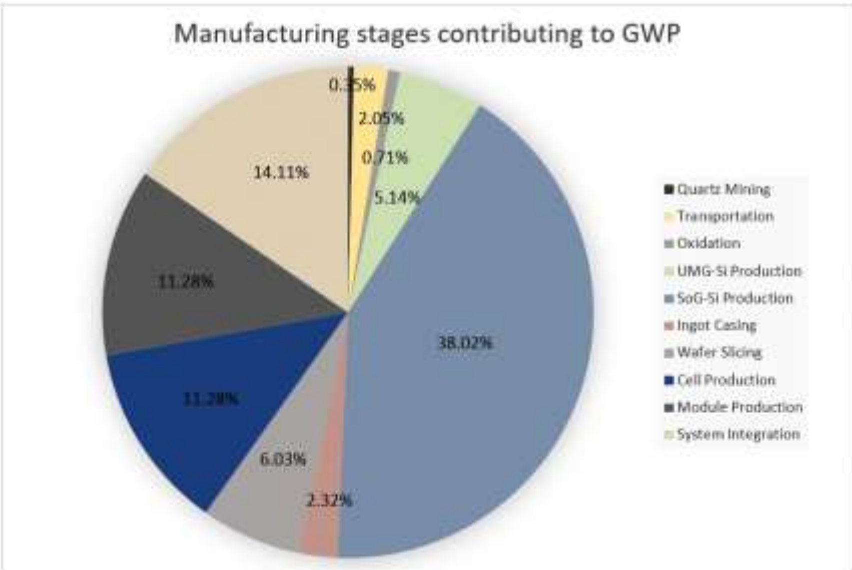


Figure 7. Manufacturing stages contribution to GWP.

For the analysis of GHGs and hotspots, (Hou et al., 2016) study's results are used and from these results, we interpret and discuss how we can improve on the hotspots. The contribution proportion of each stage is given in the below pie charts (figure 6 &7). The first one shows the contribution of manufacturing, operation and retirement stages while the second pie chart shows the split up of sub manufacturing activity contribution.

The greenhouse gases of polycrystalline Si PV come from direct and indirect sources. Direct emissions are caused by mining of quartz, fabrication of UMG-Si, and shipping while indirect GHG emissions are mainly because of energy consumption during all the processes.

As we can see from the GHG contribution pie chart, manufacturing contributes for ~89% of the total emissions, while retirement of the PV station contributes to ~10% of the total emissions. In this study, operation and maintenance GHG emissions were assumed to be 0.1% of the manufacturing stage GHG emissions and hence it contributes to 0.08% of total GHG emissions.

The majority of the contribution in the solar PV technology is from its manufacturing stage and fig particularly shows the percentage contribution of each sub manufacturing processes., ~38% of total GHG emissions is contributed by a single process SoG Si production. This process consumes the highest energy and contributes to the indirect GHG emissions. With the rapid technology development, the energy consumption is continually decreasing and hence the GHG emissions also decrease over time. The energy consumption for this process in this study is taken as 120 kWh/kg which is slightly higher than the lowest emissions of 90-100 kWh/ kg in the Chinese PV industry. If any of the processes called modified siemens process or the metallurgical routine method are implemented for fabrication of SoG Si, the energy consumption further reduces and can lead to lesser GHG emissions(Yue et al., 2014). There would be around 12 % and 23% reduction in the published GHG emissions if the energy consumption of this process is reduced to 80 kWh/kg and 60 kWh/kg respectively (Hou et al., 2016).

The next set of contributors are the solar cell and solar module production and each of them contributes indirectly around 11% of total emissions. The solar module production includes packaging glass, EVA, PV junction box, etc. Further, the Wafer slicing process contribute ~6% to the total GHG emissions and are indirect emissions from energy consumption. Then, the next contributor, UMG Si process consumes energy and contributes to indirect GHG emissions which amount to 6.03%. In quartz mining and oxidation reduction reaction of UMG Si, the chemical reactions give rise to GHG emissions directly which contribute to 0.35% and 0.71% of total emissions respectively. Furthermore, transportation assumes that trucks have carrying capacity of 50 tons and the diesel usage per hundred kilometres is 50 L/km. However, the transportation contributes to only 2% of total emissions and are negligible. Energy expenditure and emission of GHGs through the activities of mining, shipping of materials and plant operation are minute, and therefore they are insignificant. SoG Si process has highest GHG emissions and hence actions need to be taken in order to cut down the energy consumption and GHG emission during this stage.

3.3 Environmental performance of nuclear energy

Sometimes, electricity supply from nuclear power plant is considered to have zero emissions of GHGs. However, GHGs are generated during the mining, production of fuel and various other substances needed for construction and O&M of the plant. The construction and decommissioning of the nuclear power plants consume energy and the source for generating this energy emits GHGs. A complete and comparative account of GHG for complete life cycle of power production system is needed to identify and reduce hotspots of GHGs. GHG emissions per unit electricity are dependent on source of primary mix used to carry out activities of different stages of LC. An ideal power generation plant from GHG point of view is when all the input energy is derived from sources which does not emit any GHGs. Even though it is theoretically possible, it is not likely that this kind of a plant exists in current situation as the utilisation of fossil fuels is predominant especially in India and is important for many processes. Hence it is necessary to quantify greenhouse gases from LC perspective to analyse the environmental performance. The approximation of quantities of GHGs emitted is an enormous task where vast number of integrated operations of construction and operation of plant needs to be considered. In this work instead of quantifying GHGs from LCA from beginning, we take help of the studies already existing in the literature and evaluate or harmonise the information to suit India's experience with greenhouse gases generated from the activities of construction and O&M of the plant.

Nuclear energy growth in India has been relatively modest. In April 2020, nuclear energy is at 6.780GW out of total Energy production of 370.348GW of India. This makes it a modest 1.8% of total energy (Goverment of India, 2020). This is mainly attributed to independent development of technology due to exclusion from Nuclear Supply group (NSG) and due to non-party to nuclear Proliferation Treaty (NPT) of 1968. Indian government has shown expansionary posture towards nuclear energy. India already has 22 operational reactors and government has sanctioned 10 indigenous 700 MW PHWR reactors in 2017 at a cost of 700bn USD and aims to reach 22.480 GW by the year 2031(DAE_India, 2018).

India has predominantly Pressurised Heavy Water (PHWR) reactors in the country and Maharashtra has two reactors of this technology. At first, GHG gas emissions depend on a variety of factors including nuclear technology, capacity factor, lifetime, carbon intensity of primary energy mix, mining type and ore quality etc. These factors depend on the location at which the activities are carried out. The reactor is based on the technology developed by Canada and it is called Canada Deuterium Uranium (CANDU) type reactor. India also imports uranium from Canada, Kazakhstan and Uzbekistan while it produces heavy water within the country. To assess the nuclear energy supply in Maharashtra, it is required to examine environmental impacts of PHWR reactors and to approximate potential GHGs when technology and uranium import is from Canada and the plant location of heavy water and nuclear plant is in Maharashtra, India. Hence these factors have to be considered while estimating the greenhouse gas emissions of the technology in Maharashtra. In this study, relevant LCA studies were harmonised to examine GHG gas emissions of PHWR reactor for Maharashtra, India scenario.

This study has two advantages. First, the final estimates are based on reliable and robust studies which rely on credible data sources. Second, the estimates reflect the current status in Maharashtra, India. To achieve this, the following methodology is performed. First, the boundaries of the technology or the system is defined. For example, type of nuclear plant, life cycle phases included in the study, functional unit etc. In this study, we are considering PHWR as they are dominantly available plants in the country. Second, a stringent methodology is applied to filter out irrelevant studies and consider studies which are recent and relevant to the technology defined in the system boundaries. The screening process is mentioned in detail in the upcoming sections. Third, once the relevant studies are selected, factors including system configurations, key parameters, data sources and data assumptions are carefully assessed. Fourth, the outcomes are harmonised with scenarios which are applicable to the case of Maharashtra, India. Fifth, the five criteria (transparency, latest data, completeness, relevance of manufacturing location and relevance of plant location) is used to check if the study satisfies the minimum requirements. Sixth, the characteristics of the different life phases of the system from the perspective of global warming is discussed which can be useful in designing policies in the integration aspect.

3.3.1 System boundary

The goal of this study is to analyse the life-cycle environmental impacts of nuclear power plant and provide a scientific basis for policy-making regarding the sustainable development in Maharashtra, India. Hence it is important to define the system boundary of the research which corresponds to the present scenario of the case. The system boundary is shown in figure 8, which included upstream, operational and downstream processes. Pressurised PHWR type studies are considered here. PHWR reactor type uses natural uranium and does not need the extra process of uranium enrichment when compared to Pressurised Water Reactor (PWR) but it requires Heavy water as coolant or moderator. India does not have the technology for PWR reactor and also does not have expertise in the uranium enrichment process. This makes it dependent on other countries for uranium and technology, making it uncertain and expensive.

Because PHWR accounted for most India’s nuclear power plants, study focuses on PHWR technology as being representative of the Maharashtra’s nuclear power. The selection of studies procedure for analysing the life cycle study is mentioned in the section search methodology. The functional unit in most of the LCA studies in literature is 1 kWh and it is kept same in this study for maintaining cohesiveness and comparability.

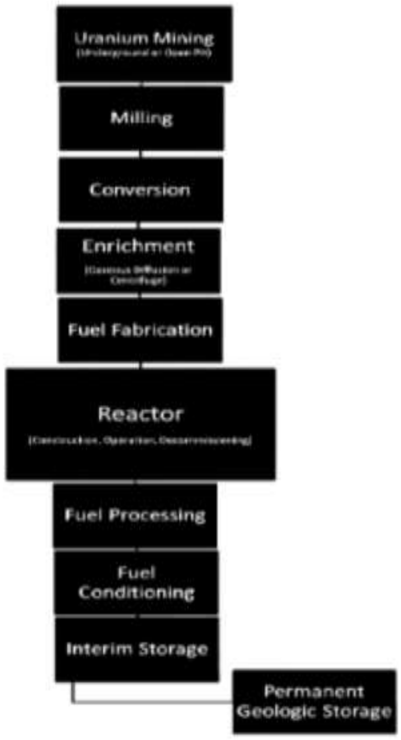


Figure 8. System boundary of nuclear power plant.

- *Upstream processes:* These are the ones which are performed before operational processes, and this includes construction of plant and material supply.
- *Operational processes:* This process has GHG emissions on a continuous basis for every 1 kwh of power produced. The process includes uranium mining, milling, conversion, fuel rod fabrication, transportation, facility operation and to maintenance, and reprocessing. Mine rehabilitation is considered in this process because of the need for mine rehabilitation is dependent on the amount of uranium required for power production.
- *Downstream processes:* These processes are carried out once the facility's operational processes come to an end, and includes decommissioning of the plant, non-radioactive waste dumping or recycling, and short term and long term radioactive waste storage after power production and plant lifetime(Warner & Heath, 2012).

3.3.2 Search methodology

As mentioned in the system boundaries, the study is limited to PHWR reactor type technology in nuclear energy. The study began with a literature search using the following search keywords on web of science, Scopus and google scholar. By using the three set of key words (table 12), the search results were filtered to 366 papers. PHWR being an uncommon technology used by other countries, not many LCAs are conducted on it. Hence the studies from 1990 are considered.

Table 12. Search methodology for PHWR reactor LCA studies.

Screening type	Selection	Papers
Keyword	LCA OR LCIA OR LCI OR Life cycle assessment OR life cycle sustainability assessment	44210
Keyword	Nuclear	791
Keyword	Electricity OR Power	354
Screening 1		72
Screening 2		1

3.3.2.1 Screening 1

The studies which lacked sufficient documentation for the harmonisation process are removed. For example, Conference papers, presentations less than 3 pages are filtered out. References which were not accessible in English were also not considered.

3.3.2.2 Screening 2

A second screening process, more robust, standard screen had a basic requirement for inclusion in the final outcome of the study. Study criteria includes the need of quality life cycle assessment and method of GHGs estimation, wholeness and outcomes, and if the nuclear technology type and the design of the reactor was of present-day relevance (which is predominantly operating currently). The second screening process limited the number of studies to one from which this analysis is conducted.

3.3.3 System Configuration

Table 13. System configuration of PHWR considered for the study.

Study	(Andseta et al., 1998)
Reactor type	PHWR
Reactor technology	CANDU PHWR
Capacity	600 MW
Lifetime assumed	40 years
Capacity factor assumed	80%

The system configurations are mentioned in table 13. The CANDU reactors are very different from other nuclear reactor types as CANDU is based on the utilisation of naturally available uranium as its fuel and uses HW as its moderator. This is advantageous as it eliminates a large energy consumption stage, enrichment of uranium. However heavy water also consumes considerable energy when compared to light water moderated nuclear reactor.

3.3.4 Data sources

Construction- The previous study of (Rose, 1983) is updated with latest information from the site of CANDU reactors for facilitating the comparison of material requirements for different sources of energy.

Uranium data- The information is based on the ground data of the Cogema who is the major producer of the fuel (uranium) in Canada and also from the operations report of 1996 from Cameco.

HW data- The information with respect to energy for heavy water production is taken from the records of Witzke of Bruce from the year 1973 to 1993.

3.3.5 GHG emissions in the study

(Andseta et al., 1998) analyses the greenhouse gas emissions in two scenarios. In the first scenario, it is calculated by considering actual energy source emissions or Ontario's primary energy supply emissions. The second scenario is a hypothetical one, where it is assumed that the energy source is completely fossil fuel. The table in appendix have the findings of the study in these two scenarios.

3.3.6 Data Assumptions

Every study has lot of data assumptions for estimating GHGs from a power generation plant. We list the assumptions made in this study for understanding, interpreting and to harmonise the results.

- Transportation- The study assumes a typical Volvo diesel transportation at 0.025 litres/t-km.
- Small quantities of GHGs from cooling and neutralisation are not considered as they are not significant.
- The uranium ores are declining in quality over a long term and it results in increasing energy consumption to produce nuclear fuel. This has been considered in the study.
- GHG emissions for the building of the defined system is estimated vaguely proportional to the quantity of substances utilised.
- Supplementary information of GHG emissions from production, shipping and installation of materials is required for complete LCA.
- During the mining, organic material is utilised and as solvents to filter concentrate. The variable nature of carbon content among these materials has led to an assumption in the published study. It is assumed that the content is equivalent to fossil fuels.
- It is also assumed that power produced in Ontario is majorly from hydro power and nuclear power.
- Few materials are incomplete needing approximation to evaluate the construction emissions (Andseta et al., 1998).

3.3.7 GHG harmonisation for the case of Maharashtra, India

The selected study analyses two scenarios for greenhouse gas emissions. One scenario considers Canadian primary energy mix for calculation of GHGs and another is a hypothetical situation in which the primary energy mix is composed of fossil fuels. For our case study, we need to understand the activities that are currently happening in Maharashtra's nuclear power plant for estimating the GHGs for the given scenario. India imports most of the uranium from Canada, Kazakhstan and Uzbekistan for feeding its PHWR reactors (Chaudhury, 2019). For defining boundary condition and simplification, we consider that the fuel is imported from Canada. However, the heavy water is produced in India. The reactor technology (CANDU) is imported from Canada and the present-day reactor design is very similar even though it is designed indigenously by department of atomic energy (Xu, 2019). Considering all these factors, the following selection of Greenhouse gas emissions is made from each of the scenario (table 14). Activities like Mining and milling, chemical treatment, U3O8 to UO3, UO3to UO2, U3O8 transport, fuel fabrication takes place in Canada and hence the GHG emissions corresponding to Canadian energy mix is taken into account. on the other hand, activities like heavy water production, construction, decommissioning happens in India and the hypothetical scenario values are taken in which complete fossil fuel scenario is considered. Since India produces 80.3% electricity from fossil fuels, to bring the emissions close to actual value, it is multiplied with 80.3%.

Table 14. Harmonising the GWP for case of Maharashtra, India.

Life cycle phase	Canada actual energy sources	All Fossil Fuel Energy Sources	Relevant selection of data	Harmonisation 80.3% fossil fuel in Maharashtra, India
Mining and milling	0.22	0.37	0.22	0.22
Chemical treatment	0.06	0.06	0.06	0.06
U3O8 to UO3	0.025	0.051	0.025	0.025
UO3to UO2	0.050	0.087	0.050	0.050
U3O8 transport	0.005	0.005	0.005	0.005
Fuel fabrication	0.01	0.11	0.01	0.01
Heavy water charge	0	9.64	9.64	7.74
Heavy water replacement	0	2.26	2.26	1.81
Construction	2.22	2.22	2.22	2.22
Decomissioning	0.61	0.61	0.61	0.61
Total	3.2	15.41	15.1	12.75

3.3.8 Discussions

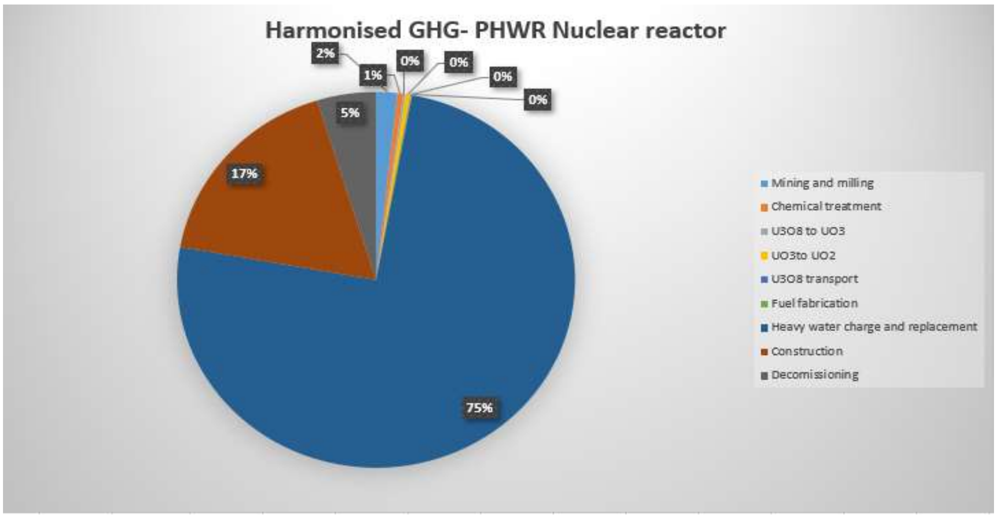


Figure 9. Harmonised GHG PHWR nuclear reactor.

It is observed from the table that for Maharashtra's case study, 12.75 g CO_2 eq/ kWh is the GWP. The two extreme situations are given where in one situation all the activities are powered by Canadian energy mix which is dominated by nuclear and hydropower and another situation where all the activities are powered by fossil fuels and the GHG estimates are 3.2 g CO_2 eq/kWh and 15.41 g CO_2 eq/ kWh respectively. It varies in that range depending on the degree of renewables used in the inputs and activities of nuclear power plant. A little expenditure of fossil fuels in the operation and construction of the plant hence produces a very large amounts of energy when compared to the energy which is directly available from the source of fossil fuels in terms of GHGs released.

The PHWR type of reactor uses heavy water as the moderator and as we can observe from the table, for the case of Maharashtra, the heavy water production contributes to around 75% (see figure 9) of the total GHG emissions. The extraction of HW is from light water with which it is naturally combined in nature and this separation is achieved through a heat source. The choice of processes and energy sources used in any operation determines the GHG emissions. The worst way is that this heat can be obtained completely from fossil fuels and best way would be to obtain the heat from the PHWR nuclear station. In our case, the heavy water plant runs on the primary energy mix of India which is powered by 80.3% fossil fuel energy sources and hence contributing to most of the total GHGs. Alternatively, if the plant is moved onsite and if it is powered by nuclear thermal energy, it reduces the emissions drastically as we can see from the table. The utilisation of nuclear thermal energy for HW extraction avoids this potential highest element of PHWR GHG emissions.

Few studies suggest high GHGs and fortunately they are based on the assumption of over utilization of fossil fuel in the nuclear fuel cycle and another assumption that nuclear fuel is not reprocessed. For future, there are many possibilities like feeding the nuclear energy back into the preparation of input materials of nuclear fuel cycle. Electricity from nuclear energy can be an input for ore extraction, refining and to process metal and other material. Continuing improvement of the nuclear fuel cycle gives a possibility to sustain energy which can be extracted from nuclear fission. So, it is important to highlight the fact that nuclear and all alternatives are dependent on fossil fuel sources at least to some extent and it is possible to reduce this dependence by feeding electricity from low carbon technologies.

Another important aspect which influences GHG emissions is the ore quality and it vary in quality as the rich ores are depleted. Currently Canadian ore quality is estimated to be 2% and it is considered to be the rich quality ore in the world. Hence the supply of uranium from Canada has the least energy consumption and GHG emission and is the best case for Maharashtra. However, India also imports uranium from Kazakhstan and Uzbekistan which has low ore qualities and fossil fuel dominant energy mix. (Lenzen, 2008) conducted a sensitivity analysis and depending on the ore quality, there can be an 83% increase in GHGs. Hence it is recommended to increase the share of Canadian uranium and reduce the imports from the other countries in the GHG perspective. With research, new materials can be introduced by new technologies. On a long term, the quality of uranium ores might decline which leads to high energy consumption and this is considered in the study. However, there is uncertainty in quantifying GHGs along with time as it depends on many other factors like improved technologies, ore exploration, ore quality etc.

The analysis and harmonisation for the case of Maharashtra provides a signal of relative magnitude of GHGs throughout the whole life cycle of the nuclear energy grounded on crucial assumptions made in each process which makes up the system. The above discussion and analysis can be used for policy making for comparing the emissions with alternatives or even identify hotspots and frame policies to further reduce GHG emissions.

4 Economic performance of technologies

A complete idea of the comparative cost effectiveness of various power producing technologies is prominent in figuring out energy related policies of any state. The price of the power is dependent on marginal cost of power produced by an electricity generating plant and regulatory measures (Munasinghe & Warford, 1982). The power price is varied for different suppliers based on the agreed bid and the technology. This is because different electricity generating plants can compete to provide power at various bids (Salvadore & Keppler, 2010). To reduce the inconsistency, estimations are utilized by sellers to assume a fixed system which gives certainty for the users. This is also accounted for inconsistencies in the power price, improvements in the grid connected system and administration costs. Hence final price billed to the consumer should vary from actual cost of power production.

For abstraction from the reality, LCOE tool is utilised as a method to analyse the cost effectiveness of different power producing alternatives. This method is considered to avoid biases among the alternative technologies (Branker et al., 2011). This tool takes into account the total power production through the lifetime of a plant and complete costs to calculate a price per kwh power generated. It generally does not involve risks or various financing means available for various alternative technologies. for example, a feed in tariff guarantees the price to be paid for electricity generated by Renewable Energy Technologies (RETs) which takes away the price risk. But this does not mean to reduce the financing risk for the alternative, which can be a hurdle. Hence, every technology must be given the same economic analysis, with difference being the complete costs, power generated and complete lifetime. The scenarios can be chosen which are near to the reality to draw conceptual parallels with reality. The LCOE is calculated using the below formula .

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Where,

$LCOE$ – Levelised cost of electricity taking average lifetime.

I_t – Investment expenditure considered capital cost in year t.

M_t – Operation and Maintenance cost in the year t.

F_t –Fuel expenditure cost in the year t.

E_t- Electricity generation in the year t.

r – Discount rate.

n – Average lifetime of the system.

As LCOE is a benchmarking methodology, there can be a high or low sensitivity for the assumptions made for estimation, particularly when extended to its lifetime years in the future. Hence, to use the estimations in the policy or decision making, assumptions are taken as accurate as possible, with corresponding sensitivity analysis and respective justifications(Darling et al., 2011). While the real market costs are dynamic, this is a static tool which takes a snapshot in determining the price per unit produced electricity. However, assumptions need to be understood and it should represent an average for the given circumstance. The method of financing is assumed same for nuclear and solar energy in this study, even though actual markets might finance them in a different method. The technological assumptions considered are generalised for the given case study. Cost and power generated is based on the Maharashtra's location, capacity for production, system efficiency, O&M, lifetime years and other parameters. The usual criticisms of LCOE is that it uses old data and may not consider full costs of plant, may not take into account real plant utilization of the technology (Gibson et al., 2008). In this study, full efforts are put to overcome these criticisms by collecting the recent data, considering most of the costs and accounting real plant utilization of both technologies.

In this study we focus on calculating the LCOE of low carbon technologies only. Once the outcomes are calculated, we compare the LCOE cost of solar PV and nuclear energy with LCOE of predominant technology, coal in chapter 5. Many studies have calculated the LCOE of coal power plant and since the technology is old and saturated, the process and assumptions are streamlined and stable. (Adibhatla & Kaushik, 2017) with the support of National Thermal Power Corporation Limited, calculated that LCOE of coal plant to be 0.04896 USD/kWh and we use the same during the integration of the aspects.

4.1 Economic performance of solar PV

4.1.1 Recent Market Trends

Solar PV capacity has exceeded 580 GW by the end of 2019 all around the world. This is 14 times increase for this technology since 2010. In 2019 alone, about 98GW was installed and this is the highest new capacity addition among all the renewable energy sources for the year.

The increased capacity addition in 2019 was mainly contributed by Asia, which accounted to 60% of the new installations. China, India, Japan, Republic of Korea played an important role by installing 47.5 GW in the same year. The US, Australia and Germany installed 17.5 GW whereas Spain and Ukraine experienced a prominent growth by adding 4GW and 3.9 GW respectively.

4.1.2 Cost components

In this study, LCOE of solar PV is estimated for the case of Maharashtra, India. Various costs of energy generating systems and electricity generated over the system's lifetime are considered to calculate LCOE in dollars/kWh. It is understood that the methodology can be sensitive to the technology and other assumptions and hence is it customary to conduct a sensitivity analysis(Darling et al., 2011) for accounting uncertainties in the system.

The fuel costs are not applicable to solar PV as it does not use any fuel over its lifetime. All the above parameters can vary significantly between individual projects and countries. Hence in order to get accurate results, this study data is collected based on the projects in

Maharashtra, India. Following the above principle, this study attempts to estimate LCOE of solar PV.

4.1.2.1 Assumptions:

The system boundaries were assumed while estimating the environmental performance of solar PV previously. While estimating the economic performance, same system boundaries are used. A polycrystalline ground mounted utility scale solar PV system is considered. As already discussed previously, Financing and subsidies are not considered in order to compare the technologies depending only on the costs and electricity generated by the systems. Some studies have come to a conclusion that the life of the PV modules can be beyond 25 years(Branker et al., 2011). However, most PV manufacturers provide the guarantee of 25 years and it is the industry norms. Hence, we use the same lifetime of the system in this study which also matches with the system boundaries. The discount rate has adequate uncertainty and it can be dealt with sensitivity analysis. 10% discount rate is used as Central Electricity Authority (CEA) has been using it in their calculations for planning and evaluation of projects.

4.1.2.2 Initial investment costs

Initial investment costs of a solar PV plant include 4 aspects, land, the hardware, installation and soft costs. Hardware, as the name suggests, includes modules, rack and mounting, grid connection, electrical components like wiring, safety, security and monitoring and control hardware component costs. Installation costs include cost incurred for mechanical and electrical components installation and inspection. Soft costs are financing costs, system design, permissions, customer acquisition, margin etc. All these three components are one-time initial investments and must be considered for solar PV plant.

The International Renewable Energy Agency (IRENA) has published a report called Renewable power generation costs in 2019 on June 2nd (Renewable Energy Agency, 2020). The data used in the document has been sourced from different sources like business journals, Renewable Costing Alliance members, tenders, industry associations, auctions and governments. The system boundaries were kept same to make the data comparable. The IRENA Renewable Cost Database which includes a mix of public and confidential data is used to compile the data for this study. The final value of investment costs they have arrived at is 612 USD/kWh in India. (Das et al., n.d.) study has collected data from project developers and they have found that capital costs are 40 million Rs per MW of solar plant, which translates to 585.2 USD/kW (1 USD= 68 Rs). Since the IRENA cost database has a variety of sources and has included soft cots etc, we would consider 612 USD/kW in this study.

4.1.2.3 Decommissioning costs

Decommissioning cost depends on location of the site and potential to recycle, sell or scrap metal. Resale value of scrap metal exceeds have also resulted in negative decommissioning cost(Brown et al., 2017). As very few plants have attained the end of their lifetime, the experience and estimation with the process is very limited. But it is estimated that of the total decommissioning cost, around 90% of costs is attributed to dismantling and removing equipment, while only 10 percent come from post dismantling activities like site grading and restoration. Net costs per MW of capacity is estimated at as varying from $177,000 to – $88,000. Which is estimated to be 1-2% of initial capital cost (Raimi, 2017).

4.1.2.4 Operating costs

The major costs of O&M for the defined system have diminished in the past decade. The main reason behind this is the improvement in efficiency of the system which in turn has deceased the area of panels required for a kW capacity. The other reasons include the pressure from competition and enhancement in the credibility of the system which have triggered in the new system designs enhancements for diminishing the costs related to O&M and new strategies which utilizes innovations like robotic cleansing and use of data analytics for preventive maintenance. Table 15 gives the details of the trends in the costs of O&M applicable for Non-OECD countries. for the year of 2019, the O&M costs for the projects was USD 9.5/kW per year and it includes insurance and other costs (Renewable Energy Agency, 2020). (Das et al., n.d.) has mentioned that the operating and maintenance costs are 2% of capital costs which is equal to 12.25 USD/kW/year. The study also assumes an escalation of 5% costs of operation every year. In this study, we assume 9.5 USD/kW/year and an escalation cost of 5%.

Table 15. Operation and maintenance costs in Non- OECD countries.

Year	Non-OECD 2019 USD/kW/year
2010	24.4
2011	22.4
2012	17.4
2013	14.6
2014	13.0
2015	11.9
2016	10.8
2017	10.4
2018	9.9
2019	9.5

Source: *(Renewable Energy Agency, 2020)*

4.1.2.5 Annual electricity generation

Annual electricity generation mainly depends on the capacity factor. From the year 2010 to 2019, the weighted average of capacity factor globally for the system considered in the study has surged from 13.8% to 18% respectively (refer table 16). The main reason for this increase can be attributed to the fact that there has been a higher share of deployment in relatively sunnier locations. Presently, after a steady increase of capacity factor in the defined time period, it seems to be saturating around 18% mark. The 5th and 95th percentile correspond to 10.7% and 23.9% of the capacity factor global range for the defined system (Renewable Energy Agency, 2020). (Das et al., n.d.) has mentioned the data source as project developers and capacity factor is taken as 20% for a solar plant in Maharashtra. This also falls in the range of global weighted average of capacity factors collected by (Renewable Energy Agency, 2020).

Table 16. Global average and range of capacity factor for utility scale PV systems.

Year	5th percentile	Weighted average	95th percentile
2010	10.5%	13.8%	23.0%
2011	10.1%	15.3%	26.0%
2012	10.5%	15.1%	25.4%
2013	11.9%	16.4%	23.0%
2014	10.8%	16.6%	24.4%
2015	10.8%	16.5%	29.0%
2016	10.7%	16.7%	25.9%
2017	11.5%	17.7%	27.0%
2018	12.3%	18.2%	27.0%
2019	10.7%	18.0%	23.9%

Source: IRENA Renewable Cost Database.

Note: These capacity factors are the AC-to-DC capacity factors, given that installed cost data in this report for solar PV (only) are expressed as per kilowatt direct current.

4.1.3 LCOE calculation

The increasing system efficiencies, reducing O&M cots, a drastic reduction in total installed costs have led to significant reduction in the electricity costs of solar PV technology and enhancement of its competitiveness in terms of economics.

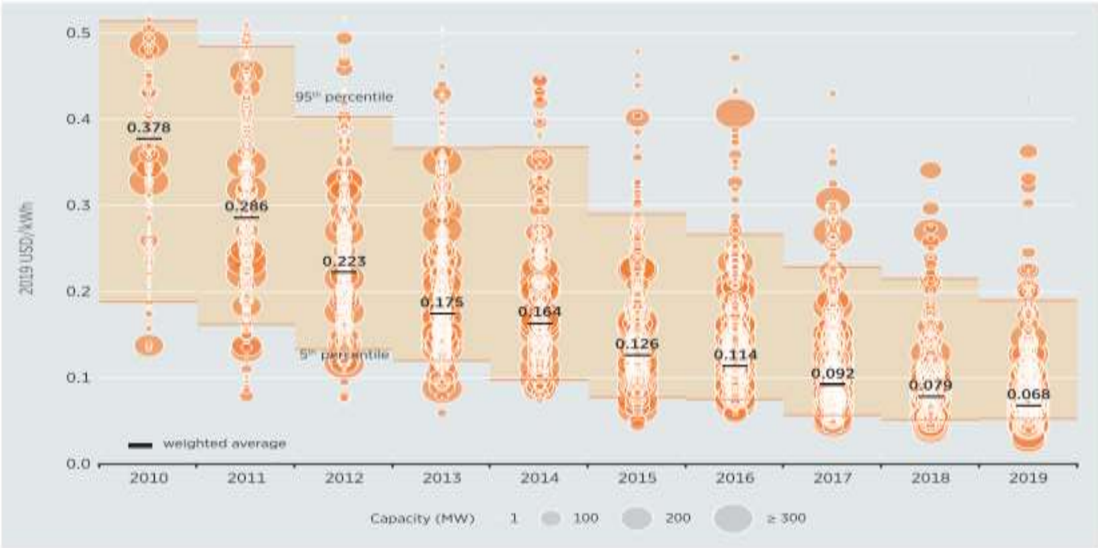
From the year 2010 to 2019, there has been a drastic reduction in utility scale projects LCOE in India(Renewable Energy Agency, 2020). In our study, the levelized costs of electricity cost was found to be 0.04482 USD/kWh (table 17). The assumptions and calculations are presented in the following table. The excel sheet of calculation is attached in the annex part of the report.

Table 17. LCOE Solar PV cost calculation.

Costs	Unit	Value
Initial investment cost	USD/kW	612
Decomissioning	USD/kW	1% of capital cost
Lifetime of the plant	years	25
Operation and maintenance costs in year t	USD/kW	9.5
Fuel costs in year t	USD/kW	NA
Capacity factor	Percentage	20
Annual Electricity output	kWh	1752
Discount Factor	percentage	10
Levelized cost of electricity	USD/kWh	0.04482

4.1.3 Global trends

The levelized cost of electricity global average for utility scale solar PV is constantly decreasing. Figure 10 shows utility scale solar PV project LCOE and range, 2010-2019.



Source: IRENA Renewable Cost Database.

Figure 10. Global utility-scale solar PV project LCOE and range, 2010-2019.

4.1.4 Sensitivity analysis

The value of project LCOE depends upon the various parameters such as capital cost, annual O&M cost, discount rate and annual electricity produced as shown in Equation. The sensitivity range of each prescribed parameter is taken as ± 10%. Here, the capital cost, annual O&M cost and discount rate are the economic factors, whereas the annual electricity generated is the technical asset. The impact of each parameter on the LCOE is distinctive in value as well as in the nature. The variation in the LCOE of solar projects corresponding to the parameter sensitiveness. Investment and O&M cost factors exhibit positive relation with the LCOE, which means the increment in these parameters will lead to the rise of LCOE. Whereas, the annual electricity generated and discount rate are having the negative relation with the LCOE as it is inversely proportional to the LCOE. The project capital cost and the annual electricity generated parameters are the most significant parameters (see figure 11).

For sensitivity analysis each parameter was varied 10 percent. However, the range of these parameters vary differently. Here we try to collect the range of the values from literature. Electricity is found to be the major influencing factor and it depends on capacity factor which was assumed 20% in this study and according to (Renewable Energy Agency, 2020) it can range from 10.7% to 23.7% depending on the location. In a similar way investment costs per kW capacity of solar PV globally ranges from 612 USD/kW to 2117 USD/kW. Furthermore, discount factor for any project in India varies from 8% to 12% (Shukla, 1997). lastly, O&M affects least for LCOE and is found to vary between 9.5 USD/kW to 18.3 USD/kW (Renewable Energy Agency, 2020). The choices in this work are made to match the real conditions of

Maharashtra and sensitivity analysis is carried out to see to what extent each parameter influence LCOE.

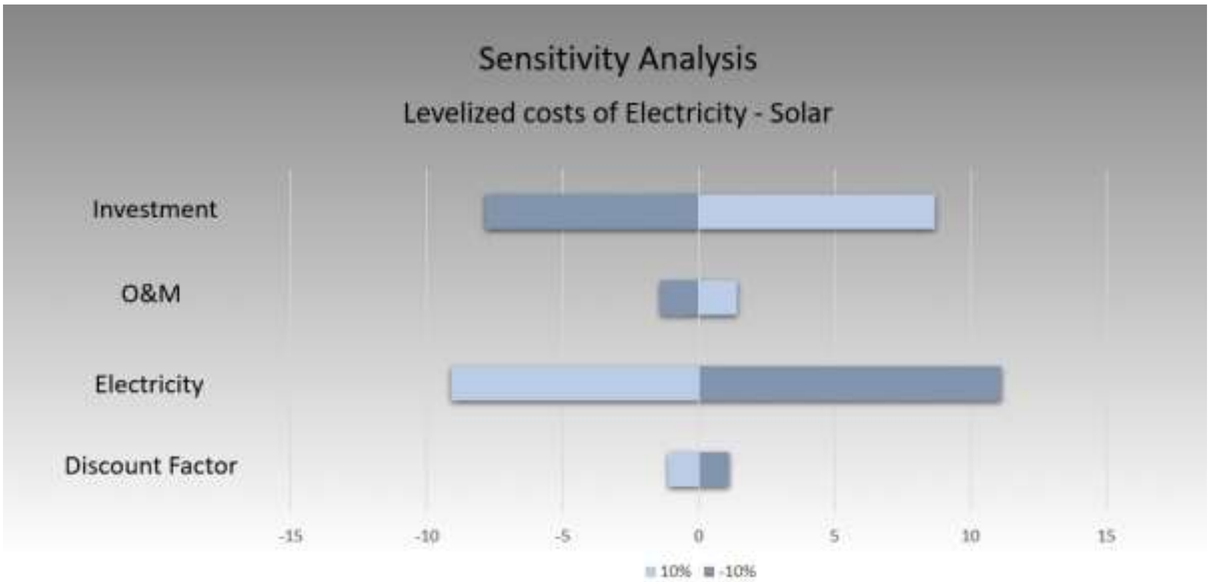


Figure 11. Sensitivity analysis of solar PV LCOE.

4.2 Economic performance of nuclear energy

4.2.1 Introduction

India's nuclear energy has a long history dated back to 1948 when Atomic Energy Commission was started just after the independence of the country. Department of Atomic Energy (DAE) which was started in 1954 has played a pivotal role in meeting energy demands in the country. In 1958, the chief architect of the nuclear program in the country, Homi Bhabha, established ''the contribution of atomic energy to the power production in India during the next 10 to 15 years'' and quoted that ''the costs of [nuclear] power [would] compare *very favourably* with the cost of power from conventional sources in many areas'' (Bhabha & Prasad, 1959). The many areas he referred was coal fired thermal stations.

However, nuclear energy growth in India has been relatively modest. In April 2020, nuclear energy is at 6.780GW out of total Energy production of 370.348GW of India. This makes it a modest 1.8% of total energy (Goverment of India, 2020). This is mainly attributed to independent development of technology due to exclusion from NSG and due to non-party to NPT of 1968.

Indian government has shown expansionary posture towards nuclear energy. India already has 22 operational reactors and government has sanctioned 10 indigenous 700MW PHWR reactors in 2017 at a cost of 700bn USD and aims to reach 22.480 GW by the year 2031 (DAE_India, 2018).

In this chapter, we approximate LCOE on the grounds of available existing literature. It is a known fact that costs vary and fluctuate depending on the availability factor, discount rates for the project and the safety regulations. Since CANDU-type PHWR are the majority reactors in India (18 out of 20 nuclear power plants in India), this study focuses on the same type of reactor.

4.2.2 Cost components

The Discount Cash Flow (DCF) tool is used to compute the unit cost of power produced. 10% discount rate is used as CEA has been using it in its estimation for planning and analysis of projects. The same has been applied to some of the earlier studies which estimated the costs of nuclear energy (Balachandra, 1990) and all costs are expressed in 2019 **(**fixed base year) rupees. For bringing the costs from previous years to the present date, the GDP deflator ratio is utilised for corresponding years as suggested by the world bank(World, 2020). The values are exhibited in the table 18 for the 19 years, 2000 to 2019. Base year is kept at 2004, from when Tarapur Atomic Power Plant (TAPP)- 3 and TAPP-4 (Maharashtra, India) were expected to generate power.

Table 18. GDP deflator data for india (From to) with constant base year as 2004.

Years	2002	2003	2004	2005	2006	2007	2008	2009	2010
GDP deflator	92	96	100	106	115	122	134	143	158

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Years	2011	2012	2013	2014	2015	2016	2017	2018	2019
GDP deflator	172	186	197	189	204	208	215	232	236

4.2.2.1 Capital cost

The investment costs usually include the cost of building the plant and the costs of HW and uranium required in the initial loading.

Kaiga I & II, 220 MW PHWR reactors which became critical in 1999 (5 years behind schedule) were estimated at Rs 28.96 bn. Later in October 1998, nuclear Power Corporation of India (NPCIL) started two 540 MW PHWR power stations named TAPP 3&4 in (DAE_India, 2000) and attained criticality by 2006 at an estimated cost of RS 62 bn(TS, 2006).

In addition to this, in the year of 2007, GOI also approved four out of the eight(planned) PHWR units which are 700 MW. Kakrapar Atomic Power Station (KAPS) 3&4 and Rajasthan Atomic Power Station(RAPS) 7&8, which are to be constructed by Hindustan Construction utilising indigenous technology estimated at Rs 123.2bn (www.world-nuclear.org, 2016). Considering exchange rates of respective years and using GDP deflator we have arrived at per reactor cost as shown Table 19. In line with the earlier Department of Atomic Energy (DAE) [2002b] estimate, we will assume that IDC constitutes 12.7 % of the total(Ramana et al., 2005) and exclude it from capital cost.

Table 19. Cost comparison of reactors.

Plant in consideration	Kaiga 1&2	TAPP 3&4	KAPS/RAPS	
Cost consideration year	1996	2006	2012	2019
Exchange rate (USD)	45.6	49.9 8	57.82	69.68
GDP Deflator factor	66.53	115	186	237
Cost (per pair) in INR in bn	28.96	62	123.2	NA
Cost in USD billion at 2019 prices	0.98	1.11	1.18	NA

In 2017, Indian government estimated 11bn USD for ten 700MW PHWR with each unit costing around 1.1 bn USD. Here Kaiga 1&2 have undergone a delay in project completion by an year and KAPS 3&4 and RAPS 7&8 are still under construction (2016-17). Hence, it is TAPS 3&4 cost is considered to be 1.11 bn USD per reactor at 540 MW.

4.2.2.2 Decommission costs

After the completion of the life and the long periods of cooling, the plant must be decommissioned and the expenses related needs to be considered in capital expenses. Some of the agencies usually makes the assumption of the decommissioning costs between 9 and 15% of the initial investment costs typically for a life span of 40 years [UIC, 2001]. The US Nuclear Regulatory Commission estimates is in the range of 20-30 % of initial investment costs. This provides the decommission cost for at 0.11 Bn USD for 540 MW TAPs 3&4 at lifespan of 40 years.

4.2.2.3 Fuel expenditure

The expenditure of nuclear fuel, uranium, on the basis of saving norm is estimated at 0.024 kg/MWh-year in literature (Balachandra, 1990).Observing that in 2018, DAE opined that a stockpile of 15000 MT/year would provide for supply security of nuclear fuel in India. This works out to 0.025 kg/MWh-year at current production of 6.78 GW of nuclear energy, reassuring of the estimated value by literature (PTI, 2018).

Typically, there are 3672 fuel assemblies in a PHWR reactor of capacity 220 MW and each of them consists of 15.2 kg of uranium oxide. Some reports suggest that the cost of every assembly is Rs. 250,000 (TS, 2002). This gives a cost of Rs 16447/kg of Uranium fuel as estimated by Ramana 2007 et al. Projecting to 2019 via GDP deflator, uranium costs Rs 37500/kg (2.37 factor).

It is estimated that a 220MW power plant requires 61 Tonnes of initial Uranium loading and 33 Tonnes of at an annual cost (Zutshi & Bhandari, 1994). Projecting it to a 540 MW plant, the requirement is 150MT and 76MT/year for initial loading and annual consumption respectively. This puts the cost at 83.85mn USD and 42.53mn USD/year for initial loading and annual consumption respectively.

4.2.2.4 Heavy water cost

The PHWR station utilises Heavy Water (HW) as coolant and moderator both. The information about the quantity of HW produced in the heavy water plants of DAE is not available in any public platforms. Ramana et al 2007, approximated the costs of HW in Manuguru plant to be 24,880/kg on the basis of CAG's computation of the costs (CAG 1994). Further authors (M. Jain, 2015) has revised the HW cost to 36,500/kg to 2015 prices and the same is used for the cost estimation (For 2019 level prices).

In DCF methods inventory is taken as upfront capital cost. For 540 MW reactor initial coolant inventory requirement was put at 177 tonnes of HW and inventory of moderator needs at 285 tonnes, correspondingly (NEI 1994). Hence the price of initial inventory Heavy water cost becomes Rs 1,686.3 Cr (0.24bn USD) for 540 MW TAPS reactors.

4.2.2.5 Heavy water make up losses

In PHWR reactor, there is a certain amount of losses of HW periodically and it needs to be refilled. These are attributed to equipment failure, HW escapes such as leaks and spills. NPCIL reported that the refilling of HW annually is 7 MT/year for a 220 MW PHWR reactor (Kati, 2004).Projecting it to 540 MW, the loss is 17 T/year. Taking HW cost of Rs 36500/Kg, the make-up loss annually comes to Rs 0.6205bn (9.256 mn USD).

4.2.2.6 Nuclear wastage cost/reprocessing cost

The reprocessing of the nuclear waste results in some costs and DAE has chosen a relatively costlier method of reprocessing for dealing with the used fuel. The method suggested by DAE is the planned three staged program where the each stage used the reprocessed fuel of other stage(Ramana et al., 2005). In the NPCIL's analysis of the economics of PHWRs, ''the cost of waste disposal has been assumed to have trade off with the amount of reprocessed fuel generated for next stage of nuclear power programme'' (Ramana et al., 2005).

Hence, to approximate the cost of reprocessing and storage of waste, it is assumed that the used fuel is just given or delivered to the reprocessing plant. Transportation cost of used fuel is estimated at Rs. 878/kg by M V Ramana et.al based on OECD's nuclear Energy Agency study(Jones, 1989). Using GDP deflator, the cost of spent fuel becomes Rs 2001/kg (2019 price). This forms nearly 10.1% of the cost of Uranium fuel.

4.2.2.7 Operating and maintaining cost

This involves various expenses including payment to human resources, components for O&M, plant or station monitoring, operation of waste reprocessing plants and facilities, catching and filtering HW losses, and similar activities. Due to lack of publicly available data, this study relies on existing literature. it is assumed that this is 2 % of the capital cost as per (Ramana et al., 2005).

4.2.2.8 Electricity Generation / Performance of plant

Once touted as one of the lowest available factors in developing world, India has continuously progressed in the next few decades. Table 20 shows the average availability factor of Indian nuclear plants for 10 years.

Table 20. Availability Factor of nuclear Plants (cnpp.iaea.org).

2005-06	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15
89	85	83	82	92	89	91	90	88	88

The average availability factor is 87% and is taken to calculate the power generated by the plant. Taking it for TAPP 3& 4 of 540 MW, it is arrived at 4148 Million Units. These data correlate to TAPS 3&4 actual performance as observed by Table 21.

Table 21. Power generated in Million Units (IAEA - Power Reactor Information System (PRIS)).

Year	2012-13	2013-14	2014-15	2015-16
TAPS-3	4373	3739	4545	4128
TAPS-4	3866	4017	3713	4178

4.2.3. LCOE calculation

For LCOE calculation, the costs are grouped as shown in table 22. While the construction costs and Decomissioning costs are one-time investments at the beginning and the end of plant life, Maintenance and operation costs are considered every year. The uranium initial loading, HW initial inventory costs are one-time investments and are taken in the initial year. The other fuel costs like uranium consumption, HW loss and reprocessing costs are recurring and are considered every year. The electricity produced is calculated for each year considering 87% and all costs are discounted to present year to LCOE calculation with the discount rate of 10%.

Table 22. LCOE nuclear energy calculation.

	PHWR LCOE For 540 MW	In million USD
It	Construction Cost	1112.7
	Decommission cost	10% of capital
	Total cost	1223.97
Mt	Operation and Maintenance cost per year	2% of capital cost
	Total cost	22.254
Ft	Uranium Initial loading	83.85
	Uranium consumption per year	42.53
	HW expenditure initial inventory	249.748
	HW make-up loss cost per year	9.256
	Nuclear reprocess cost	3.09
Et	Energy Generation Million Units per year	4128
r	Discount rate %	10
n	Plant lifetime in years	30
	Final LCOE	0.055

4.2.4 Sensitivity Analysis

The value of LCOE depends upon the various parameters such as Capital cost, annual operation and maintenance cost, discount factor, fuel costs, heavy water costs and annual electricity produced as shown in Equation. The sensitivity range of each prescribed parameter is taken as ± 10%. Here, Capital cost, annual operation and maintenance cost, discount factor, fuel costs, heavy water costs are the economic factors or costs, whereas the annual electricity generated is the technical asset. The impact of each parameter on the LCOE is distinctive in value as well as in the nature. The variation in the LCOE of nuclear corresponding to the parameter sensitiveness. All the factors except lifetime and electricity generation exhibit positive relation with the LCOE, which means the increment in these parameters will lead to the rise of LCOE. The annual electricity generated, discount factor and capital costs parameters are the most significant parameters (see figure 12).

For sensitivity analysis each parameter was varied 10 percent. However, the range of these parameters vary differently. Here we try to collect the range of the values from literature. Electricity is found to be the major influencing factor and it depends on availability factor which was assumed 87% in this study and according to (Tran & Smith, 2018) it can range from 85% to 90%. In a similar way investment costs were assumed to be 1.1 bn USD and from the studies considered here, it can vary from 0.98 bn USD to 1.18 bn USD. Furthermore, discount factor for any project in India varies from 8% to 12% (Shukla, 1997). Lifetime affects least for LCOE and is found to vary between 40 to 100 years (Tran & Smith, 2018). Lastly, since PHWR is not a common technology and Indian government keeps the information confidential, the costs of the fuel and HW is limited to some sources mentioned above. The choices in this work are made to match the real conditions of Maharashtra and sensitivity analysis is carried out to see to what extent each parameter influence LCOE.

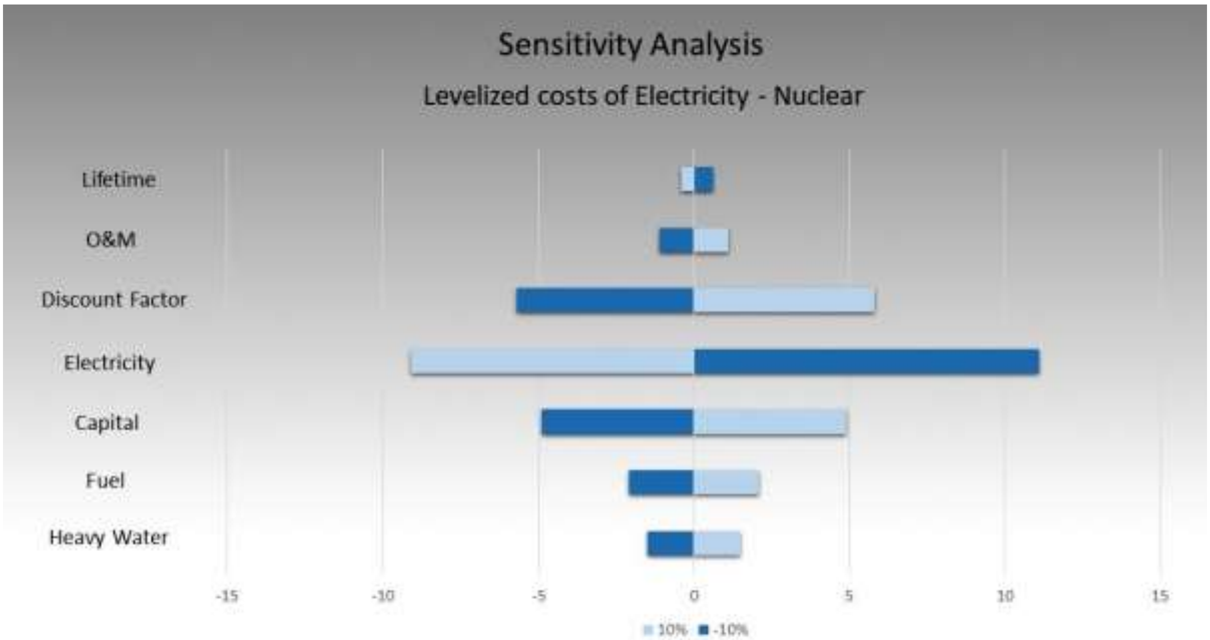

Figure 12. Sensitivity analysis- LCOE of nuclear energy.

5 Integration of environmental and economic aspects

The main goal of this section is to adopt a systematic approach to execute a more dependable comparison of the different alternative technologies, hence using the LCA outcomes in a better way to provide information to policy or decision makers.

NITI Aayog which is the think tank of GOI is responsible for setting and translating targets of SDGs. In the recent conclave conducted by NITI Aayog on SDGs, different topics were discussed. The conclave objective was to identify needs and roles of different stakeholders for effective implementation of SDGs, to discuss and identify gaps and issues and to ensure no one is left behind (Aayog, 2017). The integration method we use in this study needs to be easily adoptable and support the existing objectives and the system. MCDA is a deliberative process which provides a platform for stakeholder participation and provides a transparent, inclusive and organised framework. The process helps in identification of pros and cons and arrive at solutions or discuss the trade-offs.

5.1 Multi-Criteria Decision Analysis (MCDA)

It is a mechanism or tool for helping make complex decisions which has several incompatible objectives that different stakeholders and policy makers see it in a different way. MCDA is planted in operational research and help for policy makers mostly for exploring an optimised answer to a complex policy making issue. The importance of MCDA uses in policy making and environmental aspects has made a way for multiple stakeholder process to define issues and also to provide a platform for discussions on merits and demerits of different alternatives.

The following are the common steps carried out in the MCDA process.

1. Defining or identifying the problem which includes the context, stakeholders, their objectives and concerns.

2. Organising the problem in terms of figuring out alternatives and establishing criteria for evaluating the alternative technologies.

3. Evaluating the performances based on the criteria or indicators chosen in form of an impact matrix. In our case study, GWP is evaluated in units of g. Co2 eq./kWh and levelized costs are evaluated in terms of USD/kWh.

4. Deriving stakeholder and policy maker values like ranking the criteria in preference order or giving weightage to know the relative importance of each criterion.

5. synthesizing the outcomes utilizing a computational model to analyse pros and cons and performances of alternative technologies for suggesting a answer to the issue and to show various perspectives or derive new answers.

6. Evaluating the sensitivity of the outcomes in the parameters to know the robustness of the outcomes(Saarikoski et al., 2016).

The participatory process of MCDA is performed in a joint effort with all the stakeholders, who can add their inputs to issue articulation, organising and weights and also impact evaluation. For successful problem formulation and structuring, early involvement of stakeholders is essential. This is an iterative process and not a linear one and various types of MCDA methods are developed to rank and analyse alternative technologies. Most of these methods more or less follow these general steps but have various procedures for evaluating and organising the information and different algorithms combining it. A short briefing of various MCDA types with their trade-offs are given here.

Most used MCDA methods are taken and these are Multi Attribute Value Tree analysis (MAVT), Analytic Hierarchy Process (AHP), rank based methods and outranking methods.

In case of AHP & MAVT, problem is organised in shape of a value tree which represents a framework in pecking order of different indicators & technologies. The stakeholders are told to come up with weights to know the relative preference of every indicator for them. The weights can be allotted with respect to span of variance of the indicators in the policy-making problem. MAVT method needs subjective judgement of value functions of each criterion that normalize the environmental, economic and social impacts to a same scale. Value functions measure the preferences in each of this indicator or criterion in different parts of scale. From these value functions, a normalised matrix can be made where all the indicators/criteria can be represented in the same value range (zero to one). Then, criteria performance scores of each alternative can be multiplied with corresponding weights and then added to get the overall performance score of the technology alternative. In MAVT, participants take into consideration all the criteria or indicators simultaneously and then select the most prominent one for comparing each indicator with respect to the selected one. In AHP, the prominence of each of the indicator is made as pairwise judgements to know the order of preference among each couple of indicators under every divide of value hierarchy. Likewise, description of the performance of every alternative in every indicator is provided for pairwise judgements. Eigen vector technique is used to determine the weights for each criterion for pairwise comparison matrix. By summing up these values, overall weights for technologies can be obtained and compared to alternative technologies.

Rank based methods are different when compared to the above two methods and it uses an ordinal scale in place of cardinal scale and requires participants to give a ranking of the indicators in an order of preference. From this, the overall rankings of the technologies can be procured by summing up the indicator wise technology rankings. Therefore, this method does not consider the magnitude difference or criteria wise value differences, for example, a little variation between two technologies can be ranked in ordinal scale. But, these two alternatives can also be given same ranking if the difference is small between the values.

Outranking methods derive pairwise outranking when each pair of technologies are assessed to rank the technologies. This is an advantage over MAVT as incommensurability relationships among indicators/criteria can be accounted explicitly and pros and cons can be restricted among the criteria.

From the above process, it can be said that MCDA is characterised by instrumental and deliberative model which depends on the design of the process. The process can be utilized in an instrumental fashion to sum up preferences, quantify trade-offs for the use of policy makers, and it can be utilized in deliberative method to trigger and form environmental and social values with relevant stakeholder groups including policy makers (Saarikoski et al., 2016).

5.2 Integration

In the attempt to organise, consolidate the results discussed in the previous chapters, the MCDA approach is used. A simplified approach, weighted sum approach has been used for this purpose. To circumvent the bias influencing different indicators of environmental and economic aspect, the scores are normalised in each indicator and then an overall order of preference approximated based on the integration of two dimensions. In Maharashtra, the electricity mix is dominated by coal and hence we take coal energy into account for normalising the indicators and comparing it with the analysed technologies i.e. solar PV and nuclear energy to know how they perform relatively with the predominant technology.

In the first scenario, equal importance is given for both environmental and economic impacts. In the second scenario, we assume one aspect's weight is four times higher than that of the other to check the robustness of the results. For example, 0.8 for environmental aspect and 0.2 for economic aspect also a vice versa case. The scores are The MCDA outcomes are discussed in the below section. The alternative with the lowest sustainability score is observed most sustainable.

5.2.1 Equal weight scenario

In this section, each indicator is given equal weightage for each technology. For example, 0.5 is assigned for environmental aspect i.e., greenhouse gas emission and 0.5 is given to economic aspect i.e. LCOE (table 25). A more robust method could be used to assign stakeholder preferences in a MCDA, but this is beyond the scope of the study. Therefore, the ranking of the technology or preference of alternatives are only valid withing the limits given above and needs to be considered tentatively.

Table 23. Equal weight scenario sustainability scores.

	Weights	Solar	Nuclear	Coal
GHG emissions		38.350	12.190	886.000
environmental	0.5	0.043	0.014	1.000
LCOE		0.045	0.055	0.049
Economic	0.5	0.818	1.000	0.890
Score	1.0	0.431	0.500	0.945

As indicated in the table, solar PV is the most sustainable scoring around 0.431. Nuclear energy follows closely with 0.500. Both solar and nuclear energy performs well on environmental aspect especially when compared to predominant coal powered plants in

India. But there is a greater difference between solar and nuclear energy in terms of levelized costs of electricity. From economic perspective solar energy is the best and nuclear is the worst. Coal has the lowest sustainability score of 0.945 and mostly contributing to low performance of environmental aspect.

5.2.2 Different preferences Scenario

To figure out how the order of ranking might or might not vary with various preference weightages for the two indicators, it is assumed that one indicator is more prominent compared to other one. For this purpose, extreme prominence of four times is considered and the environment aspect is assigned 0.8 while the economic aspect is assigned 0.2 (table 24). The results are given below in the table. Here it is observed that the ranking of the alternatives has not changed with the extreme weights considered. But the scores have moved to extremes. While solar energy score improved from 0.431 to 0.198, the nuclear energy score improved from 0.5 to 0.2. However, the opposite trend was visible for coal energy as the score took a hit from 0.945 to 0.978. Hence, as the weightage for environmental aspect increases, nuclear and solar energy becomes more and more favourable relative to the s energy. The magnitude of improvement is higher in nuclear energy, but still solar PV performs better that the other two technologies at the given weightage.

Table 24. Weight preference of 0.8 and 0.2 for environmental and economic factors.

	Weights	Solar	Nuclear	Coal
GHG emissions		38.350	12.190	886.000
Environmental	0.8	0.043	0.014	1.000
LCOE		0.045	0.055	0.049
Economic	0.2	0.818	1.000	0.890
Score	1.0	0.198	0.200	0.978

Now, another extreme case is taken where the economic aspect is given a weightage of 0.8 and environment aspect is given a weightage of 0.2 (table 25). The results are given below in the table. Here we observe a opposite trend where solar score worsened from 0.431 to 0.663 and nuclear score worsened from 0.5 to 0.8. However, coal has an improved score of 0.912. The ranking of the alternatives is still the same. Clearly, solar energy is the winner in the range of the assumed extreme weights and is followed by nuclear and coal energy.

Table 25. Weight preference of 0.2 and 0.8 for environmental and economic factors.

	Weights	Solar	Nuclear	Coal
GHG emissions		38.350	12.190	886.000
Environmental	0.2	0.043	0.014	1.000
LCOE		0.045	0.055	0.049
Economic	0.8	0.818	1.000	0.890
Score	1.0	0.663	0.800	0.912

A graph (see figure 13) is plotted to know if there are any changes in the ranking at the extreme ends. This sensitivity analysis shoes that order of preference of the technologies is robust within the extreme scenario range as discussed previously. The ranking only changes when environmental aspect weightage is greater than 0.9 or less than 0.2. When the weightage is more than 0.9, nuclear energy performs worst given its high LCOE, followed by coal and solar energy. When the weightage is less than 0.2, nuclear overtakes solar energy as it performs best in terms of GHG emissions. Overall, it can be said that solar never takes the third position and performs best when the weightage is above 0.2.

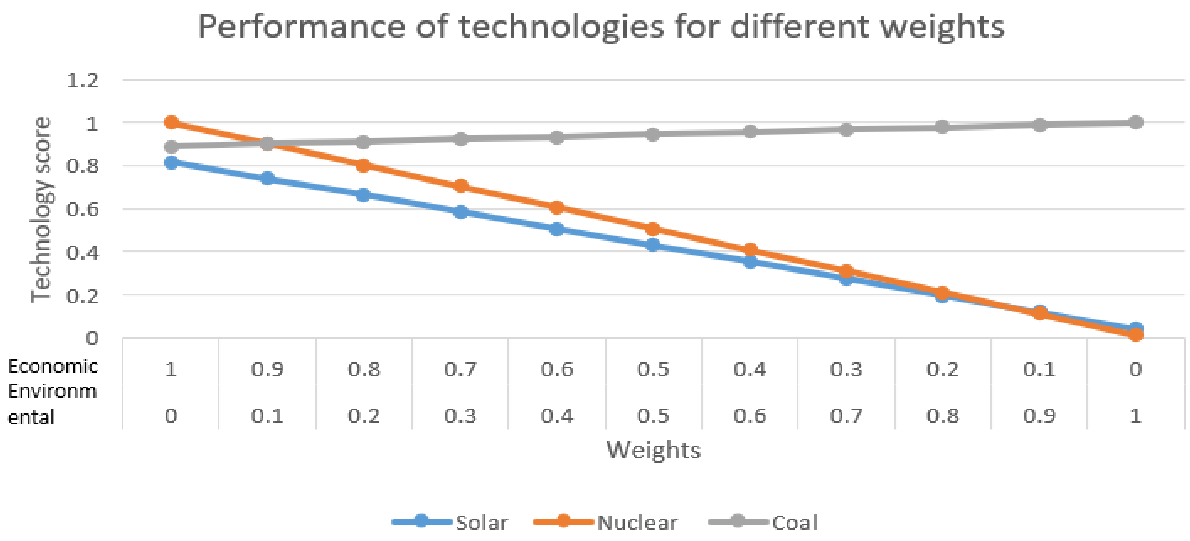

Figure 13. Performance of technologies- different weights.

Given the above trade-offs, the selection of a more sustainable technology will pivot on the stakeholder values and preferences of each sustainability indicator. Therefore, MCDA is a toll which can be used to evaluate which technology is more sustainable for power production in Maharashtra, India. The outcomes suggest that for every preference scenario taken in this work, solar energy comes out as the most sustainable option which is then trailed by the nuclear energy. Coal has the lowest sustainability score. Hence the outcomes of this work clearly depict that lowering fossil fuel proportion in the grid would lower the global warming potential significantly, and also the LCOE.

5.3 Comparison of solar PV and nuclear energy:

5.3.1 Environmental aspect

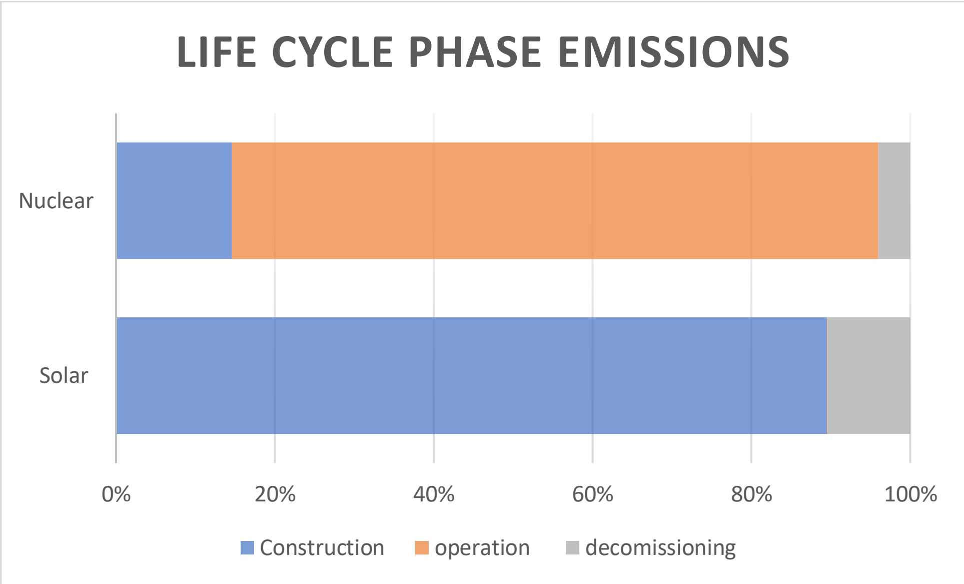

Figure 14. Life cycle phase GHG emissions.

The life cycle analysis is essential in understanding the emissions in different phases and understand which life stages has highest contributions to impacts. In this section environmental impacts of two technologies are compared and later, the possible solutions are discussed to reduce the GHG emissions. The analysis helped to understand which factors are key contributors to emissions and then think of possible solutions, technologically and policy wise.

As it can be seen from the figure 14, it is clear that the two technologies emit GHGs in different phases of their life in different proportions. In case of solar energy, building of the plant (includes the panels and other equipment setup) contributes highest to the complete emissions of all stages. The O&M emissions are very low as solar energy does not make use of any fuel and the minute emissions are attributed to maintenance or replacement of faulty equipment. Decomissioning contributes to around 10% of the total emissions. In nuclear energy, the major life cycle emissions happen during the operation stage where the fuel is needed. The mining of the uranium and heavy water production causes the emission. The construction and decommissioning have around 17% and 5% of the emissions. Hence, solar energy's emissions are majorly concentrated in the initial phase and nuclear energy emissions are spread throughout the lifetime of the plant. Therefore, we concentrate mainly on these aspects in this study.

In solar energy, majority of the emissions are during the manufacturing phase of the panels and we focus and discuss on how we can improve emissions in this stage.

- A particular process called SoG Si production contributes to 38% of the total emissions. This stage uses siemens method and upgrading technology to modified siemens method can help reduce around 23% of total emissions.
- In the system boundary, polycrystalline technology was considered because of its predominant usage in the market. If the panel type can be changed to thin films technology, the energy consuming SoG Si process is not required in this panel and It is estimated to reduce GHGs drastically. However, the efficiency of the thin films type panel is not as improved as silicon panels but the technology is evolving continuously and almost reaching up to the efficiencies of the silicon panels.
- The major emissions happen indirectly through energy consumption. Hence the primary energy mix carbon intensity plays a crucial role in the emissions. Presently, fossil fuels dominate China's electricity mix. Sourcing the panels from other countries with lower carbon intensity like Korea or European countries will reduce the emissions drastically. However, economic aspect also needs to be looked into before taking this step.
- Another influencing factor is the lifetime of the plant. Presently, the lifetime is around 25 years and it can be prolonged with improvements and enhancements in technology. It means that the electricity outcome per watt capacity increases which in turn decreases GHGs.
- The efficiency of the solar panels is constantly improving with time which in turn is improving capacity factor. Hence it can be said that electricity outcome will tend to increase and GHGs emissions reduces.

In nuclear energy, majority of the emissions are during the fuel fabrication and heavy water production and we focus and discuss on how we can improve emissions in this stage.

- The GHG emissions of nuclear power plant or station is dependent on the energy intensity of primary energy source.
- Whether electricity for heavy water production is by low carbon technologies or by coal power plants.
- The GHG intensity of the economy of heavy water production and mining locations.

The GHG intensity can increase with rising energy intensity, with higher quantity of electricity in the energy needs, and with increasing GHG intensity of the economy.

Uranium is a non-renewable resource and global rates of recovery are highest for the higher-quality ore grades, even though the majority of global recoverable resource consists of lower ore grades. The potential impact of decreasing uranium ore grades creates a major difference between nuclear and renewable technologies for future GHG mitigation potential.

5.3.2 Economic analysis

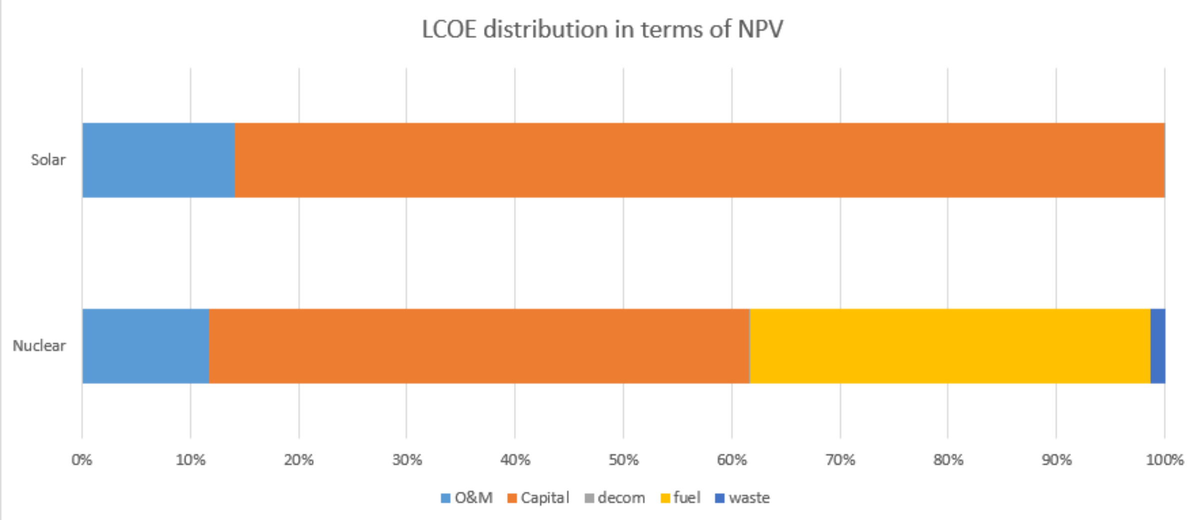

Figure 15. LCOE distribution of both technologies.

As it can be seen from figure 15, the big hurdle to adoption is high capital costs of solar PV in spite of declining LCOE. The longer-term loan, high discount rate, lower interest rates help helps in dealing with this. Unlike solar energy which is capital intensive and has no fuel cost, consumptive technology like nuclear energy is always vulnerable to inflation risk. However, a positive discount rate favours a technology which consumes fuel for operation as the costs are recurring. Positive discount rate means cash inflows are advantageous in short term while costs or cash outflows are lucrative in long term. Nuclear also involves long lasting construction times and fluctuating and increasing fuel costs which makes it more attractive over a technology like solar PV which has short installation time, capital intensive, high upfront costs and negligible costs thereafter.

5.4 Conclusions and policy implications

On the grounds of outcomes of this study, some of the policy recommendations are suggested to enhance the environmental and economic aspects of the electricity sector in Maharashtra, India.

5.4.1 Policies based on Integration

Current electricity sector in Maharashtra, India is mostly motivated by the requirement to enhance energy security, greenhouse gas emissions and levelized costs. In order to circumvent solving one aspect over the cost of another aspect, government can consider both environmental and economic impacts in the designing of strategy for power producing plants. This approach can enable to design many sustainable decisions in the future. Government must utilise LCA in policy making. This can assist to recognise hotspots and opportunities for lowering the environmental, economic and social impacts on the society when making a choice between technologies. The outcomes of the work for the first time quantify and integrate greenhouse gases and LCOE of solar and nuclear energy in Maharashtra India.

The outcome suggests that there would be improvements in economic and environmental performances of the electricity mix if the proportion of fossil fuels like coal in the electricity mix is reduced and adds up to the sustainability of the sector. Hence, further policies should be aimed at lowering or phasing out the share of coal in electricity generation. Currently the policies are directed at expand power production from coal to enhance the security of the electricity mix. The outcomes suggest that it is the least sustainable option. Coal can be preferred only in one exception when economic aspect is treated highly prominent and, in that scenario, it ranks in between solar and nuclear energy. More solar energy must be deployed in preference to coal plants as it will help reduce the global warming potential significantly and also has low LCOE while improving the energy security.

Maharashtra has significant potential of solar energy, a higher perforation of solar PV into the electricity mix as an alternative to coal is prominent for the state to improve energy security, reduce imports of the fossil fuels and reduce the global warming potential impacts from power production. However, it needs be selected with care as expanding the share of solar in the grid would contribute to other environmental and social impacts. The above trade-offs need to be analysed carefully to avoid resolving one issue at the cost of other. First, higher rate of adoption can be driven by more incentives and higher policy targets and supply chain innovation. Customers prefer increased quality, reliability of PV modules and supplementary BOS, wider standardisation in installation quality and lowered administration activities time for availing incentives from government. Second, a tax break can be provided in terms of sales or income for solar PV over fossil fuels to encourage more adoption. government can also support in a similar way it strengthened and enhanced investments in coal plant by enabling and facilitating PV manufacturing to reap cost reductions and other benefits like job creation.

However, solar energy is dependent on sun and is an intermittent source of energy. The base load must be provided by a reliable source. Hence, the two technologies (nuclear and solar) can be used as a combination to solve the problem of intermittency where nuclear energy can help in contributing to a share of base load and solar energy can contribute to a part of peak load. Nuclear energy has the lowest GHG emissions and highest costs, while solar energy has relatively low GHG emissions but low LCOE. Since both perform better than coal energy, it is required to solve the issue of high LCOE of nuclear energy to make it more viable. Policies can be framed in order to reduce the LCOE of nuclear as close to LCOE of coal energy. This can be with bundling of nuclear energy with low cost solar energy in which both can be sold together to DISCOMs along with relatively cheaper coal energy. The formulation itself has does not have financial burden. The high LCOE of nuclear cannot be reduced in this case and the new cheaper bundled price is an attraction for consumers. The initial capital costs of both nuclear and solar energy are high. Government can ease liquidity and de risk in order to make low cost finance accessible. For reducing the risk premium government can facilitate an environment of enabling policy and regulations and easing of project development.

5.4.2 Policies based on LCA

Currently the nuclear energy GHG emissions calculated in the study was based on mining of uranium in Canada. Canada has low carbon intensity of primary mix and highest grade or ore mines making it contribute lease amount of GHG emissions. However, India also has agreements for uranium imports from Kazakhstan and recently Uzbekistan. These two countries have low grade uranium mines and high carbon intensity of primary mix. Importing from these countries will contribute to higher GHG emissions. Hence it is recommended that government makes policies and agreements for increasing the share of Canadian uranium. Another hotspot, Heavy water production contributes to a major share of GHG emissions as the energy is derived from fossil fuel dominated energy mix. One possible solution for reducing emissions is that if the heavy water plant is located on the site of the nuclear plant or it can be powered by low carbon technologies, the GHG emissions reduce drastically. Government can help achieve this setup by subsidizing to industries for encouraging them to run on low carbon technologies. Government can also fund research related to heavy water production technology improvement to reduce emissions and cost.

In case of solar energy, sourcing it from other countries with lower primary energy carbon intensity will benefit environmentally. However, the cost advantage might be compromised. Hence to reduce the GHG emissions in China, first, government can put clauses during the bidding stage to encourage suppliers or companies with advanced technologies that consume less energy/emit less GHGs are given preference. Second, the government needs to amplify and strengthen research projects of environmental improvements of power producing plants or technology and also improve legislation to cap environmental impacts due to power production.

6 Conclusions

6.1 Answers to research questions

How can the combination of LCA and MCDA help Maharashtra's policy makers in deciding alternative electricity generating technologies that can contribute to a sustainable development of electricity production?

To answer the main research question, four sub-questions were formulated. The first question corresponds to the theoretical part while the remaining are focused on providing answers to practical issues regarding Maharashtra's energy sector.

- What are the most considered environmental and economic indicators in the literature?

Selecting sustainability indicators in environmental and economic aspects for this case study is a crucial step in the assessment. The goal of the research question is to help decision makers to identify dominant indicators in the literature study that can be used to know the current performance of the systems, to measure policy efficacies, actions and to unearth changes in the selected aspects.

The EU integrated project NEEDS (New Energy Externalities Developments for Sustainability) established a set of important or dominant criteria and indicators to be used for evaluation of energy technologies (refer appendix 1). The established indicators include a total of 36 indicators comprising 9 economical, 16 social and 11 environmental indicators. However, for decision or policy making purposes, a small set of few dominant indicators with less complex frameworks have more promise.

In order select indicators relevant to India's SDG 7 which aims to make the energy clean and affordable, a literature study was conducted. The studies considered were based on two criteria. The study must have used indicators in all three dimensions of sustainability and the study must have used an integration method. After the analysis on the documents selected, the indicators which are used more frequently were recognised. In the economic dimension, not only operation or implementation costs are considered, but also the costs throughout the whole project. The most used indicator for economic dimension is Levelized costs. When it comes to environment dimension, indicator Global warming potential (GWP) which measures GHG emissions that caused climate change was the most used.

GWP expresses the potential of the various GHGs to cause climate change taking the reference gas as CO2. To calculate GWP which is measured in terms of g CO_2-eq/ kwh, total GWP emissions over the lifetime of the plant is divided by electricity produced by the plant. LCOE indicator is calculated by taking complete costs of the plant over its lifetime and dividing it by the total electricity generated by the plant to estimate a price per kwh (USD/kWh). Hence, we use these indicators in our study for measuring environmental and economic performance of solar and nuclear energy in Maharashtra, India.

- What is the environmental performance of the solar PV and nuclear energy technologies in Maharashtra, India?

The goal of the research question is to estimate the GHGs for defined system and to understand the characteristics of GHG emissions from different life stages of the electricity generating technologies. A methodology was applied to perform harmonisation on the existing LCA studies, that are reliable on latest and credible data sources, to estimate GHGs that reflect current status of Maharashtra. Further, the analysis can be used to identify hotspots of GHGs in life cycle stages and frame policies to further reduce the GHGs of a particular technology.

In case of solar PV, the GHGs were estimated by harmonising key parameters like module efficiency, performance ratio, annual irradiation, primary energy mix carbon intensity, lifetime and system boundaries to the values relevant to our case study. The final GHG estimate for the polycrystalline PV ground mounted utility scale system for the case of Maharashtra was found to be 39 g CO_2 eq/kWh. 89% of the total emissions are contributed by manufacturing phase of solar modules and a particular process called SoG Si production in manufacturing contributes to 38% of the total emissions. For reducing the emissions, technology improvements are suggested in the study. Another major reason for emissions is the indirect GHG emissions through energy consumption. China's energy mix is dominated by fossil fuels contributing to major GHGs in the lifecycle. Sourcing the panels from other countries with lower carbon intensity energy emission might be an option. Overall, solar PV technology is continuously changing to improve module efficiency, performance ratio and lifetime of modules leading to lower emissions over time.

In case of In nuclear energy, the GHGs were estimated by harmonising the data based on the activities conducted in the nuclear power plant life cycle in the case study. The final GHG estimate for the PHWR CANDU nuclear reactor for the case of Maharashtra was found to be 12.5 CO_2 eq/kWh under the defined system boundaries. 75% of GHG emissions are due to the energy consumed by heating source during the heavy water production and the energy mix currently is fossil fuel dominated. The emissions can be reduced drastically by moving heavy water production onsite and powering it by nuclear thermal energy or any low carbon technology. The Canadian uranium import considered in the study has least emissions due to high quality ore and low carbon intensity of energy mix. Importing uranium from other countries where mining ore quality is low and energy mix is dominated by fossil fuels can lead to higher emissions. Overall, the potential impact of decreasing uranium ore grades over time creates a major difference between nuclear and renewable technologies for future GHG mitigation potential. However, there are many possibilities like feeding the nuclear energy back into the preparation of input materials of nuclear fuel cycle and researching for new materials that can be used as fuel by new technologies which can reduce the emissions in future.

The analysis and harmonisation for the case of Maharashtra gives an indication of relative magnitude of GHGs during the whole life cycle of the nuclear energy based on critical assumptions made in each process which makes up the system. The above discussion and analysis can be used for policy making for comparing the emissions with alternatives or even identify hotspots and frame policies to further reduce GHG emissions.

- What is the economic performance of the solar PV and nuclear energy technologies in Maharashtra, India?

To get a clear picture of the relative cost effectiveness and feasibility of solar and nuclear energy, the indicator LCOE was used. To use the estimations in the policy or decision making, assumptions were made as accurate as possible, with respective sensitivity analysis.

In case of solar PV, for Maharashtra, under defined system boundaries, LCOE cost was estimated to be 0.045 USD/kWh. The capital costs contribute to 85% of the LCOE costs and operation costs add up to 14%. Solar PV has negligible decommissioning costs and does not have any fuel and waste costs and not susceptible to inflation risk. Therefore, the technology has high upfront costs and has a short installation time making it a hurdle to the widespread adoption. In sensitivity analysis, two parameters, investment and annual electricity generated, had prominent impacts on the LCOE. However, the system components price is continuously decreasing and electricity output is continuously improving with changes in technology leading to reduction in LCOE costs over time.

In case of nuclear energy, for Maharashtra, under defined system boundaries, LCOE cost was estimated to be 0.055 USD/kWh. The capital costs, fuel costs and O&M costs contribute to 50%, 37% and 12% of the total LCOE. Nuclear energy has negligible decommissioning and waste costs. Therefore, the technology has a long installation time and high fuel costs making it susceptible to inflation risk. In sensitivity analysis, three parameters, investment discount factor and annual electricity generated, had prominent impacts on the LCOE. However, the electricity output has remained same over time and capital costs are increasing due to increasing safety standards and inflation risk.

- What are the policy implications based on the LCA and MCDA outcomes of alternative technologies?

MCDA process called weighted sum approach was used to sum up preferences and quantify trade-offs for the use of policy makers. It is used as a deliberative method to trigger and form environmental, economic and social values with relevant stakeholder groups including policy makers.

Two scenarios were considered for checking the robustness of outcomes. In one scenario, both environmental and economic aspects were given equal preference and in second scenario, one aspect was given four times higher preference than the other and vice versa. Interestingly, the overall outcomes remained same in the given scenarios. Both solar and nuclear energy performs well on environmental aspect especially when compared to predominant coal powered plants in India. But there is a greater difference between solar and nuclear energy in terms of levelized costs of electricity. Coal is the least sustainable technology with low overall score largely owing to poor environmental performance. Clearly, solar energy is the winner in the range of the assumed extreme weights and it is followed by nuclear and coal energy. However, solar PV is an intermittent source of electricity and there is also a need for base load for the grid that can be provided by the nuclear energy. Hence a combination of nuclear and solar PV can act as a replacement for a part of coal technology share in the energy mix.

Based on the outcomes of this study, policy implications were discussed on two fronts. On economic front, electricity bundling of solar and nuclear energy is recommended to reduce the overall cost and to solve the issue of intermittency of solar energy. Other suggestions included easing liquidity and de risking for low cost financing needed for capital-intensive technologies. On the environmental front, GHG hotspot phases in both solar PV and nuclear energy were identified and policy recommendations were discussed. The research could be funded to improve technologies which contributes in reducing GHGs in the hotspot phases. Another way to reduce GHGs is to strategically design policies to encourage imports of input materials from countries which are less dependent on fossil fuels. Overall, policies should be aimed at lowering or phasing out the fossil fuels and at providing enabling environment for increasing the low carbon technologies into the energy mix.

6.2 Limitations

This work, like any scientific research, has its own limitations. Firstly, a system boundary was defined for each technology when evaluating environmental and economic performances based on the current status or predominantly available conditions or data. However, there are different types of technologies in solar PV and nuclear energy and also there are possibilities different from the assumed boundaries and it can change the outcomes of the study. For example, poly crystalline Si PV was chosen in system boundaries but there are also other PV types like monocrystalline Si PV or thin films. Similarly, PV modules are assumed to be manufactured in China and this can change over time.

Secondly, one indicator is chosen from environmental and economic dimensions for this study because of the timeline of the project. However, other indicators like acidification potential, ecotoxicity or capital costs etc are not evaluated which can shift problems from one indicator to another.

Thirdly, for life cycle sustainability assessment, three dimensions needs to be considered and, in this study, only two dimensions are evaluated. The outcomes can change with increasing dimensions and indicators.

Lastly, the harmonisation process was followed to estimate the GHGs of technologies. However, this might not be accurate value and the process is an approximation based on different studies published results. The other studies have their own limitations and it is carried over.

6.3 Directions for future research

Considering the limitations of the work, it is possible to provide directions for future research. Firstly, different scenarios in each technology for system boundaries can be included to depict how the indicators value change with different system boundaries. This will give stakeholders wider knowledge of different possibilities in each technology and enables to further reduce some of the impacts.

Secondly, to make the research more comprehensive and to avoid problem shifting from one indicator to other, more indicators can be included in environmental and economic dimensions. The list of other indicators is mentioned in the appendix. However, choosing to many indicators makes the research complex for the researcher as well as the reader.

Thirdly, the advantage of MCDA is that qualitative indicators can be easily added to the study. In the present study, two dimensions were considered and other dimensions like social and security indicators can be added to make it complete life cycle sustainability study (see appendix). Some of the research also consider technical and institutional dimensions in research.

Lastly, the research could be extended to different low carbon technologies to enable policy makers for creating future energy mix. A mathematical model can be developed to create different future electricity mix possibilities and select the optimised future mix which has the least impacts on all the three dimensions and create policies towards it.

There is a need for clean energy sources and manufacturing methods for reducing the impacts in the world and there are many variables involved and more comprehensive research will avoid problem shifting from one to another. The study can be made more comprehensive by adding more relevant technologies, indicators and dimensions.

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8 Appendix

8.1 Appendix Environment indicators

Criteria / Indicator	Description	Unit
ENVIRONMENT	Environment related criteria. Source: NEEDS Research Streams 1a & 2b, using Life Cycle Assessment (LCA)	
RESOURCES	Resource use (non-renewable)	
Energy	Energy resource use in whole life-cycle	
Fossil fuels	This criterion measures the total primary energy in the fossil resources used for the production of 1 kWh of electricity. It includes the total coal, natural gas and crude oil used for each complete electricity generation technology chain.	MJ/kWh
Uranium	This criterion quantifies the primary energy from uranium resources used to produce 1 kWh of electricity. It includes the total use of uranium for each complete electricity generation technology chain.	MJ/kWh
Minerals	Mineral resource use in whole life-cycle	
Metal ore	This criterion quantifies the use of selected scarce metals used to produce 1 kWh of electricity. The use of all single metals is expressed in antimony-equivalents, based on the scarcity of their ores relative to antimony.	kg(Sb-eq.)/kWh
CLIMATE	Potential impacts on the climate	
GHG emissions	This criterion includes the total for all greenhouse gases expressed in kg of CO2 equivalent.	kg(CO2-eq.)/kWh
ECOSYSTEMS	Potential impacts to ecosystems	
Normal operation	Ecosystem impacts from normal operation	
Land use	This criterion quantifies the loss of species (flora & fauna) due to the land used to produce 1 kWh of electricity. The "potentially damaged fraction" (PDF) of species is multiplied by land area and years.	PDF*m2*a/kWh
Ecotoxicity	This criterion quantifies the loss of species (flora & fauna) due to ecotoxic substances released to air, water and soil to produce 1 kWh of electricity. The "potentially damaged fraction" (PDF) of species is multiplied by land area and years.	PDF*m2*a/kWh
Acidification / Eutrophication	This criterion quantifies the loss of species (flora & fauna) due to acidification and eutrophication caused from production of 1 kWh of electricity. The "potentially damaged fraction" (PDF) of species is multiplied by land area and years.	PDF*m2*a/kWh
Severe accidents	Ecosystem impacts in the event of severe accidents	
Hydrocarbons	Quantification of large accidental spills of hydrocarbons (at least 10000 tonnes) which can potentially damage ecosystems.	t/kWh
Land contamination	This criterion quantifies land contaminated due to accidents releasing radioactive isotopes. The land area contaminated is estimated using Probabilistic Safety Analysis (PSA). Note: only for nuclear electricity generation technology chain.	km2/kWh
WASTE	Potential impacts due to waste	
Chemical waste	This criterion quantifies the total mass of special chemical wastes stored in underground repositories due to the production of 1 kWh of electricity. It does not reflect the confinement time required for each repository.	kg/kWh
Radioactive waste	This criterion quantifies the volume of medium and high level radioactive wastes stored in underground repositories due to the production of 1 kWh of electricity. It does not reflect the confinement time required for the repository.	m3/kWh

8.2 Appendix Economic indicators

Criteria / Indicator	Description	Unit
ECONOMY	Economy related criteria Source: NEEDS Research Stream 2b contributors for different technologies.	
CUSTOMERS	Economic effects on customers	
Generation cost	This criterion gives the average generation cost per kilowatt-hour (kWh). It includes the capital cost of the plant, (fuel), and operation and maintenance costs. It is not the end price.	€/MWh
SOCIETY	Economic effects on society	
Direct jobs	This criterion gives the amount of employment directly related to building and operating the generating technology, including the direct labour involved in extracting or harvesting and transporting fuels (when applicable). Indirect labour is not included. Measured in terms of person-years/GWh.	Person-years/GWh
Fuel autonomy	Electricity output may be vulnerable to interruptions in service if imported fuels are unavailable due to economic or political problems related to energy resource availability. This measure of vulnerability is based on expert.	Ordinal
UTILITY	Economic effects on utility company	
Financial	Financial impacts on utility	
Financing risk	Utility companies can face a considerable financial risk if the total cost of a new electricity generating plant is very large compared to the size of the company. It may be necessary to form partnerships with other utilities or raise capital through financial markets.	€
Fuel sensitivity	The fraction of fuel cost to overall generation cost can range from zero (solar PV) to low (nuclear power) to high (gas turbines). This fraction therefore indicates how sensitive the generation costs would be to a change in fuel prices.	Factor
Construction time	Once a utility has started building a plant it is vulnerable to public opposition, resulting in delays and other problems. This indicator therefore gives the expected plant construction time in years. Planning and approval time is not included.	Years
Operation	Factors related to a utility company's operation of a technology.	
Marginal cost	Generating companies "dispatch" or order their plants into operation according to their variable cost, starting with the lowest cost base-load plants up to the highest cost plants at peak load periods. This variable (or dispatch) cost is the cost to run the plant.	€cents/kWh
Flexibility	Utilities need forecasts of generation they cannot control (renewable resources like wind and solar), and the necessary start-up and shut-down times required for the plants they can control. This indicator combines these two measures of planning flexibility, based on expert judgment.	Ordinal
Availability	All technologies can have plant outages or partial outages (less than full generation), due to either equipment failures (forced outages) or due to maintenance (unforced or planned outages). This indicator tells the fraction of the time that the generating plant is available to generate power.	Factor

8.3 Appendix social indicators

Criteria / Indicator	Description	Unit
SOCIAL	Social related criteria. Source: NEEDS RS 2b survey of social experts. Quantitative risk based on PSI risk database.	
SECURITY	Social Security	
Political continuity	Political continuity	
Secure supply	Market concentration of energy suppliers in each primary energy sector that could lead to economic or political disruption.	Ordinal scale
Waste repository	The possibility that storage facilities will not be available in time to take deliveries of waste materials from whole life cycle.	Ordinal scale
Adaptability	Technical characteristics of each technology that may make it flexible in implementing technical progress and innovations.	Ordinal scale
POL. LEGITIMACY	Political legitimacy	
Conflict	Conflicts that are based on historical evidence. It is related to the characteristics of energy systems that trigger conflicts.	Ordinal scale
Participation	Requirement for public, participative decision-making processes, especially for construction or operating permits.	Ordinal scale
RISK	Risk	
Normal risk	Normal operation risk Source: NEEDS Research Stream 2b for life cycle risk data	
Mortality	Years of life lost (YOLL) by the entire population due to normal operation compared to without the technology.	YOLL/kWh
Morbidity	Disability adjusted life years (DALY) suffered by the entire population from normal operation compared to no technology.	DALY/kWh
Severe accidents	Risk from severe Accidents Source: NEEDS Research Stream 2b for severe accident data	
Accident mortality	Number of fatalities expected for each kWh of electricity that occurs in severe accidents with 5 or more deaths per accident.	Fatalities/kWh
Max. fatalities	Reasonably credible maximum number of fatalities for a single accident for an electricity generation technology chain.	Fatal./accident
Perceived risk	Perceived risk	
Normal operation	Citizens' fear of negative health effects due to normal operation of the electricity generation technology.	Ordinal scale
Perceived acc.	Citizens' perception of risk characteristics, personal control over it, scale of potential damage, and their familiarity with the risk.	Ordinal scale
Terrorism	Risk of terrorism	
Terror-potential	Potential for a successful terrorist attack. Based on its vulnerability, potential damage and public perception of risk.	Ordinal scale
Terror-effects	Potential maximum consequences of a successful terrorist attack. Specifically for low-probability high-consequence accidents.	Exp. fatalities
Proliferation	Potential for misuse of technologies or substances present in the nuclear electricity generation technology chain.	Ordinal scale
RESIDENTIAL ENV.	Quality of the residential environment	
Landscape	Overall functional and aesthetic impact on the landscape of the entire technology and fuel chain. Note: Excludes traffic.	Ordinal scale
Noise	The amount of noise caused by the generation plant, as well as transport of materials to and from the plant.	Ordinal scale

8.4 Appendix Nuclear LCOE calculation

Year 0-10.

Year	0	1	2	3	4	5	6	7	8	9	10
Capital	1127.7										
decomissioning											
O&M		22.25	22.70	23.15	23.61	24.08	24.57	25.06	25.56	26.07	26.59
Fuel	84	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00
HW	249	9.26	9.26	9.26	9.26	9.26	9.26	9.26	9.26	9.26	9.26
waste		3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09
total		76.60	77.04	77.49	77.96	78.43	78.91	79.40	79.90	80.42	80.94
discount factor		0.91	0.83	0.75	0.68	0.62	0.56	0.51	0.47	0.42	0.39
NPV		69.63	63.67	58.22	53.25	48.70	44.54	40.75	37.28	34.10	31.20
NPV sum	798.242										
Total costs	2258.94										
Electricity produced		4128.00	4128.00	4128.00	4128.00	4128.00	4128.00	4128.00	4128.00	4128.00	4128.00
Discounted electricity		3752.73	3411.57	3101.43	2819.48	2563.16	2330.15	2118.32	1925.74	1750.67	1591.52
Total electricity	40367.9										
LCOE	0.05596										

Year 11-20.

Year	11	12	13	14	15	16	17	18	19	20
Capital										
decomissioning										
O&M	27.12	27.67	28.22	28.78	29.36	29.95	30.54	31.16	31.78	32.41
Fuel	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00
HW	9.26	9.26	9.26	9.26	9.26	9.26	9.26	9.26	9.26	9.26
waste	3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09
total	81.47	82.01	82.56	83.13	83.70	84.29	84.89	85.50	86.12	86.76
discount factor	0.35	0.32	0.29	0.26	0.24	0.22	0.20	0.18	0.16	0.15
NPV	28.55	26.13	23.92	21.89	20.04	18.34	16.80	15.38	14.08	12.90
NPV sum										
Total costs										
Electricity produced	4128.00	4128.00	4128.00	4128.00	4128.00	4128.00	4128.00	4128.00	4128.00	4128.00
Discounted electricity	1446.84	1315.31	1195.73	1087.03	988.21	898.37	816.70	742.46	674.96	613.60
Total electricity										
LCOE										

Year 21-30.

Year	21	22	23	24	25	26	27	28	29	30
Capital										
decomissioning										
O&M	33.06	33.72	34.40	35.09	35.79	36.50	37.23	37.98	38.74	39.51
Fuel	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00
HW	9.26	9.26	9.26	9.26	9.26	9.26	9.26	9.26	9.26	9.26
waste	3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09
total	87.41	88.07	88.74	89.43	90.13	90.85	91.58	92.32	93.08	93.86
discount factor	0.14	0.12	0.11	0.10	0.09	0.08	0.08	0.07	0.06	0.06
NPV	11.81	10.82	9.91	9.08	8.32	7.62	6.99	6.40	5.87	5.38
NPV sum										
Total costs										
Electricity produced	4128.00	4128.00	4128.00	4128.00	4128.00	4128.00	4128.00	4128.00	4128.00	4128.00
Discounted electricity	557.82	507.11	461.01	419.10	381.00	346.36	314.87	286.25	260.23	236.57
Total electricity										
LCOE										

year 31-41.

Year	31	32	33	34	35	36	37	38	39	40	41
Capital											
decomissioning											111.2
O&M	40.30	41.11	41.93	42.77	43.63	44.50	45.39	46.30	47.22	48.17	
Fuel	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	42.00	
HW	9.26	9.26	9.26	9.26	9.26	9.26	9.26	9.26	9.26	9.26	
waste	3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09	
total	94.65	95.45	96.28	97.12	97.97	98.84	99.73	100.64	101.57	102.51	
discount factor	0.05	0.05	0.04	0.04	0.04	0.03	0.03	0.03	0.02	0.02	0.02009
NPV	4.93	4.52	4.15	3.80	3.49	3.20	2.93	2.69	2.47	2.26	2.2336
NPV sum											
Total costs											
Electricity produced	4128.00	4128.00	4128.00	4128.00	4128.00	4128.00	4128.00	4128.00	4128.00	4128.00	
Discounted electricity	215.06	195.51	177.74	161.58	146.89	133.54	121.40	110.36	100.33	91.21	
Total electricity											
LCOE											

8.5 Appendix Solar LCOE calculation

Year 0-10.

Total Cost	0	1	2	3	4	5	6	7	8	9	10
Initial investment	612										
O&M Costs		9.5	9.69	9.8838	10.08148	10.28311	10.48877	10.69854	10.91251	11.13076	11.35338
Decomissioning											
Fuel Costs		-	-	-	-	-	-	-	-	-	-
Discount Factor		0.909090909	0.826446281	0.7513148	0.683013	0.620921	0.564474	0.513158	0.466507	0.424098	0.385543
NPV	612	8.636363636	8.008264463	7.42584523	6.885784	6.384999	5.920636	5.490044	5.090768	4.720531	4.377219
NPV of Total Costs	712.7687126										
Total Energy Output											
Electricity produced		1752	1752	1752	1752	1752	1752	1752	1752	1752	1752
Discounted electricity		1592.727273	1447.933884	1316.30353	1196.64	1087.854	988.9583	899.053	817.3209	743.019	675.4718
NPV of Total Output	15902.97411										
LCOE	0.04482										

Year 11-20.

Total Cost	11	12	13	14	15	16	17	18	19	20
Initial investment										
O&M Costs	11.58045	11.81206	12.0483	12.28926	12.53505	12.78575	13.04146	13.30229	13.56834	13.83971
Decomissioning										
Fuel Costs	-	-	-	-	-	-	-	-	-	-
Discount Factor	0.350494	0.318631	0.289664	0.263331	0.239392	0.217629	0.197845	0.179859	0.163508	0.148644
NPV	4.058876	3.763685	3.489962	3.236147	3.000791	2.782552	2.580184	2.392534	2.218532	2.057184
NPV of Total Costs										
Total Energy Output										
Electricity produced	1752	1752	1752	1752	1752	1752	1752	1752	1752	1752
Discounted electricity	614.0653	558.2412	507.492	461.3564	419.4149	381.2862	346.6239	315.1126	286.466	260.4236
NPV of Total Output										
LCOE										

Year 21-26.

Total Cost	21	22	23	24	25	26
Initial investment						
O&M Costs	14.1165	14.39883	14.68681	14.98054	15.28015	
Decomissioning						61.2
Fuel Costs	-	-	-	-	-	
Discount Factor	0.135131	0.122846	0.111678	0.101526	0.092296	0.083905
NPV	1.907571	1.768838	1.640196	1.520909	1.410297	5.135014
NPV of Total Costs						
Total Energy Output						
Electricity produced	1752	1752	1752	1752	1752	
Discounted electricity	236.7488	215.2261	195.6601	177.8728	161.7026	
NPV of Total Output						
LCOE						

8.6 Appendix nuclear energy published GHG

Source (Andseta et al., 1998).

Life cycle phase	Canada actual energy sources	All Fossil Fuel Energy Sources
Mining and milling	0.22	0.37
Chemical treatment	0.06	0.06
U3O8 to UO3	0.025	0.051
UO3to UO2	0.050	0.087
U3O8 transport	0.005	0.005
Fuel fabrication	0.01	0.11
Heavy water charge	0	9.64
Heavy water replacement	0	2.26
Construction	2.22	2.22
Decomissioning	0.61	0.61
Total	3.2	15.41