Road map for the energy transition in Bali, Indonesia

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L. Losch
Delft, September 2020

Executive Summary

On the 22nd of April 2016, now also known as the ”Earth day”, the Paris Agreement has been brought to live. This agreement is constructed by all nations to fight together against a common enemy, namely climate change. Over the past few years it has become more difficult then ever before to ignore the effects of global warming. While species which have lived on the face of earth for over a thousand years are dying out, while natural disasters such as typhoons, tsunamis, extreme droughts and floods are drastically increasing in occurrence and while we measure new record years of climate change perceiving every year over the past decade it finally becomes inevitable to start taking measures to fight against climate change in order to allow humans and all other species living on this planet to survive. The Paris Agreement is one of the leading most respected agreement combating this cause, it bring together all the nations to sum up their efforts in order to try and mitigate and adapt the effects of climate change. The main goal of this act is to enforce the global response to the danger coming from the change in climate. To achieve this goal a target has been placed which states, **the global temperature rise this century should stay well below 2 degrees Celsius**.

Every country has made its own individual pledge to help achieve the goal set by the Paris Agreement. Indonesia the 4th most populated country in the world is one of them. Indonesia is not only one of the most populous countries, but also one of the most polluting countries, with emissions coming from deforestation and enormous coal-fired power generation pipelines. Next to this, Indonesia’s location makes it highly vulnerable to the consequences of climate change. Therefore, Indonesia pledged to reduce it’s greenhouse gases, however up until now their targets have been rated as “Highly Insufficient”, meaning that they only show modest signs of improvement. The cause of this, is their development of coal fired plants, as they plan to build further 6 GW of such power plants by 2022 and around 27 GW by 2028. Therefore, it becomes inevitable to star moving the investments in coal for the next years towards renewable energy sources, such zero-carbon methods are for Indonesia to start the right pathway to attain the Paris Agreement and sustainable development.

This is the reasoning behind the development of this research. However, since entire Indonesia seems like a too big of a challenge for one research. Therefore, this research aims at picking one of it’s islands and hoping that by designing an effective road map for the energy transition on this island will lead for others to follow. The island of choice has been Bali, a well knows and highly visited island in the archipelago. The target set by Indonesia are taken over for the case of the energy sector in Bali. These targets are the following, first a foremost a total greenhouse gas reduction of 11% by the energy sector compared to the reference scenario should be achieved by 2030. Second, to help meeting the first target a 23% penetration of renewable energy in the total electricity mix should be achieved by 2025. Last, these two targets should not hinder the expansion of the total capacity to satisfy the growing electricity demand at all time. From these targets and a literature review about energy transition on islands and renewable energy technology on islands the following main research question as been constructed:

What plausible road map can ESDM follow, in order to accelerate the energy transition in Bali, while assuring that the demand is covered, to help Indonesia achieve their targets?

In order to find the solution to this question four sub research question have been set up. These require the implementation of a system dynamics model. From the literature study and research done on similar islands which have already achieved a successful transition towards renewable energy, a total of 15 different scenarios have been constructed. These scenarios are possible outcomes of particular applications of 8 different policies, which the Ministry of Energy and Mineral Resources (MERM) or in Indonesian Energi dan Sumber Daya Minera (ESDM) has the power off to apply.

First, a system analysis is given, which introduces all of the information required of the system, which is in this case the island of Bali and its electricity network. This analysis also demonstrates the current

structure of the electricity network and explains why the transition of renewable energy is happening at such a slow pace. There are multiple reasons for this, ranging from cultural barriers to overcome as also geographical difficulties for the construction of renewable energy sources. In addition, there is also the issue that the balinese people are used to coal and oil powered electricity and see renewable technologies as methods coming along with a high risk.

After the system analysis setting the boundaries of the complex system a road map development is introduced. In this chapter, it is explained how the different policies have to be applied, in order to construct the 15 different simulations of the future. This is followed by a chapter describing the model setup. First a conceptual model is designed including all of the mechanisms in work at the electricity network transition. The implementation of these feedback loops and of the policies into the system dynamics model is explained in great detail. Next to this, a table can be found in this chapter including all of the main input variables with the sources and assumption taken to determine their values.

Before running the simulation with the final input variables, a verification and validation of the system dynamics model is demonstrated. This chapter verifies that the computerised model represents the conceptual model introduced before. Next, a validation testing if the simulation can support what it stands for is carried out. This has been done by investigating whether the main theories and assumptions elemental for the conceptual model are valid. In addition to this, the model is checked on errors and whether all of the units included in all of the equations are valid. At the end of this chapter a sensitivity analysis is executed. In this sensitivity analysis the different input variables are modified, in order to see the response on the output variables. This ensures that the system dynamics model representing the electricity network of Bali is indeed valid and can be use for further analysis.

In the follow up chapter, the results of the different simulations are given and they are being compared to the main targets introduced at the beginning. From the total of 15 scenarios there are only 5 which meet the most important requirements. Therefore only these 5 scenarios are deployed into a trade-off table. The conclusion of this chapter is that the scenario S12+TE is the best choice for ESDM. This scenario represents a 24% growth rate of the solar PV sector stimulated by ESDM. Next to this, it requires a modification of the onsite oil fired power plants, so that they can run on cleaner fuel, namely liquefied natural gas. In addition to this, this scenario also requires to raise the taxes on fossil fuels, give out subsidies for solar PV projects, fix the land cost of farmland which has potential for solar farms and it includes an evolution of efficiency of photo voltaic cells from 17% to 30% within the next 10 years. This scenario would have a total cost of 2,050 million US dollars, to ensure them that they would achieve all of their targets by 2030. This result is then being reflected on in the final chapter, where some concluding remarks are given on the different results and methods. Next to this, several ideas are given to help improve any future follow up work on this research.

L. Losch
Delft, September 2020

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List of Abbreviations

Abbreviation	**Definition**
SDGs	Sustainable Development Goals
ESDM	Energi dan Sumber Daya Mineral
MEMR	Ministry of Energy and Mineral Resources
IRENA	International Renewable Energy Agency
RPJMN	National Medium Term Development Plan
RUEN	National Energy Plan
CO2	Carbon Dioxide
GHG	Green House gas
RET	Renewable Energy Technology
SD	System Dynamics
LTLF	Long-term load forecasting
NEP	National Energy Policy
RUPTL	Rencana Usaha Penyediaan Tenaga Listrik
EAC	Energy Attribut Certiicate
REN	Renewable Energy scenario
NGS	Natural gas Sceanrio
REF	Referecnce Scenario
HS	Hybrid Scenario
GWh	Giga Watt hours
MWh	Mega Watt hours
IEA	International Energy Agency
NPV	Net Present Value
LCOE	Levelized Cost of Energy
PT PLN	PT Perusahaan Listrik Negara, Eng: State Electricity Company
IPP	Independent power producer

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Introduction

The world population is growing with an increasingly fast pace and predictions are stating that by 2050 it already reaches about 9.8 billion (Worlddatalab, 2018). This number has been growing on a continuous basis since the end of the Black Death around 1350. The biggest change occurred during the industrial revolution, caused by medical advancements and increases in agricultural productivity. Even tough, the rapid increase in world population proves that humans are advancing in technology and health, this brings along several challenges which the world has to face, if humans want to protect the planet they live on. Several targets and treaties have been signed by large communities, in order to ensure that such problems are dealt with. One of these examples are the Sustainable Development Goals (SDGs), also known as the Global Goals, accepted by all member states of the United Nations Member States in 2015. These goals are a call of action to protect the planet and ensure that all people enjoy peace and prosperity in the future (SDGs, 2015). One of the main challenges humans can no longer afford to ignore is Global warming, because it becomes an ever present and increasingly more inescapable topic within predictions about the future.

A widely accepted solution to aid slowing down global warming is the energy transition from fossil fuel towards renewable energy sources. This is due to the fact that the energy sector is currently one of the main contributors of producing human emissions of greenhouse gases, such as carbon dioxide (CO2), nitrous oxide, methane, and others. These gases are the main causes for the increase in temperature of Earth's atmosphere. This change in climate has potential negative ecological, physical and health impacts. In addition the frequency of extreme weather events is rising as are the sea-levels, therefore threatening the existence of all living beings. Simultaneously to the growth of the worlds population, the demand and consumption of energy is rising drastically. Concerning the goals set by the Paris Agreement and the United Nations the transitioning towards renewable energy seems more and more inevitable, the only question remaining is how fast humans can adopt to this new technology.

This thesis is dedicated towards the energy transition of electricity networks. Focusing on setting up a road map, which will aid accelerating the transition phase. First, a bit of context on the problem in hand will be given, followed by a quick introduction on the current research done on energy transition. Finally, the research goal will be introduced, next to the main research questions required to help attain the goal. At the end, an outline of the structure used for this research will be given.

1.1. Problem Context

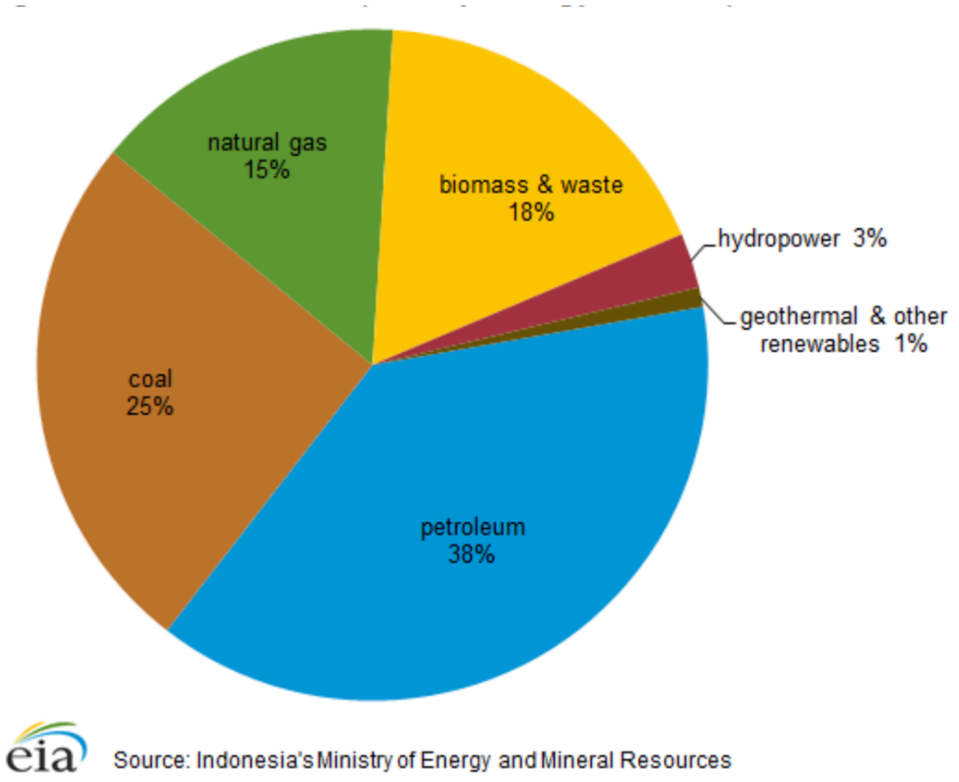
The transition towards renewable energy production instead of the commonly used fossil fuel will not occur over night. Even tough, the technology already exists to a certain extend a society still needs to adapt it's infrastructures and mindsets to transition successfully to to this new way of producing and storing energy. Several researches have been conducted, which prove the benefits of such a transition on a small scale and even on a larger one. As already mentioned before the energy sector is the main contributor to the drastic change in our climate and therefore, this research will focus on how the Paris Climate Agreement's objectives of keeping global warming to well below 2 degrees can be assisted.

This will be achieved by constructing a plausible road map towards clean energy transition for a country or state of relevance.

Nevertheless, to successfully transition to a sustainable energy system, there are several challenges that need to be tackled. One such problem is the lack of knowledge on the positive potential of the different sustainable energy technologies and the lack of motivation to change from the current infrastructures. There are several countries leading the way in the energy transition, such as Denmark and Germany (Sperling, 2017), therefore this research will be more interesting for countries whose energy system is still dominated by fossil fuels to plan their transition according to lessons learned from the front runners. The following indicators help determining a country or state of relevance.

- Population & Population growth
- GPD & GDP growth
- Total CO2 emission per year
- Current share of renewable energy production
- Development of renewable energy sector
- Potential of renewable energy sector
- Affected by climate change
- Available Data

This research will center around the electricity network of Indonesia, which is the 4th most populated country in the world and the 10th most polluting (GHG emissions) country in the world according to the data retrieved from statista. (Statista, 2017). In Figure 1.1 the current electricity mix by source of generation for all of Indonesia is shown, where merely 8% is coming from renewable sources. Furthermore, their renewable energy sector is only growing with a very slowed down pace and investments are stalling (Müller, 2020).



Source: Indonesia's Ministry of Energy and Mineral Resources

Figure 1.1: Share of energy source in primary consumption in 2014 (Attwood et al., 2017)

However, with a constantly growing population and GDP, the energy demand in Indonesia is predicted to keep on rising, which will further pose complications on the Indonesian Government to reach their energy targets set during the Paris Agreements. Besides, based on the consequences of extreme weather events and the socioeconomic losses they cause, Indonesia is highly affected by climate change.

Another argument why Indonesia is such a significant case, succeeds from the fact that they are a major fossil fuel-producing country. Indonesia is the largest exporter of coal and the fourth-largest coal producer worldwide. They could invest the money received from exports to grow their renewable sector, such as the Arab countries, which are among the countries with the fastest growing renewable energy sector (WorldBank, 2018).

Nevertheless, Indonesia is not only rich in natural resources, but also possesses a high potential for renewable energy. Due to it's location near the equator with many sun hours and above the subduction zones between the Eurasian plate and the Indo Australian plate their geography is dominated by volcanoes. All of this implies that they have the ability for a future dominated by clean energy production such as Wind, Solar, Geothermal, Hydro power and Biomass (Bhuwneshwar, 2016).

Energy Targets

The long term target of the Paris Agreement is to restrict the rise of the global average temperature to under 2 degree Celsius, because this will mitigate the risks and effects of climate change (UnitedNations, 2017). To play their role Indonesia agreed upon a reduction of **29 % of their greenhouse gas emissions by 2030**. From which, a total of 11% should be achieved by the energy sector. In order to achieve this goal, they aim to produce **23% renewable energy of the total mix by 2025, and 31% by 2050.**(WRI, 2018) It is assumed for this case, that this also implies a 11% reduction of the electricity network and that the electricity mix is supposed to include 23% renewable sources. It has to be noted that while trying to achieve these targets, it also has to be ensured that the total grid capacity is increasing to meet the new rising demand. Table 1.1 sums up the targets set for Indonesia to achieve by 2030.

Table 1.1: Targets for Bali's electricity network

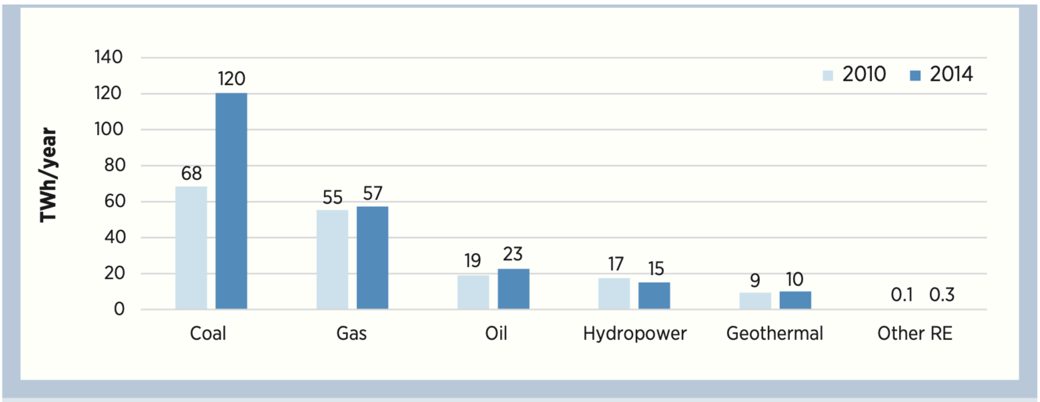
Target	2025	2030
Capacity increase	demand + 5%	demand + 5%
Diversification electricity mix	23%	/
GHG reduction	/	11%

Therefore, this research will focus on how the Indonesian government or more precisely the Energi dan Sumber Daya Mineral (ESDM), or in English the ministry of energy and mineral resources (MEMR) should act if they want to achieve these targets.

However, with the limited time of this Master thesis research it is unfeasible to do this for the entire country. Currently there is very limited experience in Indonesia on how to integrate renewable energy into local grids and how to build them into power system planning. (IRENA, 2017) Therefore, it is of high importance for Indonesia to commence with successful examples of grid integration's of renewable, in order to overcome the concerns and the multiple technical, administrative and regulatory challenges. It is for this reasoning that this research will focus on Bali one of the smaller, but most visited and energy consuming islands. The local government in Bali takes a positive behaviour on promoting clean energy use (Kumara et al., 2014). It is further assumed that the same targets mentioned in table 1.1 hold for Bali. The results from this research will then be applicable to help first Bali and later also entire Indonesia to meet or even exceed their targets.

1.2. Current Research

The energy targets for 2025 and 2030 are not the first attempts from the government to try and reduce their Greenhouse gas emissions (GHG). However, according to (IESR, 2019) the previously attempted targets for the year 2019 have all been missed. The National Medium Term Development Plan (RPJMN) targeted renewable capacity of 17 GW and renewable share in the primary energy mix at 16% by 2019, the National Energy Plan (RUEN) aimed at increasing renewable capacity to 13.9 GW by 2019 or 17.5% of total capacity, with the total share of renewable only being around 7% in 2019 this target has been clearly missed. Besides this, the One Million Rooftop Solar Initiative (Gerakan Nasional Sejuta Surya Atap - GNSSA) declared in 2017 by MEMR and other stakeholders, including IESR, 2019, hoped to increase the use of rooftop solar PV in residential, commercial, public and government buildings, and industrial complexes to reach Gigawatt (GW) order before 2020. Since the current adoption of rooftop solar PV is only at 16.66 MW, this initiative is also missing its target.



Source: IRENA analysis and MEMR, 2015

Figure 1.2: On-grid power generation in Indonesia, 2010 and 2014

The failed targets can be utilized to determine when and what went wrong and how to learn from the mistakes, in order to successfully achieve the new goals. Next to this, another way to use the past failures or success to achieve their goals can be looking at similar states or islands which have already attempted to increase the share of renewable energy in their electrification mix.

Currently, some islands such as Samsoe, El Hierro and Iceland are leading the way of the transition towards a 100% renewable energy production. There is an increasing amount of cases, where islands are switching from 100% diesel generators towards more renewable powered electricity grid (Playbook, 2020). Samsoe is the worlds first 100% renewable energy-powered island. When looking back a bit further than 10 years, Samsoe's idea got jump started from a competition done by their Minister for Environment, Svend Auken. Today they are producing more electricity from renewable energy than they consume, which is mostly produced by 11 onshore and 10 offshore wind turbines, totaling 34 megawatts. Due to these changes towards a 100% renewable energy production Samso achieved a negative CO2 footprint per inhabitant, equalling negative 12 tons per inhabitant. The average CO2 footprint in Denmark is 10 tons per inhabitant (Sperling, 2017).

El Hierro a spanish island belonging to the Canary Islands located in the Atlantic Ocean has achieved similar goals to Samsoe. Gorona del Viento El Hierro SA, a wind power-based pumped-hydro system published that El Hierro achieved a 54% renewable share in 2019. In addition, they managed to power the entire island completely on renewable energy for 25 days in a row. With these accomplishments the island El Hierro attained a decrease of almost 7,000 tonnes of fuel and avoided the emission of 23,000 tonnes of carbon dioxide (CO2) into the atmosphere.

It's clear that such a transition is a very complex problem and depends on multiple actors and exogenous and endogenous variables. El Hierro and Samsoe are both relatively small islands compared to Bali, however as (Bhuwneshwar, 2016) demonstrates in his paper, Bali's renewable energy potential with 100,664 GWh/yr is enough to cover its demand. He demonstrates that with five sources of clean energy, namely solar, wind, hydro-power, geothermal and biomass sufficient energy can be produced to meet the demand of 4,993 GWh/yr by 2020 and even in the future. Especially solar energy has a very high potential, however less than 1% of its potential is being currently used. (Bhuwneshwar, 2016) indicates that this technical potential is not possible to harvest without the proper policy and market intervention. Currently Bali receives about 30% of its electricity from Java through an underwater 150kV transmission cable with a capacity of 350 MW. The remaining electricity need is being retrieved from local oil burning facilities and coal powered plants situated in Bali (PLN, 2015).

There are multiple studies conducted on the benefits of the energy transition towards clean sustainable energy. Nevertheless, there are little publications on the different pathways on how to organize this transition or which of the currently available renewable energy sources is the most optimal for a country. There is one publication on plausible different pathways Indonesia can take, to try and reduce the greenhouse gases from the energy sector on the Java-Bali grid (Handayani et al., 2017). A similar method can be applied to analyse the potential of the energy transition on Bali, however there are multiple uncertainties and barriers which have to be included in such an analysis.

In the case of Bali, the different actors are arguing about the numerous barriers which are laying in front of a transition towards renewable energy. They are not clear on which of the barriers is the main matter for a slow development (Günther, 2018). Therefore, the use of a model simulating different possible futures is very suitable to help determining the main uncertainties and how to find the most effective policies to stimulate this transition.

1.3. Research Goal

The goal of this research is, to generate a road map to help the main Ministry of Energy and Mineral Resources in Bali to achieve their energy targets introduced in table 1.1 and transition towards a more sustainable future. While producing a road map and a simulation model, which will be able to be reproduced for similar islands, with the hope of boosting the overall renewable sector in Indonesia and in the world. To achieve this several scenarios simulating possible futures will be generated and compared to each other based on total cost, CO2 emissions and whether they can meet the ever growing energy demand in Bali. This will be done by applying different policies which the ESDM can install to ramp up the investments and decrease the production time of renewable energy sources.

1.4. Research Question

The main research question this study aims to answer is as follows:

What plausible road map can ESDM follow, in order to accelerate the energy transition in Bali, while assuring that the demand is covered, to help Indonesia achieve their targets?

The following sub question have been established, to help finding a suitable solution to the main research question.

1. How is the current electricity network build up in Bali and what are the factors behind the slow development of renewable sources? (RQ1)
2. Which policies may be applied to achieve these targets and what are their influence on the development of Bali's electricity network? (RQ2)
3. Which policy or combination of policies can help meeting all of the required targets, while ensuring that the capacity increase meets the demand? (RQ3)
4. Which set of policies (scenario) are most cost efficient in helping Bali to meet their targets? (RQ4)

The first research question is utilized to get a better understanding on the different variables and actors which have an impact on the electricity system in Bali. The main stakeholders will be identified, next to the most critical exogenous and endogenous variables, so that ESDM identifies the main actors they need to work with. The second research question will assess policies, which can be deployed by ESDM. Next to this, it will assess policies applied by other islands or states which have had a positive impact. After bringing policies into the picture, question three will focus on the simulation model, trying to explain all the feedback loops and connections between the variables. The last two questions are about implementing the policies into the model, in order to set up a plausible road map which can be followed.

1.5. Thesis Outline

The following chapter begins with a background on the different topics of interest for this research. In this chapter the main research papers which have been used to find an answer to the main research question will be introduced. The follow up section covers the methodology, explaining the research approach deployed for the different sub questions. Chapter four covers a system definition, introducing specific characteristics of the area, actor analysis and the current situation of the electricity network in Bali. After analysing the current situation chapter 5 will lay out the development of the different scenarios introduced in the road map. Chapter 6 includes the models description with an explanation on the conceptual model and its implementation into the system dynamics model. Chapter 7 carries out a verification and validation analysis required before running the model. After which, in chapter 8 the results of the model can be found followed by a conclusion and reflection in chapter 9.

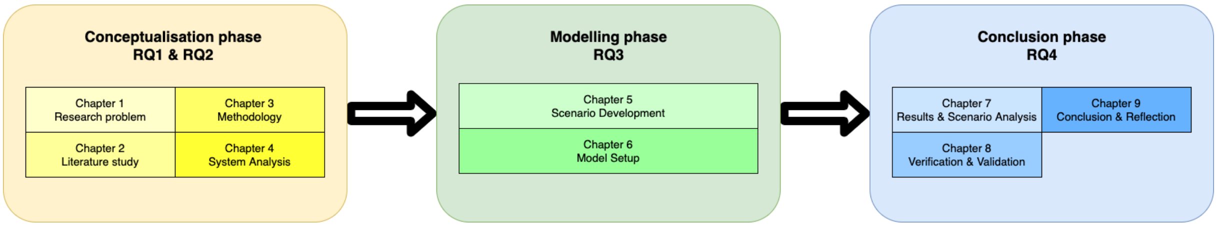


Figure 1.3: Research Flow Diagram

2

Background

This chapter will include an investigation and evaluation on the available literature on the research area. This background will assists in setting up the main research question based on a knowledge gap found in the reviewed papers. This section will introduce the literature study performed on the three research areas namely, Renewable Energy Technologies (RET), Energy Transition on Islands and modelling in System Dynamics (SD). Online databases such as SCOPUS, ScienceDirect and Google Scholar have been used to find all of the literature. Figure 2.1 displays the different research areas which have been reviewed for this thesis.

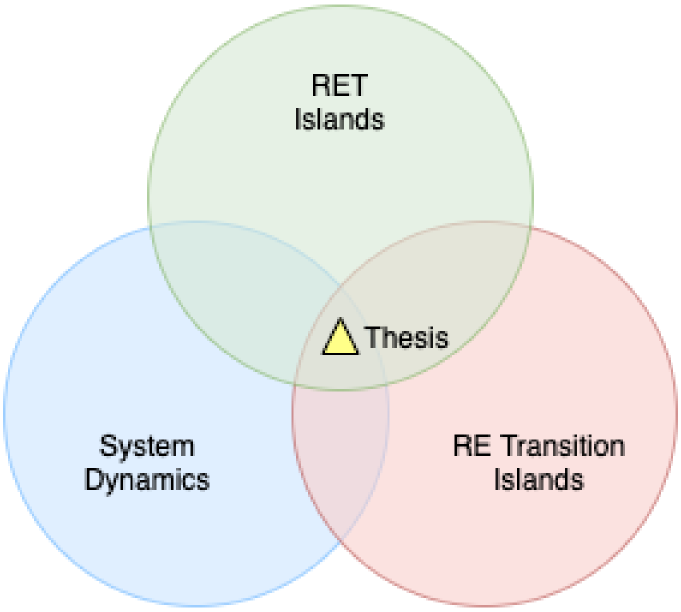


Figure 2.1: Literature study topics overview

The research topic of this thesis lies within the aforementioned three different research areas. However, it is clear that these three topics coincide and that several papers will belong to both or all of the research field. An overview of all the papers with their publication date and their research topic is given in table 2.1.

Table 2.1: Literature study overview

Author	Year	RE Transition	RET	System Dynamics	Island
Abdella, J. & Shuaib, K.	2018	x	x		
Alam et al.	2015		x		
Argote, L.	1990		x		
Bhuwneshwar, P.	2016	x	x		
Bianco et al.	2009	x			x
Blechinger et al.	2016	x			x
Cunningham	2014		x		
Dincer	2011		x		
Forrester	1961			x	
Hu et al.	2013			x	
Handayani, k.	2017	x	x		x
IESR	2019	x			
Iman Gosh	2018		x		
Lazard	2019	x	x		
Liu et al.	2014			x	
Manton Amanda	2015		x		
Meadows & Robinson	1985			x	
Mediavilla et al.	2012			x	
M.D Ross	2015	x	x		
Pruyt, E.	2013	x		x	
Radu et al.	2019	x			x
Runk	2016	x			
Sperling, K.	2017	x			x
Sterman, J. D.	2000			x	
Stoft, S.	2002			x	
Struben, J. & Sterman, J.	2008		x	x	
Swasti et al.	2016	x			x
Swasti et al.b	2016	x			x
Taibi et al.	2017	x			x

First a look at historical data and similar studies on renewable energy transition on Islands will be taken, followed by a research on the renewable energy technologies used on such islands, to identify feasible options for Bali. Next a review on similar papers based on system dynamics, mostly regarding models related to renewable energy transition will follow. Finally, the knowledge gap is introduced at the end of the chapter.

2.1. Renewable Energy Transition (Islands)

The amount of scientific articles published on the topic of renewable energy technology and its transition has increased substantially over the past years. It seems as if it is globally accepted that the transition towards renewable energy sources is the solution to keep global warming well below 2 degree Celsius.

”Islands have been acting as lighthouses.” these are the words of (Taibi et al., 2017), specialist at IRENA in renewable energy, mathematical modeling, global energy balances, energy technologies and energy policy. (Blechinger et al., 2016) discusses the high potential islands have for the production of energy from renewable sources. His work provides a global overview on solar, wind, hydro and geothermal. All of which will help to reduce CO2 emissions. An example island is Hawaii, which set its target to become completely dependent on renewable energy by 2045, the most determined goal in America.
Another example is El Hierro, in September 2019 the Spanish island managed to supply the energy demand of it’s entire population (10,000) for 18 days with a combination of wind, hydro-power and en-

ergy storage. According to (Radu et al., 2015), its mountains make the island of EL Hierro the perfect place for wind farms, where the excess energy can be stored in a system which elevates water via a pump into an self made lake. When there is no wind, this stored water will be guided through turbines to produce more electricity.
Samsoe a small island off the coast of Denmark, is one more suitable example case. They decided to turn their backs on long-term plans to build nuclear power station, in order to focus solely on renewable technologies. The 4,000 inhabitants of the island own shares of the wind turbines and profited next to this of new jobs that have been created. (Sperling, 2017)

These success stories can be used as a lesson learned, that when investing into the right type of renewable energy source lots of positive opportunities lie ahead. Islands especially have been dependent on fossil fuels for the past years, which meant that the transition will not happen easily and that learning from each other mistakes while they go along is highly important. Entire nations have the possibility to learn from islands, by using the same road maps and methods for larger countries or unions. As many experts say having islands acting as ‘lighthouses’ might be the momentum nations require to invest and trust in a renewable future.

An important factor that all these islands had to deal with and need to be constantly monitored when transitioning towards renewable energies is the energy load forecasting. According to (Swasti et al., 2016a) the forecast of energy demand has always been a very critical tool in the managing of electric utilities and that it is dependent on many different variables. In this paper they differ between three types of forecasting, short-term, mid-term and long-term forecasting, which are all correlated to different variables. In the case of energy transition the process usually lasts longer than 10 years and is therefore required to use one of the long-term forecasting methods. Long-term load forecasting (LTLF) is very important in the planning of power systems, scheduling expansion of generation units and it usually spans from 1 year to 20 plus years (Swasti et al., 2016b). According to (Bianco et al., 2009) LTLF is mainly influenced by economic factors such as GDP, population growth and economic development.

(Widyastutia and Widiywati, 2016) demonstrates how the electricity demand is rapidly growing with the population of Indonesia, which currently depends mostly on petroleum and coal, only about 8% of it’s energy production comes from renewable. Their target is to have this number raised to 23% by 2025 and 31% by 2050. The small islands are mostly dependent on petroleum, even though they have such a high potential for other energy productions. As an example, the touristic island Bali currently currently consumes 1,320 MW of electricity, which comes from Java (30.3 percent) and local fossil fuel energy sources (69.7 percent) even tough, according to (Bhuwneshwar, 2016) the total technical potential of clean energy in Bali is 100,664 GWh/yr.

However, as (M.D Ross (2015)) shows, all of Indonesia has a relatively underdeveloped renewable sector, even though it has such a high potential. The dominant sector in their energy production remains fossil fuel with 88.5%. Another more up to date source, the Indonesian Clean Energy Outlook, (IEA, 2011) depicts that the renewable sector only contributed to 12.2% of installed capacity mix in 2019. In this paper it becomes clear that the renewable generation mix has been stagnant since 2011, ranging around 11% to 13% of electricity mix. For example, the Solar PV energy, which is one of the largest potential clean sources in Indonesia uses only 0.0028% of its potential by November 2019.

Next to this, according to PT PLN (Persero) Distribusi Bali data (RUPTL, 2019), the electricity load in Bali is assumed to reach 1,041 MW by 2021. Currently, the power plants feeding Bali are only able to produce 1,274 MW, where 340 MW come from a 150-kV undersea cable in Java. If one power plant falls out due to natural disaster or maintenance or any other reason there will be a power outage. As a solution for this a project from PLN plans to replace oil power plants with gas and relocating mobile power plants to Bali, in order to increase electricity supply.

This raises the question why an islands such as Bali is not following the same trend, then similar island like Samsoe, El hierro or Hawaii. Next a more detailed review will be done on renewable energy technologies used on islands.

2.2. Renewable Energy Technology (Islands)

As already mentioned in the introduction the price of electricity on islands is quite high, which is often caused by the fact that they use oil powered plants for which they need to import the fuel from the mainland. Therefore it is quite surprisingly to see that a country such as Indonesia which consists of multiple islands does not invest more into it's renewable sector and increases the development of fossil fuel. The statistic in figure **??** displays the value of investments in the renewable energy sector in Indonesia from 2014 to Q3 2019. Until the third quarter of 2019, the investment value in renewable energy amounted to one billion U.S. dollars. According to (Attwood et al., 2017), Investments in energy capacity in Indonesia are dominated by the coal industry. The steam coal investments have been growing by an average of 13 per cent from 2006 until 2014. In 2014, 50 per cent of the total generation capacity is retrieved from coal powered plants.

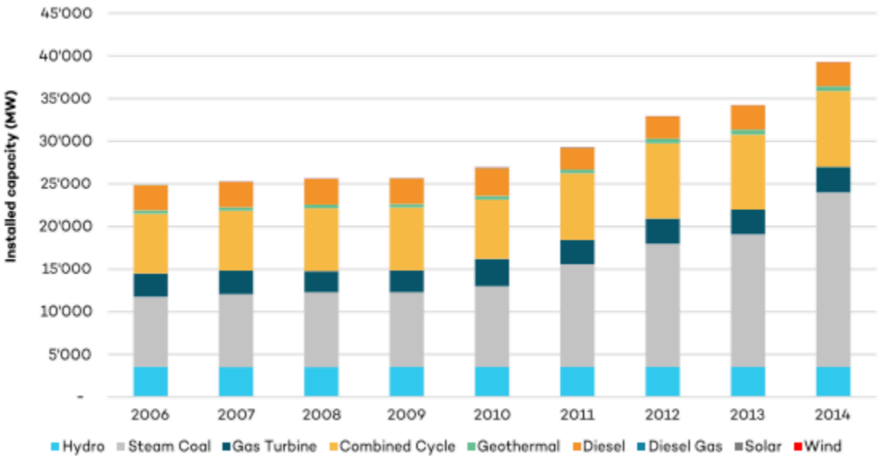


Figure 2.2: Increase in capacity per sector in Indonesia (Attwood et al., 2017).

According to the Indonesian government the total primary energy consumption increased by 43% between 2003 and 2013. At the same time the investments into renewable energy have stalled over the past years (Müller, 2020), while seeing an increase in investments into the coal industry, which is illustrated in the figure below **??**.

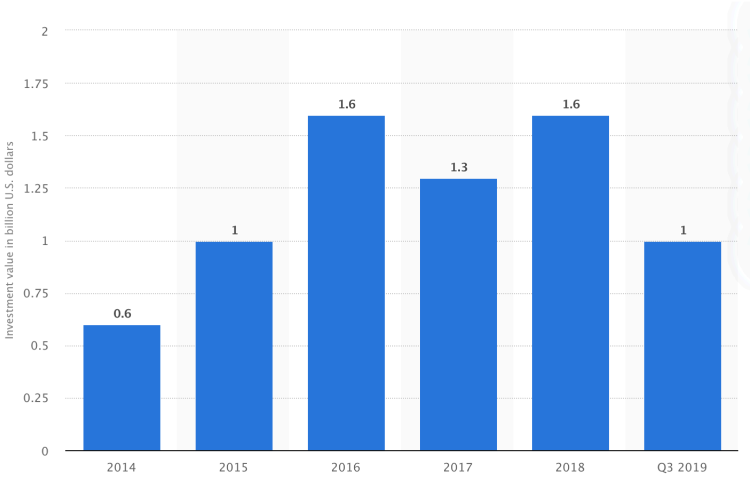


Figure 2.3: Value of investments in renewable energy Indonesia 2014-2019

(Bhuwneshwar, 2016) introduces in his research the potential of the five clean energy sources available in Bali. He estimates their total technical potential in GWh per year. (Handayani et al., 2017) makes use of a simulation model, in order to predict the different possible futures of clean energy source on the Java-Bali grid. However, they do not take into account the evolution of the renewable energy technologies or the total cost due to this transition, as they mention them self in their reflection chapter.

Solar PV

(Creutzig et al., 2017) illustrates the potential solar photovoltaic (PV) have to help mitigating climate change. They are doing this by demonstrating how solar PV has been underestimated consistently in the past. Their analysis concludes that a rapid learning curve added with the right policies implemented is crucial for solar PV deployment. Their assumption is that with the right coordinated steps to progress, solar PV could supply as much as 30 to 50% of electricity in a competitive market.

(Iman Ghosh, 2018) predicts that the price of solar photovoltaic cells is going to decrease dramatically over the next years, because solar panels are not considered anymore an experimental technology, but more of a trusted energy source. Governments also enact national programs to encourage solar power. One of these program is feed-in-tariffs (FiT), where the customer is given incentives for power they produce with solar energy. (Cunningham and Cunningham, 2014)

According to (Manton, 2015,) solar energy is a very promising one as it is widely available around the globe. Next to this, he states that solar power may serve to sustain the lives of people living in developing countries, as it is competitive in terms of costs. Furthermore, solar energy devices can benefit the environment and economy of developing countries. Solar energy is a fast accelerating industry that is available in many areas depending on how the sun's rays hit the Earth (Dincer and Rosen, 2011). According to (Alam et al., 2013)) only about 0.02% of its full potential is currently being used.

Wind

After introducing the solar PV sector, now a look will be taken in the potential of wind powered energy. (Butera, 2018) mentions that wind powered electricity is a rising sector and has in certain countries enormous potential. However, they say that wind similar to solar revolves around the climate and area. This is due to the fact that if a country is willing to harness its wind potential, they require suitable surfaces of land with enough average velocity of wind throughout a year.

According to (Azad and Rasul, 2017), the main issue with wind and solar energy is its irregularity. This means that, because the system cannot produce electricity in the night and is dependent on the meteorological situation of the area, the electricity production is not easy. One solution is to connect the electricity generated from wind and solar immediately to the main grid or a more costly solution is to store the electricity in batteries or any other methods to store energy. However according to (Bhuwneshwar, 2016), the total technical potential of wind power is quite limited compared to solar and geothermal in Bali. This is due to the fact that there is no regular wind pattern to be found and that if there are high wind speeds, they usually are coming in forms of typhoons which are too strong and require the windmills to be looked in position, in order to mitigate damage. Therefore, the wind powered energy will be neglected in this research.

Geothermal

Next to wind and solar, there is also the possibility to generate electricity from the heat coming from the inside of earth. This energy source has a high potential in areas close to volcano's, where there is constant heat produced. (Fridleifsson, 2001) mentions that retrieving electricity from geothermal energy is nothing new in this world, since we are doing it already commercially since 1913. During four decades humans have generated up to hundreds of mega watt of electricity and it is assumed that these numbers will be further increasing. They also mention that only a small part of the total geothermal potential in the world has been utilized. Next to its potential, Geothermal is also one of the cheaper methods of renewable energy as they illustrate by giving the values of the current electrical energy cost. Geothermal lies in between 2-10 US dollars per kwh production of electricity compared to 5-13 for wind and 25-125 for solar PV.

Nevertheless, (Terjal, 2019) introduces one of the barriers, which slows down the development of renewable energy. Even though, Bali is a volcanic island and therefore possess high potential of geothermal energy, the Balinese people keep on rejecting the planning of the Geothermal Power Plant (PLTP) in Bedugul. This comes from their traditions and believes, since the balinese population glorify their volcanoes and believe that they retrieve their spiritual energy from them. For them the volcanoes are sacred and no power plant is supposed to be build in their sacred land. Therefore, the development of Geothermal energy will be neglected in this research.

Bio diesel & Hydro power

Bio diesel and Hydro power are two more renewable energy sources, however as (Bhuwneshwar, 2016) shows their potential in Bali is rather neglectable and they will not be able to compete. Therefore no further investigation will be done into these two methods.

After introducing the separate possible renewable energy sources, which could be used in Bali, it is inevitable to state that solar PV has the highest potential. With all of the other four renewable energy sources bumping into barriers or limitations it has been decided that this research will focus from on the development of solar PV only.

2.3. System Dynamics Modelling

System Dynamics (SD) first developed from the work of Jay W. Forrester in the 1950s. His book *Industrial Dynamics* (Forrester, 1961) is still a statement of philosophy and methodology in the field. The main characteristic of system dynamics is to understand and depict the system in feedback loops, rather than just a linear process. According to (Meadows and Robinson, 1985) the internal causal structure causes the complexity of the system. System Dynamics has well been accepted around the world and is growing, since it is an easy to follow modelling approach. SD is a computer-aided approach to policy analysis and design for complex systems. It uses two main concepts for modelling; feedback loops and stocks and flows. A feedback loop portrays a causal path between endogenous variables, where each variable is influenced by the previous one.

The use of system dynamics in the energy sector has been increasing in the past years and several models on the energy transition can be found. (Liu et al., 2014) made use of a system dynamics model, to simulate and forecast different scenarios China can take, in order to achieve their 2020 emissions targets. (Mediavilla et al., 2012) uses SD to study the replacement of oil and non-renewable fuels while taking into account the physical limits of these fuels. (Hu et al., 2013) analyses different possible pathways the German government can follow for the mitigation of GHG emissions. A similar approach to what the three previously mentioned papers will be used. A system dynamics model similar to (Liu et al., 2014) will be build, to simulate the electricity network development in Bali. Next, the transition towards clean energy will be introduced in a similar fashion than (Mediavilla et al., 2012) did. Finally, the same analysis used by (Hu et al., 2013) for the GHG emission will be deployed in the system dynamics model. However, non of the previously mentioned models include the analysis of future scenarios, while including the diffusion and evolution of the renewable energy technologies, which will be added to this model. More about the construction of the simulation model will follow in chapter 3.

System dynamics has gained attention in the energy sector, because it is very applicable when handling complex systems including feedback loops spanning over a long time. In addition, system dynamics models can insert different policies, which lead to separate simulations of the future. To set up a system dynamics model for the case of Bali's electricity network the steps of (Sterman, 2000) will be followed.

2.4. Road map & Scenario definition

The system dynamics model will be used to generate different plausible scenarios of the future, in order to help ESDM setting up a road map which they can follow to achieve their targets. However, first the exact meaning of such a road map and also the scenarios needs to be determined.

Road map

(Robert et al., 2004) describes a road map as a planning technique, which helps for strategic and long-term planning. Most of the times these are build around goals or targets. (Peter, 2006) characterizes a road map as a plan to identify the best technology adoptions. Next to this, (Garcia and Bray, 1997) argues that a road map is a tool to determine the needs to meet the set targets. (Laube, 2006) says that it is a timetable illustrating the different steps the main actor has to take, in order to achieve the main targets. Therefore, in this research a road map will be seen as a strategy on how the main actor can achieve its main targets. In this case there will be multiple strategies resulting from the different implementations of policies. An analysis of these strategies or scenarios will be conducted, in order to determine the best scenario. Once the best scenario has been determined, ESDM has to look back and follow the implementations of the policies required to result in this scenario.

Scenario

A scenario is defined as one of the possible outcomes from the simulation model. The main aim of using scenarios is to figure out the dynamics of change and adopt these information to attain solution to the set challenges. Such scenarios help the main actor and also the other stakeholders to see how the current and alternative policies and paths impact the future (Harrington and Simon, 2020).

2.5. Knowledge gap

When looking back at the background chapter the following questions arise; which are the main factors behind the slow development of the energy transition in a country such as Indonesia. Why do they keep missing their energy targets, when the potential of clean energy is clearly able to cover their energy demand? How can the use case of Bali be beneficial for Indonesia and what is the best suited road map to follow, in order to achieve this?

There are several cost-optimisation or CO2-optimisation tools and renewable energy penetration tools online, however none that concentrate on generating an actual pathway to follow, to achieve these results. Therefore, the main issue this research will focus on, is how this transition can be achieved in a limited time span.

For the sake of simplicity this analysis will consist of a single instrumental case study approach. The case study will as already mentioned focus on Bali, which is one of the most visited islands in Indonesia and has therefore one of the highest energy consumption. With a population of 4.22 million and annual tourists of around 6 million and both rising, a more sustainable Bali will have a significant impact on the reduction of CO2 emissions for Indonesia. Next to this, this research will help other similar islands in Indonesia and in the World help to accelerate their transition to a more sustainable future and reduce their CO2 emissions.

Research Question

What plausible road map can ESDM follow, in order to accelerate the energy transition in Bali, while assuring that the demand is covered, to help Indonesia achieve their targets?

After taking a look at the background of the main topics related to this research and setting up a knowledge gap with the main research question, now the methodology on how the research question will be answer will follow.

3

Methodology

The following section will introduce the main research question, alongside the sub research question. These are implemented, in order to aid finding and simplifying the answer to the main research question. Next to this, the research approach for this study is introduced, a case study. The case study is about the energy transition on the island Bali, Indonesia. First, the main research question is repeated and the sub questions are added with methods on how to answer them. After this, the outline of all the road maps will be explained, followed by indicating the approach taken for the system dynamics model. Finally, it is described how these methods will be combined in this research.

3.1. Research Question

According to (BP Energy Outlook, 2018) the energy transition will not be achieved over night as the world continues to electrify. Current predictions conclude that coal will still be the front runner in 2040 with one third of the total energy production, while renewable is estimated to only be around 25%. As already mentioned, Indonesia could have a relative high impact on the global energy production and therefore also on the global GHG emissions. It is vital that a country such as Indonesia starts making use of their potential in renewable energy and cuts down on the fossil fuel production. In order, to help leading them towards the right direction, this research will focus on the electrification system in Bali, which will help Indonesia meeting its energy targets.

- **What plausible road map can ESDM follow, in order to accelerate the energy transition in Bali, while assuring that the demand is covered, to help Indonesia achieve their targets?**

The research method will be a combination of qualitative and quantitative methods. It is important to frame such a research method, in order to minimize bias and to allow for replications, which will be desirable in this case. However, the constraints and boundaries of the method have to be clearly noted. Therefore, the methodology is designed in a way, that it will be easily reproducible for analysing the economic and environmental potential of this research. The research method used per sub question will be elaborated below, with an explanation on the different characteristics of the data needed for the input and which output is expected.

3.1.1. Sub questions & Methods

Four sub research questions have been deployed, to help answering the main research question. These sub questions are introduced in this section with a description on the methods used to find the solutions or data.

1. **How is the current electricity network build up in Bali and what are the factors behind the slow development of renewable sources? (RQ1)**
   To answer the first sub question desk research has been performed, in order to gather useful data and information to help build a simulation model of the electricity network. In addition to this, different actors have been contacted, which are playing a role in Bali's electricity network

such as PT PLN the main electricity distributor in Bali, ESDM the ministry of energy and mineral resources and the author of the two relatable papers (Bhuwneshwar, 2016) and (Handayani et al., 2017). Unfortunately, no answer has been received from either one of these actors. Therefore most of the data has been retrieved from online resources. The data which could not be retrieved by means of online resources will be estimated based on similar cases, for example the cost of operation and maintenance of a coal fired power plant will be taken from a similar sized plant in another country. The answer to this sub question can be found in Chapter 4.

2. **Which policies may be applied to achieve the agreed upon targets and what are the resulting impacts of each policy on Bali's electricity network? (RQ2)**
   The second question requires further desk research on historical data from similar cases. First, desk research on the characteristics of the island Bali has been performed to retrieve more knowledge on it's clean energy potential. By analysing the different decisions (policies) ESDM can take in order to achieve its targets, several different plausible pathways have been developed. These pathways are related on the decision making whether to apply a policy or not. These policies are supposed to help accelerate the energy transition or reduce the total cost. To find such suitable policies, similar cases of islands will be analysed. The knowledge gained from these islands will be used as lessons learned. Two policies which have already been applied (NEP, 2014) will also be utilised in this research. Both of these policies are aiming at a decrease in GHG emissions resulting as a consequence from a penetration of renewable energy or natural gas. The set up of this sub question follows in Chapter 5 and the answer to it can be found partly in chapter 5 and in chapter 8.

3. **Which policy or combination of policies can help meeting all of the required targets, while ensuring that the capacity increase meets the demand? (RQ3)**
   For the last two sub questions a system dynamics model will be established. The software Vensim is employed to simulate the different scenarios of the future. Once the analysis of the first and second sub research question has been done, the results will be inserted as input data into the system dynamics model. The resulting simulations from the model are also based on the characteristics retrieved from the area analysis, in order to determine whether the construction of the required power plants is feasible on the island of Bali. At the end, the different outcomes will be investigated with the guidance of the targets and the scenarios which do not meet a target is eliminated. The answer to this sub question will be given in Chapter 8.

4. **Which set of policies (scenario) are most cost efficient in helping Bali to meet their targets? (RQ4)**
   Finally, the last sub question can also be answered with the help of the system dynamics model. While constructing this model several feedback loops and mechanisms have to be implemented make the model as close to reality as possible. The policies and feedback loops can be manually activated or shut down in the model, which allows to analyse the impact of each one of them. Next to this, the model will calculate the total cost per scenario. The resulting outcomes of the Vensim model will simplify the decision making for policy makers. The answer to this sub question will be given in Chapter 8 and 9.

3.2. Scenario Development & Road map

According to (Robert et al., 2004) a technology road map is an adaptable planning technique, which serves as assistance for strategic and long-term planning. This can be done by meeting short-term and long-term goals with specific technology solutions. (Peter, 2006) describes it as a plan, which applies to any new product or system and involves technology forecasting to identify suitable emerging technologies. It is also generally accepted that road mapping techniques help companies or governments to survive turbulent environments or meet their strategic goals. (Garcia and Bray, 1997) and (Laube, 2006) argue that the generation of a road map has three major uses. First, it aids at to meet a consensus about the needs and the technologies required to full fill these needs. Next to this, it is a tool which provides a forecast of the technology developments. Lastly, it generated a framework which help managing and planning these technology developments. In addition, it can also be used as an analysis tool to record the advancement and evolution of new industries.

In this case, the suggested road map for Bali to follow will be determined after generating several plausible scenarios about the future. More about these scenarios will follow in the chapter 5.

Lessons Learned

As already mentioned in the literature study, several similar islands, the so called ”lighthouses” of the energy transition will be used in order to generate possible and feasible scenarios about the future. Success full and failed policies from these islands and also from ESDM will be evaluated, in order to determine which policies should be applied in the analysis of the scenarios.

When including the different policies to the system of the electricity network of Bali, the entire system becomes even more complex. However, this study is mostly interested in the long term solutions of the system, not in the individual properties of people, products, or events. Therefore, a system dynamics approach seems very interesting for this case. A more detailed reasoning on the method of system dynamics follows below.

3.3. System Dynamics

The aim of a system dynamics project is to increase the theoretical understanding and to implement policies for improvement. In order to achieve this, the models boundaries have to be identified to capture all the important feedback loops, exogenous and endogenous variables, delays and empirical data to formulate the model as precise as possible.

(Forrester, 1961) introduced system dynamics for the first time to the world of management in 1950. It has since been widely accepted in this world, mostly because of how it understands the system with feedback loops and does not only use linear processes. System dynamics assumes that the complexity of a system is due to mechanisms in the system itself. Since system dynamics is already around for such a long time it is also not completely new to the field of energy transition as already mentioned in the background chapter.

The electricity network in Bali is composed of multiple mechanisms, which makes it a complex system. However, this does not yet testify the need of a system dynamics tool. The main variables such as electricity demand and the growth rate of the different energy sectors could also be simulated in a linear fashion with the help of a spreadsheet. However, the inclusion of the different policies changes the behaviour of the main variables over time and includes the purpose of using the system dynamics model for a decision making tools, similar to (Castroetal, 2009; Mediavilla et al, 2013).

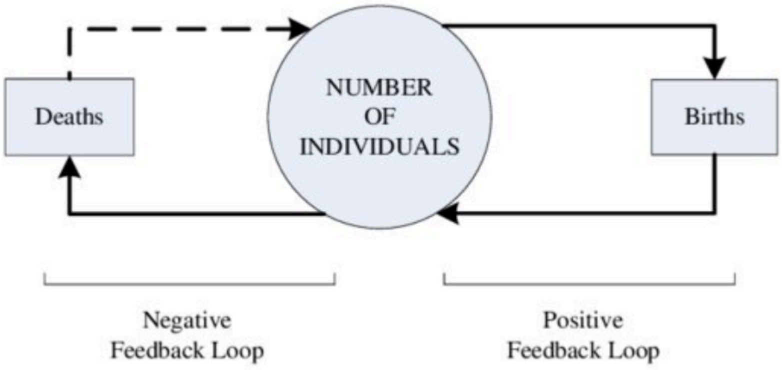


Figure 3.1: Positive and negative feedback loop of population

Vensim is a computer based system dynamics modelling approach. The main mechanisms in this software are feedback loops, stocks and flows. The main idea of this is to simulate the behaviour of the main variables over time, for example the growth rate of the solar PV sector in Bali. The structure of the model is built according to the observed relations between the involved variables. A feedback loop describes the effect a disturbance has on the magnitude of the concerned variable. A common example for this is the population of a country which is depicted in figure 3.1.

In figure 3.1 there are two feedback loops acting on the system, a positive and a negative one. The positive feedback loop are the births, an increase in new Born's will lead to an increase in population. Contrary, an increase of deaths will lead to a decrease in population, hence a negative feedback loop. Another way of illustrating this is shown in figure 3.2, which depicts a stock with it's inflow and outflow. Flows go into and out of the stocks. The level of the stock changes according to the flow rate over time. In this example, the stock would be the population and the inflow is represented by the birth rate and the outflow by the death rate. It is also possible that a stock has multiple inflows and/or outflows. Such in and out flows are affected by the feedback loops. In addition, there can also be a time delay acting on the system. Differential equation are used in the model, to study the rate of change of such stocks and flows.

Figure 3.2: Positive and negative feedback loop of population

Time boundaries

Before starting to construct the different mechanisms and feedback loops into the model, the time boundaries have to be set. First the base date needs to be selected, which is in this case the 1st of January 2020. Next, the final time is required, which is chosen to be 2030 the date at which the targets need to be achieved. Due to the relatively long lifetime of the model, the unit for time has to be years. However, in order to achieve an accurate output of the model the time step will be 0.015625. This time step implies when the new values of each variable in the model will be calculated. An Euler integration type will be used to calculate these values. Once the simulation is done the behaviour and result of each separate variable can be analysed over time. When including all of the important variables defining a system, this software can simulate a close to reality simulation, which can be used for decision making processes.

Most appropriate tool?

To sum up, system dynamics has proven to be a very suitable tool for complex systems with feedback loops and long time horizons. Therefore, it seems like a good fit to use for this study, since the electricity network in Bali is a very complex system with multiple positive and negative feedback loops. Moreover, a system dynamics model can reproduce different policies, which generate alternative possible futures. Such a system dynamics model is a very useful appliance for this research.

However, there are also different options for this research, such as a regular spreadsheet or another simulation model. First of all, even if there are no stocks, feedback loops, delays, or non-linearities a system dynamics model is still quicker to build and easier to understand than traditional spreadsheets. When dealing with a big amount of data, it is important to be clear with the presentation to prevent calculation errors. Moreover, in this case there are the likes of stocks, feedback loops, delays, or non-linearities present and therefore SD seems like the better choice compared to spreadsheets.

3.4. Combination of Theories

A combination of the methods introduced in this chapter will be used, to find a solution to the main research question. First, with the help of desk research, online resources and the background review a deeper knowledge on the electricity system in Bali has been gained. This information has been used, to find all of the mechanisms, feedback loops and variables effecting the system. Based on the information gathered a first conceptual model has been set up, which is representing the development of the electricity network in Bali. Once the conceptual model of the current system has been designed, the different policies will be introduced. This policy test helps the design purposes, since it gives the possibility of running different scenarios and analysing their behaviour. The outcomes of the model will help determining which scenario is most beneficial based on the targets set by the ESDM.

Now that the methodology on how to answer each sub question has been given, a system analysis exploring all the characteristics of Bali's electricity network will follow in Chapter 4.

4

System Definition

In the following chapter an research on the specific geographical area of Bali follows, including an analysis of the actors involved in the energy system of Bali. The information in this chapter helps to determine the systems boundaries, and discover the characteristic input variables required to build the system dynamics model as close to reality as possible. Starting with a geographical area research, including an description of the islands geographical structure and atmospheric conditions. After which the current electricity network of Bali is introduced. The consecutive section illustrates the initiatives and targets already set by the Ministry of Energy and Mineral Resources (ESDM).

4.1. Area Description

The following section will discuss the geographical characteristics of the island of Bali. First its topography will be explored. An explanation of its climate and seasonality will then be provided. Finally, precipitations and bathymetry will be reviewed. All these natural characteristics play a key role in designing a model as close to the real world as possible.

Figure 4.1: Bali's geographical location Lineback and Gritzner, 2014

Bali is an island and province of Indonesia located 8.33 degrees south of the equator and 155.17 degrees east of the Greenwich meridian. Relative to rest of Indonesia, it situates itself east of the bigger island of Java, home of the Indonesian capital Jakarta, and west of the smaller island of Lombok. Its enclosed on the northern side by the Bali Sea and by the Indonesian Ocean on the south, as clearly visible in figure Figure 4.1 below.

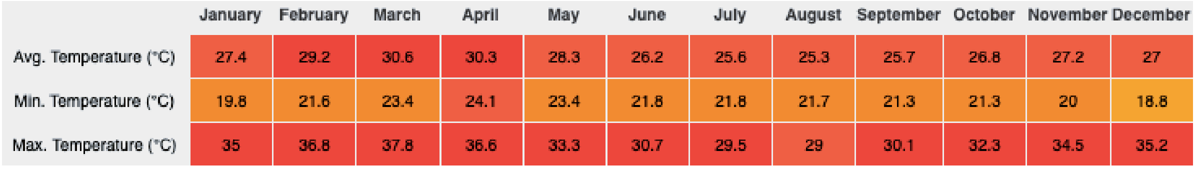
The island covers around 5780 km2 and is of volcanic nature. As a matter of fact, Bali's northern mountains which cross the island from east to west are home to three volcanoes, two of which are still active. Mount Agung, also known as 'mother volcano', is the easternmost and highest peak on the island reaching around 3030 meters above sea level. This active volcano is considered as one of the most likely volcano's worldwide to erupt in the next 100 years "Volcanoes in Bali", n.d.

The presence of these high peaks have a significant influence on the local climate as clouds coming from the west get stopped by these, contributing to the exceptional terrain fertility that characterizes all the west and southern part of the island. In Figure 4.2 one can see how the north side of the mountains slope pretty steeply creating quite narrow lowlands along the coast. On the contrary, the southern part of the mountains slope in a leaner fashion creating the mentioned fertile lands which are central in Balinese culture, the vast majority of the rice fields are in fact situated in this area. Next to this, it only increases difficulty to have such a difficult terrain with a lot of denivelation and slopes. This means that less of the total area can be utilised for solar farms or windmills, since it is impossible to build a wind mill in a slope pointing 10% up or downwards.

Figure 4.2: Bali topographic map Observatory, n.d.

Climate

Bali is located only 8 degrees away from the equator, the island presents a tropical weather with fairly warm temperatures all year round. As observable in Figure 4.3, the average temperature on the island never drops below 25°C. The warmest period are the months of March and April while the coolest temperatures are recorded during December and January.



	January	February	March	April	May	June	July	August	September	October	November	December
Avg. Temperature (°C)	27.4	29.2	30.6	30.3	28.3	26.2	25.6	25.3	25.7	26.8	27.2	27
Min. Temperature (°C)	19.8	21.6	23.4	24.1	23.4	21.8	21.8	21.7	21.3	21.3	20	18.8
Max. Temperature (°C)	35	36.8	37.8	36.6	33.3	30.7	29.5	29	30.1	32.3	34.5	35.2

Figure 4.3: Monthly average temperatures in Bali Climate-Data.org, n.d.

Unlike higher latitude countries, which present four different seasons during the year, Bali experiences only two different seasonal periods. The west monsoon season, also known as the rainy season, spans from November until March, while the dry season (formally, transitional season) starts in April until October. The major difference between these two periods is the wind direction. However, the average sun hours per day are not changing a lot during the year, with an average annual solar irradiance in Bali, which varies from 1490 to 1776 kWhm2/year (Castillo, 2016). Figure 4.4 displays the total technical potential of Solar farms in Bali according to (Bhuwneshwar, 2016).

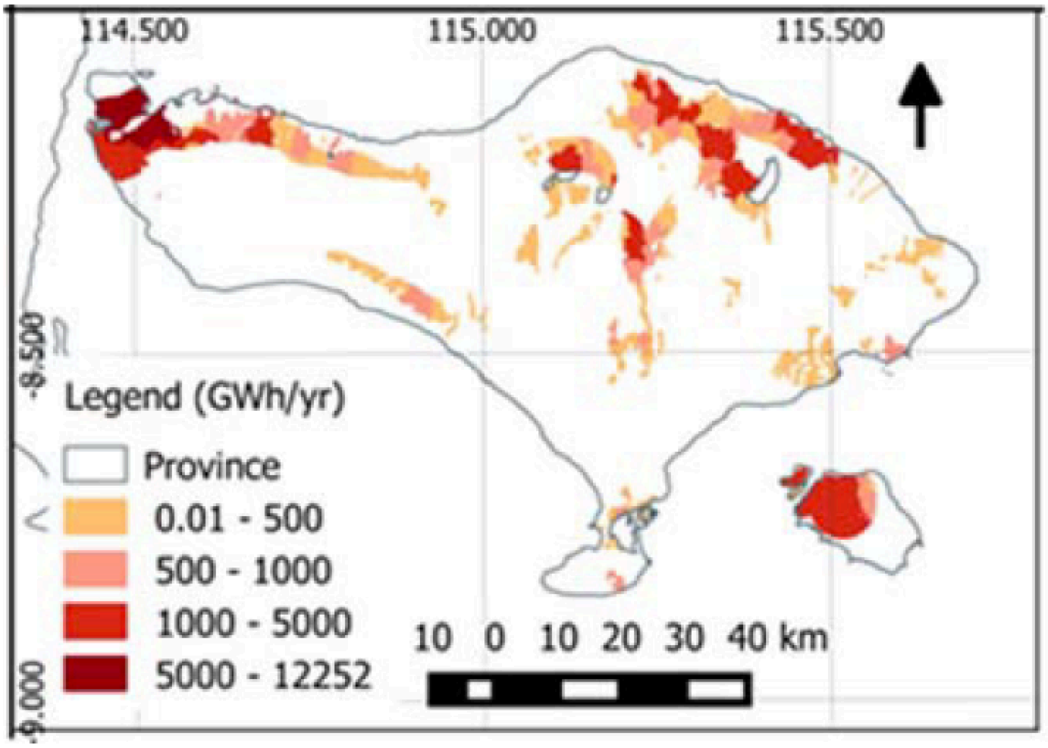


Figure 4.4: Technical potential of solar PV farms in Bali (Bhuwneshwar, 2016)

This figure is taken from (Bhuwneshwar, 2016), where the technical potential for solar PV has been calculated by using topography, land cover, and accessibility conditions of the area. The red areas in 4.4 indicate areas where solar farms could be constructed. These areas have been determined by excluding all of the land in Bali which has a slope equal or higher then 30%. Next to this only areas which are at an accessible distance from the nearest road (up to 5000m) and which are just covered by herbs and grasses (open fields, bare land, bushes etc) have been considered.

From this the total available area has been estimated to be 580 square kilometers, based on the red parts and the scale of the map. This has been double checked by taking the total technical potential and dividing it by the capacity of one solar panel. According to (SUNMetrix, 2014) one solar panel has an average size of 1.8 square meters and can deliver on average 180 kWh/year per square meter with the average solar irradiation of 1,600 kWh/year per square meter. When dividing the total technical potential for solar of 98,738,000,000 kWh/year by 180 the outcome is 548,544,444 square meters or 549 square kilometers, which is the total potential area for solar farms in Bali.

It should be noted that the analysis for the potential of geothermal powered plants has been neglected, because it is assumed that they will not be able to change the mind of the Balinese people. As already mentioned such a project would disrespect their culture and believes.

4.2. Current Electricity Network

In 2019 the total energy demand in Bali has been 4,993 GWh per year from which Bali consumes 1,320 MW of electricity on average (Handayani et al., 2017). The peak load in 2019 has reached a value of 1,100 MW, while the total grid capacity currently only stands at 1,275 MW (RUPTL, 2019). This capacity is complied by the electrical system in Java through the Java-Bali grid. This connection consists of a 150kV submarine transmission cable with a capacity of 350MW. The rest of the electricity demand is supplied by fossil fuel powered plants in the province of Bali itself, which are power plants running on oil namely PLTG Pesanggaran, PLTG Gilimanuk and PLTG Pemaron and a steam coal powered plant. The capacities of these four power plants are 150, 250, 100 and 450 megawatts (MW), respectively. The 350 MW supplied from Java are mostly retrieved from coal (65%), some of it comes from Natural gas (26%), the rest is from geothermal (5%) and other renewable sources (4%). However, for simplicity reasons it is assumed that this energy is entirely retrieved from coal powered plants. Figure 4.5 illustrates the total mix of electricity supply on the island of Bali, including the 350MW from Java.

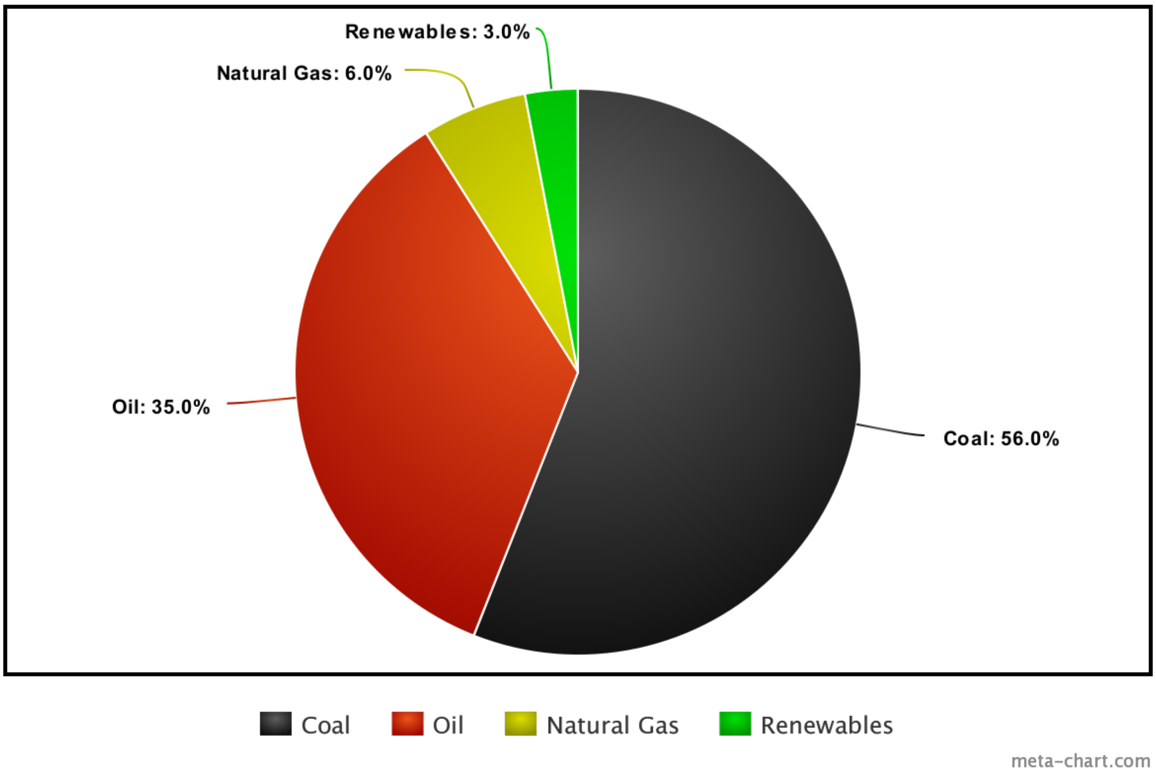


Figure 4.5: Bali power generation mix in 2015 (PLN, 2015)

The current share of renewable energy sources is remarkably low in Bali and in Indonesia in general. However, as already previously mentioned islands are acting as ”lighthouses” of the energy transition. Therefore, when Bali manages to increase their share of clean energy in the electricity mix, this will have positive impacts on Indonesia, with the hope that more islands will follow and the transition happens at an more elevated pace. There are positive signs that this is plausible, since Bali seems to take a confident stand regarding renewable energy.

The minister of the Energy and Mineral Resources (MEMR) Ignasius Jonan, stated in August 2019 that he wants Bali to generate an extra 350 MW of electricity from renewable sources over the next six years, in order to meet the growing demand and decrease their GHG emissions. This increase in capacity from renewable would see them rise in the energy mix to 17.5 percent of the total consumption by 2025, which is when their estimations predict that Bali's demand will surpass 2,000 MW, mainly due to the increase in tourism.

Barriers

The main barrier causing a slow development of the renewable energy sector is the growth in tourism. The rapidly increasing number of tourists that this island has witnessed over the past years has its impact on the electricity network. On average this growth lies around 20% per year, which causes a rapid increase in electricity demand in Bali. ESDM needs to act quickly in order to deal with this rapid change, which decreases the chance of a new technology penetrating the market. For example, if the government has to take a decision between a new technology or an older reliable one, they will go with the old less riskier one. This is shown in the investment of technologies in Bali as shown by (IRENA, 2012), where it is discussed why investors in countries like Indonesia tend to go with the technology that they are used to. The main reason for this is, that the investors are familiar with the current methods and believe that new technology is correlated with an increasing risk factor.

Renewable Energy Potential

In table 4.1 the total potential of each renewable energy in Bali is given. The total demand of electricity in 2019 was 4,993 GWh per year. From the table below it becomes evident that solar PV is the only method which has enough technical potential to cover the demand by its own. The second highest renewable potential could be retrieved from Geothermal, however as already mentioned this will be excluded due to ethical reasons. The remaining three sources do not have a potential high enough to be considered in this research. Therefore, this research will only focus on the development of the solar PV sector and which set of policies hence which road map ESDM should follow, in order to maximize the use of this sector.

Table 4.1: Technical Potential of Clean Energy in Bali (Bhuwneshwar, 2016)

Renewable source	Technical Potential Clean Energy (GWh/Yr)
Biomass	692
Solar	98,738
Wind	24
Hydropower	73
Geothermal	1,137
Total	100,664

4.3. Initiatives & Future plans

It seems like the current trend in Bali and Indonesia is an expansion of the coal sector. According to (RambuEnergy, 2015) they constructed a new coal fired power plant in Celukan Bawang in 2015, despite lots of strikes from the Balinese people. According to (RambuEnergy, 2015) this expansion has been necessary to satisfy the climbing energy demands. The construction of this power plant has also been fought against by (Greenpeace, 2018). Even tough, this power plant is operated by PT General Energy Bali, the construction of it has been shared between China Huadian Engineering Co, Ltd., Merryline International Pte. Ltd., and PT General Energy Indonesia. At the moment of completion of the first three generators combining to a total capacity of 450 MW, already new plans for expanding this power plant have been done. These new plans include two additional power plants each contributing 330 MW to Bali's electricity grid. (Reuters, 2018) argues that this legal fight over the construction of new coal fired power plants, illustrates the energy dilemma Bali is currently situated in.

4.3.1. Energy Targets

During the Paris climate agreement in 2015 Indonesia agreed upon reducing their greenhouse gas emissions by 29 % by 2030, with 11% of this coming from the energy sector. To achieve this goal, they have already layed out a plan in 2014. Government Regulation no. 49 is Indonesia's energy policy, which has been put in action in 2014 (NEP, 2014). This plan updated their 2006 plan and continues to apply up until 2025. In the NEP of Indonesia the GHG emission reduction is supposed to be achieved by an increase in development of the renewable and natural gas sector. NEP14's targets for the 2025 electricity mix are:

1. 32% coal
2. 22% oil
3. 23% renewable
4. 23% natural gas

However, when taking a look at the current electricity mix in Bali in figure 4.5, one can without a doubt say that these target will most likely be difficult to be achieved. (NEP, 2014) has been brought to live, to raise Indonesia's energy independence by diversifying their energy mix and making use of more local fuels instead of exporting them. Next to this, their plan was to decrease the importation of oil by replacing the capacity of oil by natural gas or renewable energy.

To sum up, the main target ESDM aims to achieve is the reduction of greenhouse gases resulting from their electricity network. In other words they want to decrease the GHG emissions from the energy production. **By 2030 they aim at achieving a 11% GHG reduction compared to the baseline scenario.** In order to achieve this goal they aim at **diversifying their energy mix, by increasing the share of renewable or natural gas.** In addition, is has to be ensured at any time that the diversification of the electricity grid needs to **meet the electricity demand at any time.**

4.4. Actor Analysis

By now the electricity network of Bali has been explained with the main targets and plans influencing it over the next years. In addition, a geographical description with the technical potential of renewable energy sources has been introduced. Now it is time to introduce the different stakeholders. In the work of W. Edward Freeman, a stakeholder is defined as "any group or individual who can affect or is affected by the achievement of the organization's objectives" (Freeman, 1984).

In the works of (Eden and Ackermann, 1998 ; Bryson, 1995 and Freeman, 1984) stakeholders are defined as follows:

- Any person, group, or organization that can place a claim on the organization's attention, resources or output, or is affected by that output.

- People or small groups with the power to respond to, negotiate with, and change the strategic future of the organization.

A stakeholder analysis has always been important. For example, Barbara Tuchman (1984) explains the story of The March of Folly from Troy to Vietnam, where a series of disastrous misadventures followed, caused by ignoring the interests of, and information held by, key stakeholders. Stakeholder analyses are arguably more important than ever because of the increasingly interconnected nature of the world. Pick any challenge our world faces nowadays from – economic development, poor educational performance, natural resources management, crime, AIDS, global warming, terrorism – and it becomes inevitable that "the problem" includes of influences multiple people, groups, and organizations. And the same is the case for the electricity network in Bali.

In order to conduct a successful stakeholder analysis it is important to clearly understand stakeholders and their interests, both separately and in relation to each other. In order to do this, first all of the stakeholders involved will be introduced with their interests, followed by a power versus interest grid. The table below introduces the relevant stakeholders included in the system with their interest and impact weight.

Table 4.2: Stakeholder identification

Stakeholder	**Interest**	**Impact**
Ministry of Energy and Mineral Resources (ESDM)	• Meet all the energy targets • Supply enough electricity to meet demand	high
Bali Provincial Government (BPG)	• Meet all the energy targets • Help Indonesia to achieve their targets	high
State Electricity Company (PT PLN)	• Supply enough electricity to meet demand at all time • Total cost • keep monopoly on electricity distribution	high
Private Investors (PI)	• Cost benefits	high
Independent power producer (IPP)	• Destroy monopoly of PT PLN • Supply enough electricity to meet demand • Cost benefits	medium
Local inhabitants (LI)	• Access to clean electricity at all time • Protect sacred beliefs	low
International Renewable Energy Agency (IRENA)	• Development in renewable energy sector • Decrease in fossil fuel energy production	low
China Development Bank (CDB)	• Cost benefits	high
Engineering company (EC)	• Cost benefits	low
Greenpeace (GP)	• Development in renewable energy sector • Protect locals from environmental impacts	low

Figure 4.6 sums up the power and interest of each actor and illustrates them in a matrix. This graph can be divided into four quadrants. The top right quadrant includes the actors with high interest and high power, hence they need to be managed closely. The top left quadrant represents the actors with high power but with less interest. These actors need to be kept satisfied. The two bottom quadrants represent actors with low power. Here again the left one stands for low interest and the right one for high interest, these actors need to be monitored and kept informed.

In figure 4.6 the key actors are given in a red color, which have been identified to be crucial for the success of achieving the energy targets. Take note that the main actor ESDM is also included in this matrix, who is the problem owner. The actors in orange represent the ones with either high power and low interest or high interest and low power. Finally in green are the actors with low power and low interest, but can still not be ignored.

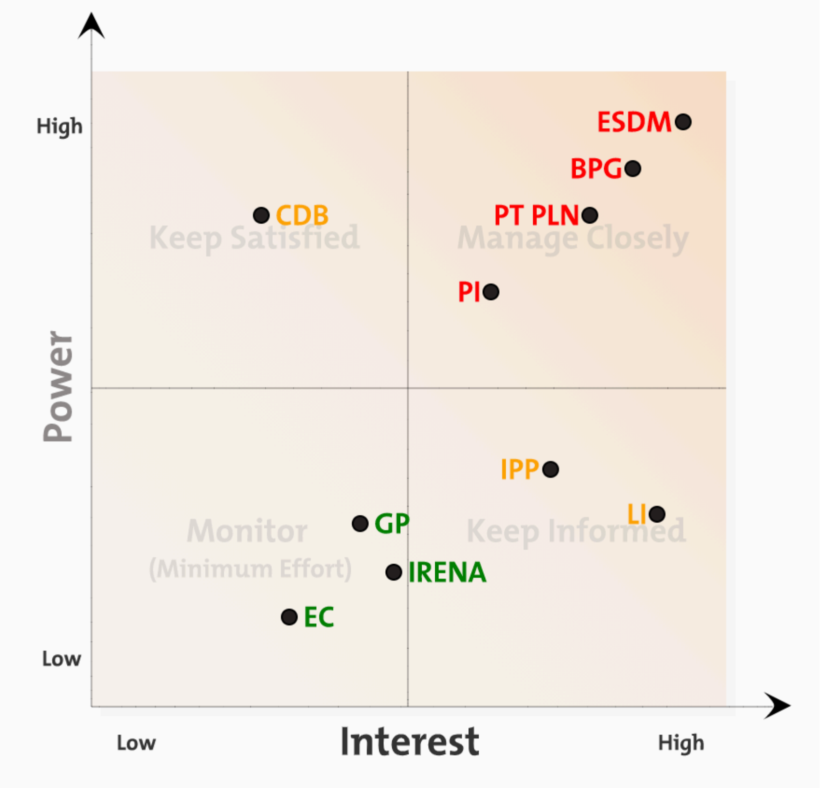


Figure 4.6: Power vs. Interest matrix of the main stakeholders

4.5. Conclusion

To conclude, this chapters provides an answer to the first research sub question, which states:

- *How is the current electricity network build up in Bali and what are the factors behind the slow development of renewable sources?*

The current electricity network in Bali is mostly dominated by fossil fuel, such as coal and oil powered power plants. In Indonesia, Coal has been the dominant energy source to generate electricity since a long time. Therefore, the trust in this method of generating electricity is very high to the local people and investors such as the China Development Bank. A project with the size of this one requires a lot of cost and therefore the help of such investors. However, Investors always analyse their investment based on the risk of return on investment. Since they are more familiar with projects related to coal or oil fired power plants, they are less likey to invest in a new technology such as renewable energy. Therefore little investment and growth rate is recorded in the renewable energy sector. Next to this, Bali is a volcanic island which does not have the easiest topography to build wind farms, therefore there is no current energy produced with windmills and no future plans to develop this sector have been found. Its geographical characteristics would be optimal for power plants using geothermal technology. However, the Balinese population is strongly against the construction of such power plants on their volcanoes, because they are sacred in their culture and they forbid the construction of power plants situated on the volcanos. Next to this, the current electricity network is dominated by the company PT PLN. This monopoly reduced the likelihood of new independent power producers, since they can not compete with the prices set by PT PLN.

After ESDM determines the final road map they want to follow based on the results from the simulation model they can make use of the actor analysis. While using this actor analysis and relating it to the final scenario, they can figure out which collaborations will be most beneficial.

5

Road map Development

In this chapter the road map development will be explained. First, the main target which will be used as requirements are introduced. Next, the policies which are leading to different possible futures of the development of the Bali power system are given. A total of 8 policies will be introduced in this chapter, followed by a short description about them. After which the different possible outcomes concluding from the insertion of these policies will be presented. Finally, the total set of possible road maps is depicted in a figure.

5.1. Targets

In this section the main targets based on the goals set by the Paris Agreement are introduced. The main goal is aimed at reducing the total CO2 emissions in line with the Indonesian pledge to the Paris Agreement. From this main goal 4 different requirements are set up. These requirements or also targets are ultimately helping to determine whether a road map is plausible or not.

1. **Capacity increase**
   First and foremost, it is of highest importance that the chosen outcome has at any time of the simulation enough capacity in the electricity grid to be able to meet the estimated peak load. Therefore an outcome will only be considered plausible when it meets this requirement.

2. **Diversification of electricity mix**
   This target is related to the diversification of the electricity mix. As already tried by the (NEP, 2014). This requires that the renewable sector or the natural gas sector achieves a penetration of 23 % of the total electricity mix by 2025. If a scenario meets all the other requirements except this one it will still be considered plausible.

3. **GHG emission reduction**
   This target is linked to the Paris Agreement pledge of Indonesia to achieve a 11% GHG emission reduction compared to the reference scenario by 2030. Therefore, only outcomes which achieve a reduction of 11% compared to the reference scenario will be considered plausible.

4. **Cost**
   The last one is less of a target and more of an analysis tool. Each scenario will be compared on its total cost over the time span of the model. With the help of this the cheapest scenario which meets all the requirements will be identified.

The 4 targets will be used as a requirement list, to verify the use fullness of a certain road map. Instead of only using the main target about a reduction of their greenhouse gas emissions, a total of 4 targets is chosen to broaden the system and find more areas in which policies can be applied.

5.2. Policies

In this section the policies, which will be implemented into the system dynamics model are listed with a short description on their functioning. They are all employed for the same purpose, namely help achieving the 4 targets. It has to be noted, that these are not all of the possible policies which could be applied in such a system, however after the background review on similar cases they are the most likely ones to occur. For the sake of simplicity, at this point of this research it is assumed that these are all the possible policies in hand of ESDM.

Policy 1: Natural Gas

The first policy will enhance an expansion of the liquefied natural gas sector. Currently, there are no such facilities on the island of Bali, however they can replace the oil powered plants. This policy will aim at a penetration of 23% of Natural gas in the total electricity mix. This will be achieved by modifying the current engines in power plants running on oil, so that these can produce electricity by burning liquefied natural gas, instead of oil. The benefits of such a transformation are, that when burning Natural gas instead of oil less harm full emissions are unleashed into the atmosphere. Burning LNG emits less GHG per unit of electricity compared to oil and coal.

The table below 5.1 indicates how many grams of CO2 equivalent each electricity source produces for generating one kW for one hour. For coal, oil and natural gas these values are related to the power plants, where burning the fossil fuel results in electricity. However, for solar PV the designated number refers to the energy / CO2 emissions required to manufacture the solar PV panels, which are on the current market (Dones et al., 2003).

Table 5.1: GHG emission by electricity generation source from (Dones et al., 2003).

Electricity source	**GHG emissions (g CO2 equiv / kWh)**
Coal	1,690
Oil	1,200
Natural gas	640
Solar PV	73

In table 5.1 the CO2 equivalent emissions of each electricity generation source are given, except for the other renewable. These are being excluded of this calculation, because it is assumed that there will be no growth and hence no change in the total GHG emissions over the referred time period.

Policy 2: Renewable Energy A

Policy 2, the renewable energy A policy is aligned with the goals set by the National Energy Policy (NEP, 2014). Accordingly, this policy stimulates the development of renewable energy. However, as chapter 4 already demonstrated in Table 4.1, solar is the only renewable energy source with a technical potential high enough, to be competitive. Consequently, this and also policy 3 keep the current state of the other renewable, namely geothermal, hydro, biomass and wind at the same level over the respective period. In this policy, the power system expands the use of the solar PV potential of Bali to accomplish the Paris target.

Nevertheless, it has to be noted that a penetration of 23% by 2025 seems rather unlikely, especially since the government of Indonesia is increasing the development in coal powered plants and the current share of renewable in the entire country is only about 8-10% according to (IRENA, 2017) and only 3-5% in Bali. When enabling Policy P2, ESDM will stimulate the solar PV sector, in order to achieve a penetration of 23% into the total energy mix. The impact of GHG emissions reduction policies and feedback loops will be analysed, in order to achieve an end result as close as possible to the Paris targets.

Policy 3: Renewable Energy B

Policy 3, the renewable energy B policy is similar to policy 2. Both are concentrating to achieve an increase in the solar PV sector, with the difference being that the growth rate will be increased differently. Policy 3 aims at achieving the 23% penetration of renewable in the electricity sector by 2025. The same feedback loops will be considered and evaluated for this scenario.

Policy 4: Hybrid

Policy 4 is a mixture between the first and second policy. In this simulation of the future, the development of both the natural gas and solar PV sector will be increased, while satisfying both the increasing demand and the 11% GHG emission reduction by 2030.

Policy 1 until 4 are considered to be the main policies, which are inevitable for ESDM to use if they want to achieve the targets set by the Paris Agreement. Therefore these policies will be the first decision making step in the road map. In figure 5.1, this decision making process is illustrated by the five different paths at the start. A choice between 5 different paths has to be taken here, including the choice to not imply any changes to the network.

The following 4 policies can only be applied in addition to policy 2 or 4, since their main aim is to help achieving the 23% penetration of the solar PV sector and when choosing policy 3 this will already be accomplished. Furthermore, these policies will not show an additional impact on the development of the natural gas sector and therefore can not be applied with policy 1.

Policy 5: Fixed Land Cost

Once the solar PV sector increases significantly, the awareness of the local people on it’s benefits will rise. This increase in demand will lead to farmers increasing the price for their fields which could be used for solar farms. This is where policy 5 will take its effect and set a fixed price on land which has potential for solar farms. This policy will only be applied if policy 2 or 4 should not achieve target 1 and 3.

Policy 6: Solar PV subsidy

Policy 6 will stimulate the growth of the solar Pv sector by giving out solar Pv subsidies and therefore decreasing the levelized cost of electricity from solar PV. This will lead to an increased interest of investors, because their point even break will be achieved at an earlier stage. In the road map, this policy will be applied after at the 3rd decision making point, hence after activating policy 2 and 5 or 4 and 5.

Policy 7: Fossil Fuel Tax

Policy 7 is similar to policy 6 with the difference being that instead of making the solar PV sector more attractive, this policy will raise taxes on fossil fuel based electricity and hence increase the LCOE of fossil fuels. Which will inevitably lead to an increasing interest in solar PV, because it becomes more cost competitive. In the road map, this policy will be applied at the 4th decision making point, hence after activating policy 2, 5 and 6 or 4, 5 and 6.

Policy 8: GHG emission restriction

Policy 8 will focus on decreasing the greenhouse gases from power plants running on fossil fuel, by setting a maximum allowable emission to electricity factor. This can be achieved by handing out fines to factories which are exceeding the allowed limit. This will cause such factories to upgrade their processes in order to make them more efficient. This policy will only be applied if policy 2, 5, 6 and 7 or 4, 5, 6 and 7 should not achieve target 1 and 3.

Another obvious policy would be to decrease tourism growth since this is the biggest contributor to the rapid growing electricity demand. However, this will only be applied in the most desperate times, since the economy of Bali is built around their tourism. All of these policies follow the National Energy Policy (NEP, 2014), which aims at raising the share of natural gas and renewable energy in the national energy mix by 2025. However, the energy target in NEP also includes nuclear which will not be included in this study, anyway it is highlighted in NEP that nuclear is the least favorable option.

These are all of the policies applied in this research and an explanation on how they will be implemented into the system dynamics model will follow in the next chapter. It has to be clearly stated that there are most probably more policies, which could be applied in the system, however this goes beyond the scope of this research because more policies will lead to more possible outcomes which have to be analysed. However, these policies are the obvious ones and which have already been applied in other countries, hence this research will still be representative. Now we will take a look at the scenarios resulting from the implementation of these policies.

5.3. Scenarios

Including the reference scenario, a total of 13 scenarios result when applying the policies described above to the system. In this section the resulting scenarios will be explained, with a description on the road map which has to be followed in order to end up with a specific scenario.

5.3.1. Reference Scenario 1 and 2 (REF)

The first scenario is a simulation of the current trend, which will be used as the reference scenario. However, it is quite unclear whether this reference scenario requires the exact same electricity mix compared to the current one or if it already includes the increase in electricity generated by coal as this seems to be the trend in Indonesia. Therefore, there will be two reference scenarios, one which keeps the exact same electricity mix and another one, which includes the increase in electricity produced by coal. Both reference scenarios cover the increase in capacity required to meet the growing electricity demand.

Reference Scenario 1 (REF1)

According to the data retrieved from online resources, coal-fired power plants are the dominant technology in the Bali power system. In 2020 the total capacity of the coal power plants in Bali is 766 MW, which is including the electricity supply from the Java underwater cable. Even though, this is a mixture between different sources the share of coal dominates this with more then 75%. Therefore this can be assumed to be electricity generated from coal fired plants, in order to simplify further calculations. This means that in 2020 Bali generates 63.9% of it’s electricity from coal. This pathway does not include any GHG mitigation policies, it simply increases the electricity capacity with the same electricity generation mix as it was in 2020.

Reference Scenario 2 (REF2)

The second reference scenario will take into account the current expansion trend of coal fired power plants (Harsono, 2020). In 2010 Bali agreed upon the construction of new coal fired power plants as a response to the drastic rising electricity demand. Albeit, this new project has been heavily protested against the first power plant has been set up and operating since 2015 with two more to follow in the next years (EJAtlas, 2019). Therefore the REF2 will take into account this increase into the new electricity mix. Nevertheless, also this pathway does not include any policy input and it merely used as the baseline scenario.

Both of these baseline scenarios will be used as reference, to calculate the impact the different policies have on the total GHG emissions. It is not clear from online resources, which of both is supposed to be the actual reference scenario for the targets set during the Paris Agreement and therefore both will be used in the analysis, where it will become evident if there is a significant difference between them. After explaining the two reference scenarios, now the other possible scenarios following from the implementation of the policies will elaborated on.

5.3.2. Scenarios resulting from policies

First of all, it has to be noted that the scenarios in this research do not span all of the possibilities for the future of the electricity network in Bali. These are merely the outcomes resulting when implementing the policies introduced in this chapter or a combination of these policies. However for this research it is considered to be enough to analyse the total of 12 scenarios.

Table 9.1 illustrates how the different policies are working with each other to create all of the possible outcomes. The reason why there are additional policies following after the implementation of P2 and P4 is that these policies are not able to meet the increasing capacity by themselves. Therefore additional policies will be added until they meet the primary requirements. Hence, even if the model runs all of the 12 pathways there will only be a maximum of 4 outcomes which meet the main requirements plus the reference scenario. The elimination of the scenarios will follow in the result section.

Table 5.2: Scenarios resulting from policy implementation

Scenario	Description
S1	Scenario 1 is the result, when ESDM decides at the beginning (2020) to activate policy 1.
S2	Scenario 2 is the future in which ESDM decides to follow policy 2 from the beginning on.
S3	Scenario 3 results, when ESDM switches on policy 3.
S4	Scenario 4 is the hybrid future, where ESDM determines to follow a development on the renewable and natural gas sector, hence policy 4.
S5	This simulation of the future includes 2 steps, first policy 2 will be activated, followed by policy 5.
S6	This simulation of the future includes 3 steps, first policy 2 will be activated, followed by policy 5 and then policy 6.
S7	This simulation of the future includes 4 steps, first policy 2 will be activated, followed by policy 5, policy 6 and finally policy 7.
S8	This simulation of the future includes 5 steps, first policy 2 will be activated, followed by policy 5, policy 6, policy 7 and finally policy 8.
S9	This simulation of the future includes 2 steps, first policy 4 will be activated, followed by policy 5.
S10	This simulation of the future includes 3 steps, first policy 4 will be activated, followed by policy 5 and then policy 6.
S11	This simulation of the future includes 4 steps, first policy 4 will be activated, followed by policy 5, policy 6 and finally policy 7.
S12	This simulation of the future includes 5 steps, first policy 4 will be activated, followed by policy 5, policy 6, policy 7 and finally policy 8.

5.4. Set of Road maps

In figure 5.1 the road map leading to all of the 12 scenarios plus the reference scenario is given. This figure demonstrates the timeline, how the policies needs to be activated by ESDM, in order to result in a certain scenario. As already mentioned the simulation starts in the present year 2020. At this point ESDM can chose between 4 different policies. After each year they need to control how well their current policy is performing. In the case of choosing policy 2 or 4, ESDM has the opportunity to employ additional policies, should they be under performing at the control points each year.

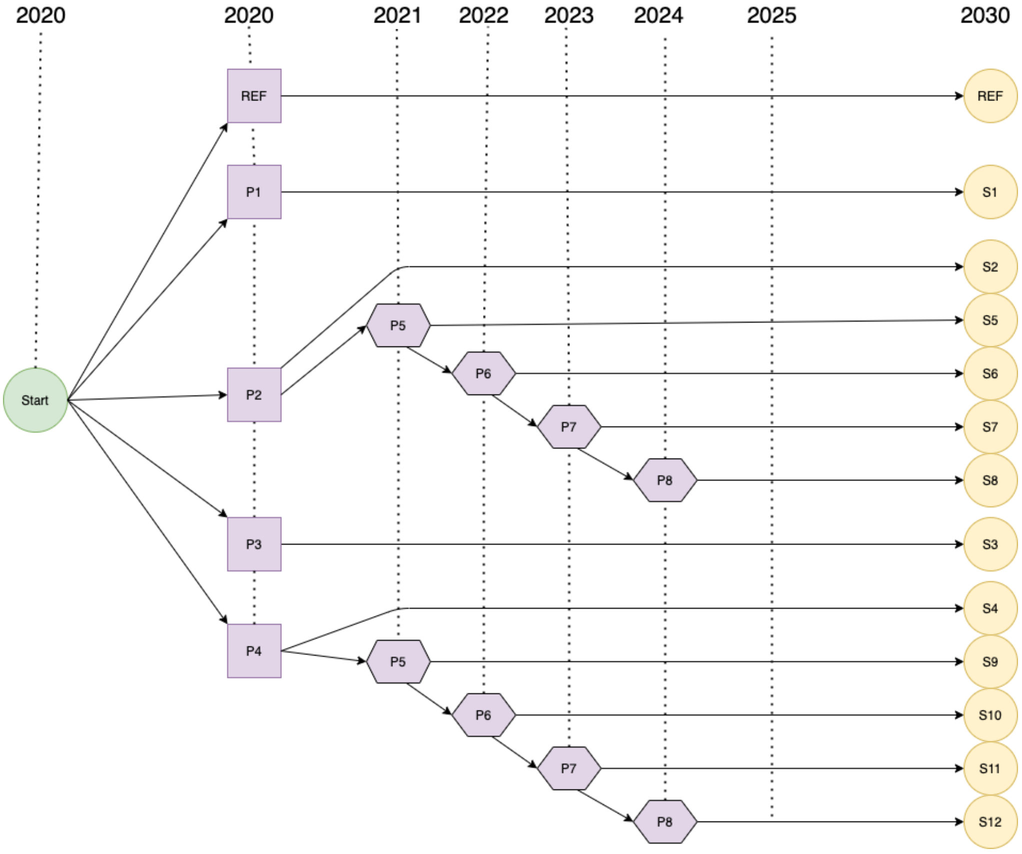


Figure 5.1: Road map

Technology evolution

It has to be noted that for scenarios 8 and 12 there will also be the possibility to include the evolution of technology for solar photo voltaic cells. This however will only be applied should S8 and S12 not meet the requirement. The technology evolution will increase the efficiency of the solar panels and reduce the GHG emissions required to produce them.

Having introduced the targets of the energy transition and the relevant policies to be implemented leading to the different scenarios, it is time to present and set up the system dynamics model.

6

Model Setup

In the following chapter the information gathered in the previous chapters will be summed up together to help building first a conceptual model and later a system dynamics model. Chapter 3 aids to construct and determine the different mechanisms involved in the model and Chapter 4 and 5 are used to gather data and gain a deeper knowledge of the power system in Bali, Indonesia.

First, an overview of the model will be introduced in the form of a conceptual model, with an explanation on the different mechanisms/feedback loops. Followed by the implementation of the conceptual model into the system dynamics model. Later, the data gathered for the input values of the model and the assumptions taken thereby are given. Finally, the different CO2 emission policies which can be introduced by ESDM are implemented into the model.

6.1. Conceptual Model

In the figure below a simple conceptual model of the entire electricity network as it was designed at the beginning is shown. On the left the increasing electricity demand is calculated, which is based on the population, GDP growth and tourism growth.

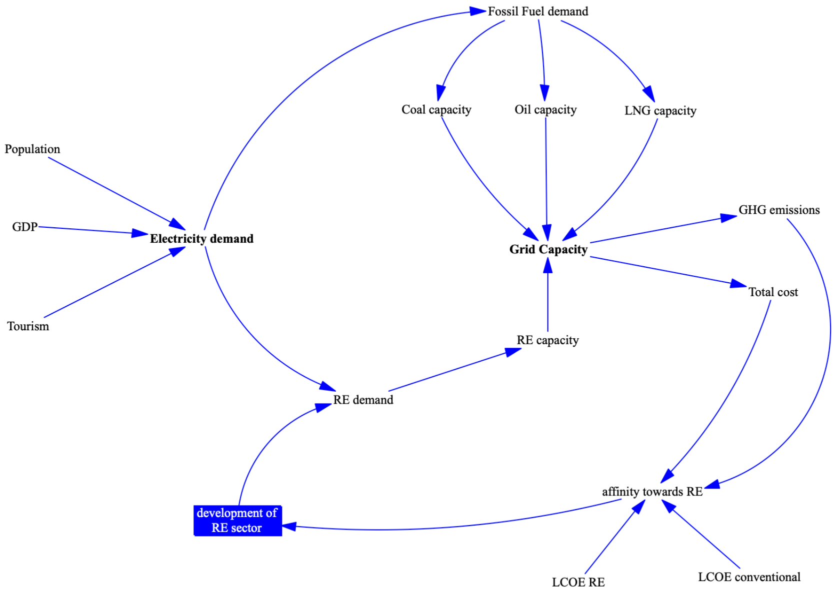


Figure 6.1: Conceptual model

The increasing electricity demand requires an increase in the total capacity of the grid. On the top of this figure, the current state of the network is depicted, namely the fossil fuel plants. The prediction of the electricity demand and the calculation of the grids capacity could both be calculated with a spread sheet in Excel, because there is no feedback loop or delays occurring. The development of the fossil fuel sector can simply be calculated with the help of step functions. This is reasonable, because the capacity of fossil fuel is dependent on the construction or demolishing of a new power plant which happens at one moment in time, hence a step function.

Considering the modeling part of this research, it is the development of the renewable energy sector which is of relevance. The variable ”development of RE sector is represented in a blue box, which indicates that there is a separate conceptual model for this variable. This is due to the fact that this part of the conceptual model is including feedback loops and delay functions, whose impact is going to be analysed with the help of the system dynamics model. In addition, as already mentioned in chapter 4 the development of RE will on focus on the development of the solar PV sector.

6.2. Sub Models

In appendix A an overview of the the complete system dynamics model can be found, when taking a look at the complete overview it is recognisable that the entire model can be divided into five sub models. This is done for reasons of simplicity, because working on separate sub model makes it easier to keep an overview on the relation of certain variables. All of these sub models are implemented into the system dynamics model, even though it is mostly interesting for sub model 3.

1. **Electricity demand and peak load forecast**
   This sub model includes the calculation of the forecast of the electricity demand in Bali in GWh/year and of the peak load demand in mega watts (MW). These values are of high importance, because in order to avoid a shortage of electricity the ministry of energy and mineral resources has to ensure that the total capacity of the grid in Bali is always superior to the peak load demand. Several article argue that in the near future Bali will be under threat of an electricity deficit due to the drastic increase in tourism (IDNFinancials, 2019).
   Next to this, the electricity mix including the share of each power generation in percentage is given in this sub model. This is of importance, especially for scenario two (NGS) and three (REN1 and REN2), because they aim at achieving a penetration of 22% and 23% of Natural gas and Renewable energy in the total electricity mix, respectively.
   In addition to the calculation, this sub model also includes the different switches used to turn on and off the different scenarios. While setting the value of one of these switches to 1 the model will simulate the respective scenario. For example, in figure A.1 given in the appendix A, if the value of the variable ”Natural gas scenario switch” is equal to 1 and all the other switches are set to 0, then the system dynamics model will run the scenario with a 22% penetration of Natural gas.

2. **Fossil Fuel capacity increase**
   In the second sub model, the current structure of the Bali electricity network is depicted. In this sub model the capacity increases of each fossil fuel is calculated. Figure A.2 illustrates the set up of how the capacity of Coal, Oil and Natural Gas is implemented into the model.

3. **Solar PV capacity increase & LCOE**
   An overview of sub model three can be found in figure A.3. This sub model simulates the growth rate of the renewable energy sector, in other words the solar PV sector. The different feedback loops described at the begining of the chapter are implemented into this sub model, in order to analyse the impact of each mechanism on the total growth rate.
   The impact of a deceasing LCOE with respect to the LCOE of conventional methods is implemented in this sub model.

4. **Greenhouse gas emissions**
   The last sub model includes the calculation of the total GHG emissions per electricity source. A.4 calculates the decrease of GHG emission of each scenario with respect to the chosen baseline scenario.

5. **Total Cost**
   This sub model calculates the total cost per outcome. This value is based on the initial cost of a new build power plant or solar panels, added up with the total operational and maintenance cost over the 10 year time span. For coal, oil and natural gas based factories the total fuel cost over this time span are also included.

In appendix A you can find all the visual representations of the system dynamics model with a more detailed explanation on each sub model. Appendix B expresses a table with all the equations used during the simulation of the Vensim model.

6.3. Solar PV Conceptual Model

In this section the conceptual model of the solar PV development will be discussed and the different feedback loops acting on it will be introduced. Next to this, the mechanisms such as learning by doing are illustrated and it is described how they have been implemented into the system dynamics model. Figure 6.2 depicts an overview of the conceptual model illustrating the different mechanisms and feedback loops acting on the development of the solar PV sector. This conceptual model emphasizes the impact on the total grid capacity and it's total GHG emissions. Each letter from A till G represents a feedback loop, the variables included are the key variables of the solar PV sector. This conceptual model includes several feedback loops and delays, which is why this is considered to be the core of interest of this research and most time has been spend to develop this part of the model. The core variables of interest are the solar PV capacity and its growth rate.

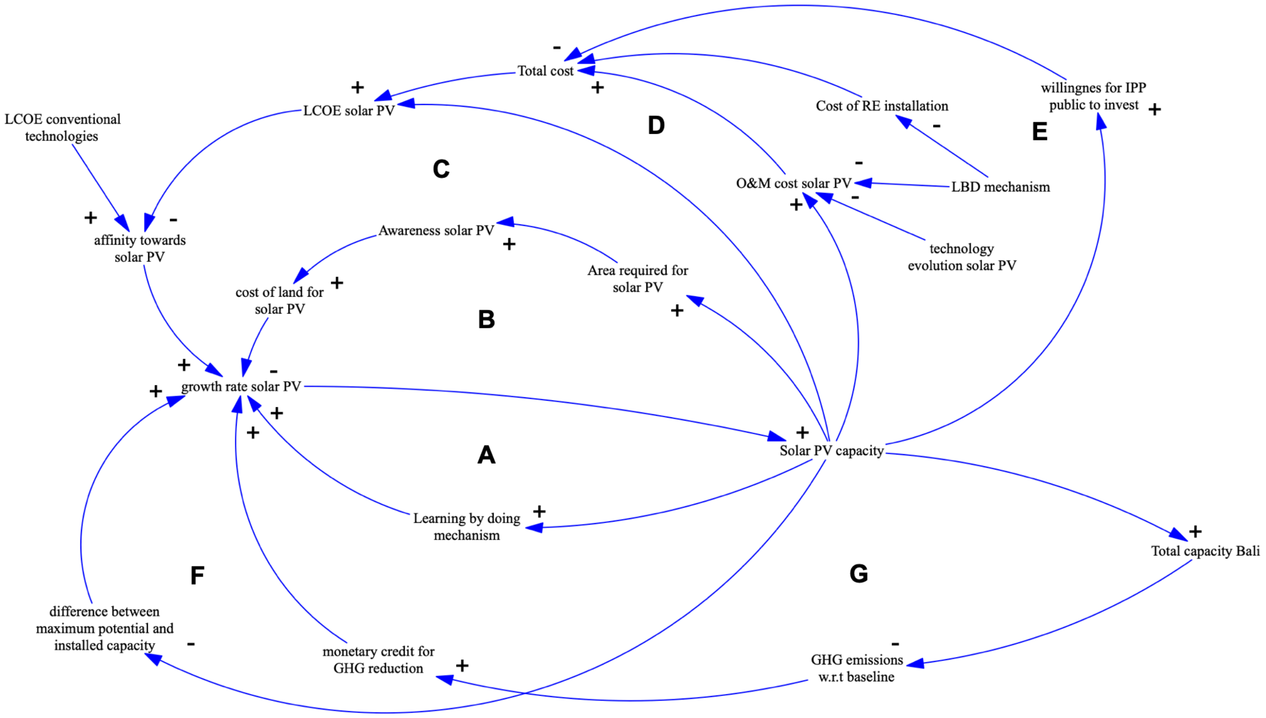


Figure 6.2: Conceptual model of the different mechanisms and feedback loops of the solar PV sector

It should be noted that certain feedback loops are having an impact on several variables. For example the learning by doing mechanism will increase the growth rate of the solar PV sector, because the entire supply chain will become more efficient. Next to this, it will also have an impact on the cost, because more efficient processes will decrease the operational and manufacturing cost. Therefore, in figure 6.2 one can find the learning by doing mechanism and also the ”LBD mechanism” related to the cost of RE installation and O&M cost.

6.3.1. Feedback loops solar PV model

To get a better understanding on the conceptual model the different feedback loops acting on this sub model will be elaborated in more detail. First their impact is explained by stating if they are have a positive or negative relation. Next to this, it is explained how the feedback loops are implemented into the system dynamics model.

Table 6.1: Impact of Feedback Loops

Feedback Loop	Impact of Feedback Loop
A	positive
B	negative
C	positive
D	negative
E	positive
F	negative
G	positive

In table 6.1 the impact of the different feedback loops are given. A positive feedback loop such as A demonstrates that, if an increase in solar capacity occurs an increase in the effect of learning by doing will occur which leads to an increase in the growth rate of solar PV. If two variables are related to each other with a minus sign, than an increase in one of them will lead to a decrease of the other one. For example, if the LCOE of solar PV is increased, the affinity towards solar PV will decrease and hence a minus sign is added to relate these variables.

The variables are divided into two different categories, namely, endogenous and exogenous. Endogenous variables are defined as variables, which are influencing and being influenced by other variables. This is different for exogenous variables, which are influencing other variables however they stand outside of the system by not being affected by any other variable or actor in the system. Table 6.2 shows the separation of the key variables given in figure 6.2.

Table 6.2: Key variables in solar PV sector

Endogenous Variables	Exogenous Variables
Learning by doing mechanism	Cost of Land
GHG emissions w.r.t baseline scenario	LCOE of conventional technologies
LCOE solar PV	O&M cost solar PV
Affinity towards solar PV	Cost of solar PV installations
growth rate solar PV	technology evolution solar PV

The model will simulate the change of these variables over the chosen time span and the value of these variables at the end of the time span (2030) are the outcomes of the system dynamics model. However, in the system dynamics model a lot more variables are implemented, in order to try and simulate the real world as accurate as possible. These variables are not included in this chapter because their values are only secondary results and are means to calculate the final relevant outcomes.

6.4. Implementation of System Dynamics Model

In this section the implementation of the feedback loops is given. Not all of the previously introduced feedback loops are implemented separately, because some of them are having a similar impact on the same variable. Therefore a total of 4 feed back loops will be introduced in this section.

6.4.1. LCOE for solar PV feedback loop

The affinity towards solar PV is related to the levelized cost of electricity (LCOE) of solar projects. An increase in affinity will increase the likelihood of national and also international banks and private investor to start investing into solar PV projects. The opinion of actors towards a new technology depends highly on the cost of generating electricity (Norberg-Bohm, 2000).

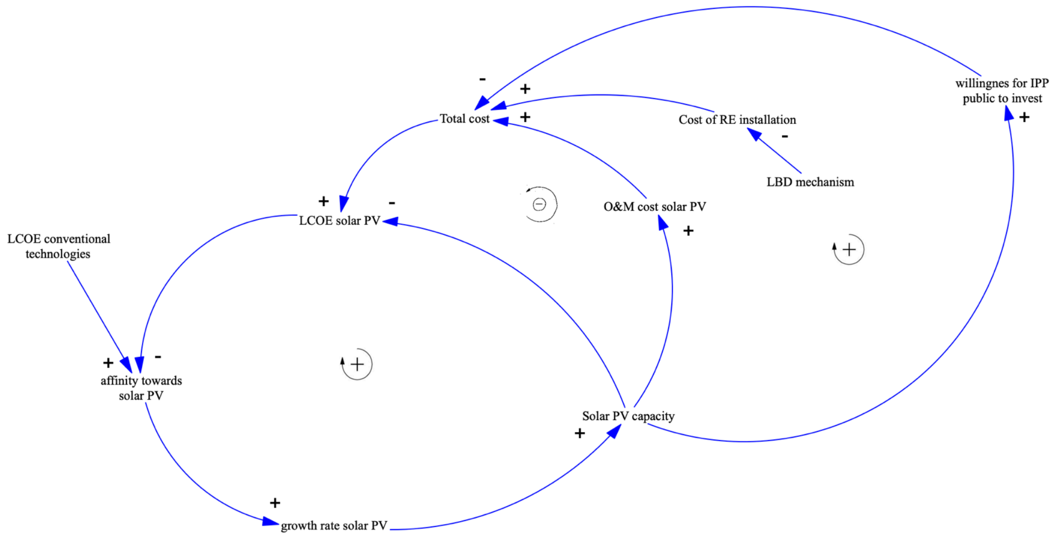


Figure 6.3: Affinity towards solar PV expressed in LCOE feedback loop

Figure 6.3 shows the implementation of feedback loops C, D and E into the model. As it visible in this illustration, the affinity towards solar PV and its growth is dependent on the LCOE for solar PV and of the LCOE for conventional methods. In this case, the conventional methods are the methods used for electricity generation in 2019, namely, Coal, Oil and Natural gas. An increase in operational and maintenance cost or installation cost leads to an increase of the total cost. This ends up in an elevated LCOE for Solar, only if the according electricity generation is not growing at the same rate. Next to this, an increase in total solar PV capacity installed in Bali will lead to an increasing interest of private investors, since they are shown the potential of these new businesses.

Levelized cost of energy (LCOE) is a frequently used method for estimating the electricity cost of an electricity generating project. The LCOE calculates the minimum cost of electricity required to achieve the break-even point over the lifetime of the project generating electricity (Lazard, 2019). It can be expressed as the net present value of all the costs included over the lifetime of the project divided by a discounted total electricity output from the plants over its period of life. The total cost required for the project, includes the investment cost, fuel cost and operational and maintenance cost. This requires to predict these variables over the entire lifespan of the project. These costs are accumulated, which allows comparison of electricity costs generated from different sources.
In mathematical terms the LCOE can be written as follows (IRENA, 2019):

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t+M_t+F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{6.1}$$

It = investment cost at year t
Mt = operation and maintenance cost at year t
Ft = Fuel cost at year t
Et = Electricity generation in year t
r = discount rate
n = lifetime of the project

As already mentioned before, Formula 6.3 forecasts the net present value (NPV) of each cost at time t, with yearly time steps. These costs are summed up and divided by the total electricity output in year t, which is discounted to year 1. According to (EIA, 2013) it has to be noted that the calculations with LCOE have to be taken with precautions, because they usually include multiple assumptions and neglect effects such as taxes. However, the analysis concluding in this research emphasizes more interest in the behaviour of the different LCOE's, then in the exact value. After all, the same formula will be used for the different methods, solar as also for the conventional ones.

Nevertheless, formula 6.3 of the LCOE is not appropriate for the system dynamics model. This is due to the fact that this equation as it stands is a time based simulation, in order to get the NPV of each cost the total cost over the entire lifetime is required, however Vensim simulates and calculates the value of the variables step by step and can not recall values over the whole period.

Another equation is required to insert the calculations of LCOE into the Vensim model. This is important because the value of each LCOE changes with each time step and has an influences on other variables. This is due to the fact that Vensim calculates the values of the variables at each time step, which results in the dynamic behaviour. A similar problem has been accounted by (Bildik, 2014), who calculates as a substitute NPV of each cost, the equivalent annual cost of investment and all other time related costs are fixed. According to (Short et al., 1995) equivalent annual cost (EAC) are the annual cost of purchasing and operating an asset over its lifetime.

$$EAC = \frac{I_0 \cdot r \cdot (1+r)^n}{(1+r)^n - 1} \tag{6.2}$$

The equation above shows how the EAC can be calculated in the model (Stoft, 2002). In this equation, Io represents the investment costs of an asset and r and n have the same meaning as in equation 6.4. With the help of the next formula, retrieved from (NREL, 2013) the LCOE at a certain time t can be determined, once the EAC has been found.

$$LCOE_t = \frac{EAC}{E_t} \cdot M_t \cdot F_t \tag{6.3}$$

LCOEt represents the LCOE of the technology at any time t. Et, Mt and Ft are again the different types of cost as in equation 6.4. This equation can be utilised in a system dynamics model unlike equation 6.4. Once the LCOE of the different technologies can be calculated within the model, only the affinity towards solar PV variable is left from figure 6.3. This variable serves as a representation of the decision making process of the actors. (Struben and Sterman, 2008) model this variable in their paper with an exponential curve. According to them it is a frequently utilized equation to represent the decision of actors having the choice between different options/paths. In this case the decision lies between solar PV or conventional technologies.

$$a_i = a^* \cdot exp(-\beta(\frac{LCOE_i}{LCOE^*} - 1)) \tag{6.4}$$

a* stands for the affinity towards the chosen reference LCOE, in this case the LCOE of conventional technologies. The equation above illustrates the decision making of cost comparison between two different methods. If for example the LCOE for solar PV is more cost consuming compared to the LCOE of the conventional methods, then the affinity decreases and the growth rate of the solar PV sector decreases with it.

6.4.2. Learning by doing feedback loop

The increasing development of new technologies often complicates the understanding of the entire system, however such new technologies is always followed by a learning curve. The effect of such a learning curve is widely accepted and used in the economic and scientific world, as shows (McDonald and Schrattenholzer, 2003), (Kamp, 2007), (Ibenholt, 2002) and (Kobos et al., 2006). This mechanism is used to help analyse the behaviour of performance improvements of the solar PV sector in Bali. This feedback loops calculates the estimation of an individual variable of technology progress, the learning rate. This indicator illustrates the percentage improvement of the technology for its increase in installed capacity.

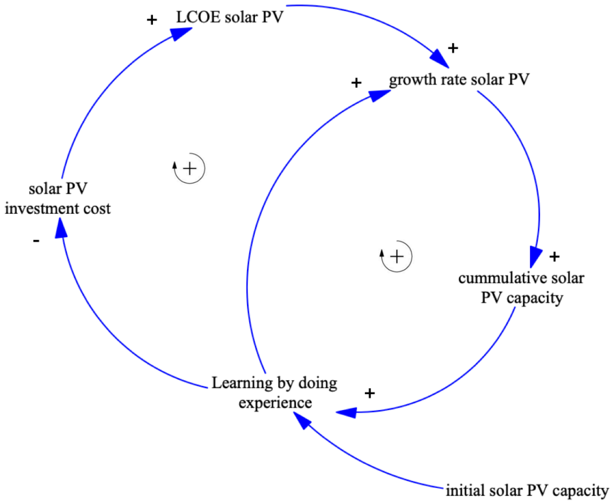


Figure 6.4: Learning by doing mechanism

This mechanism is not new to system dynamics, (Pruyt, 2013) and (Hekkert et al., 2007) have made use of this in their work. Figure 6.4 depicts how this mechanism is inserted into the model. Figure 6.4 represents feedback loop A of figure 6.2. From the illustration above one can see that there is a positive relation between the cumulative solar PV capacity and the learning by doing experience. An increase in experience with solar PV systems results in an increase of the growth rate and a decrease of the installation costs of solar PV, because the locals or the hired company learns how to construct solar PV systems in a more efficient manner. In addition, this increase of experience will lead to an elevation of productivity, which concludes in a decease of the initial installation costs of the panels. This results in a decrease in LCOE for solar PV and hence a more likely increase in solar PV installations. A more detailed explanation on the calculation of the LCOE will follow.

While the experience on a certain new technology increases, it's producers and installers gain a deeper knowledge and generate new more efficient ways to manufacture and operate the new product. This leads to a reduction in initial cost of solar PV. The relation between these two variables is nothing new and has been utilised before (Argote and Epple, 1990) and (Koomey and Hultman, 2007). According to (Koomey and Hultman, 2007) a very familiar equation for this factor of the learning curve is as given below:

$$SPC = A \cdot \frac{cc}{cc_0}^{-\alpha} \tag{6.5}$$

In this equation SPC stands for installation cost per unit for the specific technology, CC stands for the cumulative capacity at a given time and cc0 represents the installed capacity at time t=0. Alpha is a the learning factor and influences of fast or how steep the learning curve is, this depends on the initial capacity and the location and locals. A is the cost per unit at time t=0. However, in the system dynamics model the effect of the learning curve will not be directly related to the capacity, but to the amount of solar PV units constructed. This is due to the reason that for this calculation it is required to now the total potential and current state. Since the total area available and the current are occupied for solar panels are known, it is easier to calculate.

There are different types of behaviour of learning curves for different occasions as shown in (McDonald and Schrattenholzer, 2003). Due to the fact that the system in hand is of nature a very complex one, it is most likely to see the behaviour of the most common learning curve known as the sigmoid curve or also the “S-curve” model. A general representation of this behaviour is depicted in the figure below 6.5.

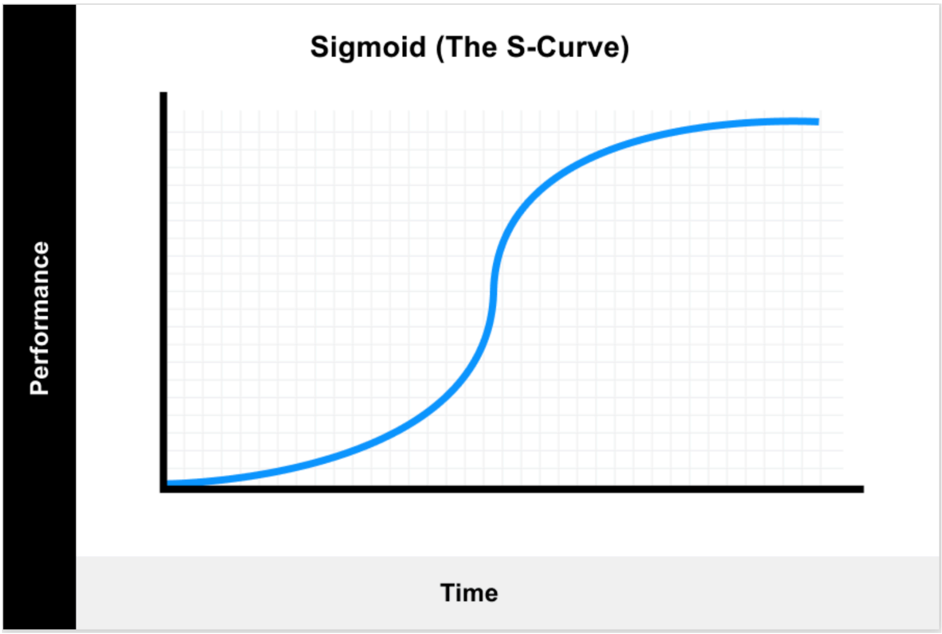


Figure 6.5: S-curve (Sigmoid function) x-axis represents the time and the y-axis represents the increase in performance. Valamis, 2020

This function starts with a slow learning process at the beginning where the learner studies the new task and requires time to do so. This matches the case of the solar PV sector in Bali, because there are no solar farms present yet, hence it will take time to get used to the new technology. The sudden steep part of the curve indicates an increase in learning pace and a decrease in time required to finish the task, due to an increase in productivity. The last part of the curve indicates a flattening out effect, which simulates the moment when the learner knows how to deal with the new technology or environment.

$$S(t) = \frac{1}{1+e^{-t}} \tag{6.6}$$

Above is the mathematical expression of this sigmoid equation, which will be used in the system dynamics model. The use of such a learning curve can accelerate the performance and productivity of the learners and therefore shrink the total cost and increase the growth rate.

6.4.3. Technology awareness mechanism

Feedback loops B and F from figure 6.2 both deal with the awareness increase of solar PV systems in Bali. These feedback loops indicate the change of mindset of the locals once they realise the benefits of a new technology. Opposite to the learning by doing mechanism, these feedback loops have a negative impact on the final output, the installed capacity of solar PV.

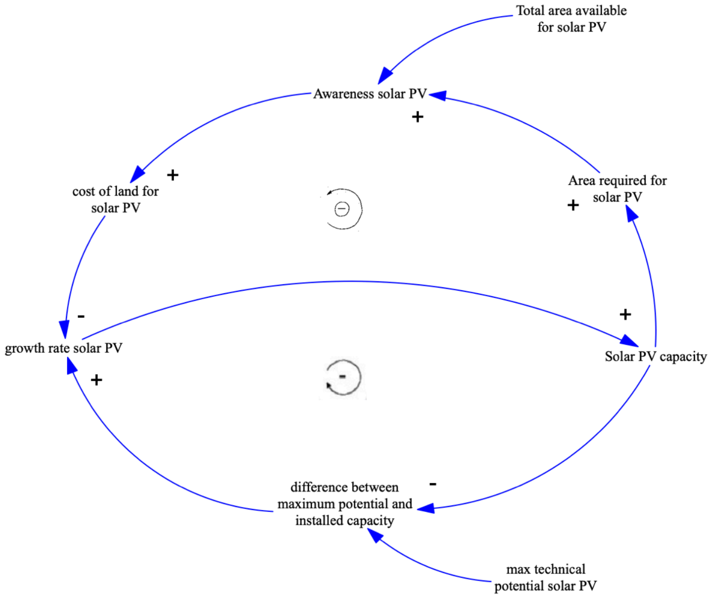


Figure 6.6: Technology awareness mechanism

Figure 6.6 demonstrates the implementation of this mechanism in the model. Straightforwardly, an increase in solar farms, hence capacity leads to an increase in area required for these farms, which elevates the awareness of the landowners. When farmers or any other kind of owners of land, which has high potential for solar farms, realise the potential their land has it is very likely that these actors will start increasing the price of their land. This will lead to an increase of the LCOE for solar PV and therefore a decrease in the growth rate of solar PV.

Furthermore, if the solar PV capacity increases significantly it will unavoidably reach it's maximum potential at one point. From historical data, this usually results in a decrease of the growth rate slope, because once the difference between the total technical potential and current capacity goes towards zero, the investments will decline. This is due to the fact that the resulting reimbursements will shrink, since the new projects are not able to expand at the same rate as the previous ones. However, with the current capacity of solar PV in Bali only reaching around 10 GWh per year (in 2019) and it's total potential lying at 98,738 Gwh per year according to (Bhuwneshwar, 2016) it is fairly unlikely that this mechanism will take effect in the time span of the model. Therefore, this feedback loop will be neglected, as the impact of the slowing down is already included in feedback loop B.

A similar formula compared to equation 6.1 has been used by (Pruyt, 2013). However, in this case the comparison between the current and total potential available will be denoted in area. For this the total potential area for solar PV in Bali is required. Following up, the change in growth rate can be calculated with the following formula:

$$P_{area} = P_0 \cdot (\frac{A_{tp}}{A})^{\beta} \tag{6.7}$$

P area is the new cost of land per square meter at time t, P0 is the cost per square meter of land at time t=0, Atp is the total potential area for solar PV, A is the area currently utilized at time t and beta is the cost factor. The fraction in parenthesis on the right hand side represents the awareness of solar PV from figure 6.6.

6.4.4. Greenhouse gas reduction feedback loop

In this section the mechanism of the greenhouse gas will be explained. The ultimate goal of the Paris agreement is to reduce the total greenhouse gas emissions from the electricity sector by 11% by 2030.

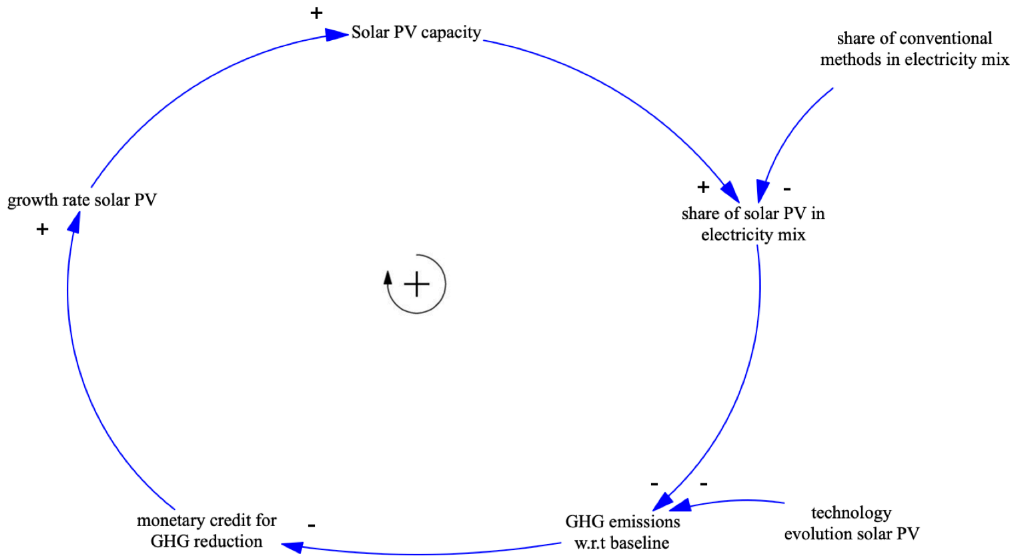


Figure 6.7: Greenhouse gas reduction mechanism

Figure 6.7 depicts the implementation of this mechanism into the system dynamics model. If ESDM starts growing the solar PV sector the share of electricity generated by solar PV will increase. This increase in cleaner elecricity generation will lead to a decrease in greenhouse gas emissions compared to the reference scenario. This decrease in CO2 emissions will attract more interest into the solar PV sector and that certain international associations such as IRENA start helping ESDM. Therefore it is assumed that this will lead to monetary bonuses which will decrease the total cost and hence decrease the LCOE for solar, which will finally lead to an increase in the growth rate of solar PV. In addition to this, the reduction of GHG can also result in other powerful benefits, such as public health, due to the fact that the overall air pollution will shrink.

6.4.5. Data & Assumptions

The following table 6.3, introduces the sources of the key input variables and constraints. Take note that there will be more variables in this table as there where in table 6.2, since there are more variables and constraints in the SD model compared to the conceptual model. In addition to the sources of each variable, the main assumptions taken per variable is included.

Table 6.3: Data sources of key input variables and main assumptions

Variable / Constraint	**Source**	**Notes & Assumptions**
Peak load 2019	(RUPTL, 2019)	This number has been taken from the official electricity supply business plan
Electricity demand 2019	(Bhuwneshwar, 2016;RUPTL, 2019)	
Java supply capacity 2019	(PLN, 2015)	Two different values for this have be found online, both have been used to determine if a big difference occurs in the final output, which was not the case.

Electricity demand increase	(RUPTL, 2019)	This number has been taken from the official electricity supply business plan, each year a new RUPTL comes out and the electricity demand has been set to follow the trend over the past 5 years. It is also assumed that the increase as it stands for Indonesia is the same for Bali.
Coal capacity 2019	(EJAtlas, 2019)	It is assumed that all the coal fired power plants situated in Bali are retrievable online.
additional coal capacity	(EJAtlas, 2019)	The new build coal factory in 2015 is already included at the start, and the new additional 2 times 330 MW engines are added in 2022 and 2026.
Diesel generators capacity	(Wartsila, 2018;PLN, 2017)	There are currently three diesel powered plants in Bali, there capacity has been summed up together for the total capacity of diesel powered electricity.
Liquefied natural gas (LNG) capacity	(NEP, 2014)	This is assumed to be 0 at the beginning, neglecting the little percentage of LNG powered electricity coming from the Java supply.
Time delay to modify diesel to LNG		No exact value could be found for the required size of engines, therefore it is assumed this will take one year.
Operational hours coal	(Frazier et al., 2017)	Assumed to be running for 20 hours per day on average.
Maintenance factor coal	(Frazier et al., 2017)	
Coal plant efficiency	(Frazier et al., 2017)	
Operational hours Oil	(Council, 2017;Wartsila, 2018)	Assumed to be running for 20 hours per day on average.
Maintenance factor Oil	(Council, 2017;Wartsila, 2018)	
Oil plant efficiency	(Council, 2017;Wartsila, 2018)	
Operational hours LNG	(Frazier et al., 2017)	Assumed to be running for 20 hours per day on average.
Maintenance factor LNG	(Frazier et al., 2017)	
LNG plant efficiency	(Frazier et al., 2017)	
initial solar PV under construction		several online resources indicate different values, therfore this initial value has been estimated after running the model several times and utilising a simple trial and error method
average delay solar PV construction	(Gajda, 2017)	It is assumed that the average construction time in Bali will be the same as in the US
average lifetime solar PV	SUNMetrix, 2014	Values are ranging from 20 to 25+ year, in the calculations in the model 25 years have been used.
initial solar PV units	Kumara et al., 2014	This has been calculated backwards from the total current capacity of solar PV available in Bali.
discount rate		The discount rate has been assumed to be 2%
expected growth rate by ESDM	(Arinaldo et al., 2018)	This value represents the growth rate stimulated by ESDM without any of the feedback loops or policies activated. The number has been taken from historical values on the growth rate of the renewable sector in Indonesia.

average size of solar PV unit	SUNMetrix, 2014	The averag size of solar panels used for solar farms has been used.
total potential solar PV	(Bhuwneshwar, 2016)	
solar PV efficiency	(Dones et al., 2003;IRENA, 2012)	The value of the average solar panel currently on the market has been taken for the efficiency, this value is supposed to rise significantly over the next several year as argued by some authors.
annual average solar irradiation	(Handayani et al., 2017;Arinaldo et al., 2018)	It is assumed that the value given in this paper for Java is also applicable for Bali.
average GHG emissions coal	(Dones et al., 2003)	The GHG emissions for coal powered power plants in South East Asia has been employed.
average GHG emissions solar PV	(Dones et al., 2003)	The GHG emissions for coal powered power plants in South East Asia has been employed.
average GHG emissions diesel	(Dones et al., 2003)	The GHG emissions for oil powered power plants in South East Asia has been employed.
average GHG emissions LNG	(Dones et al., 2003)	The GHG emissions for natural gas powered power plants in South East Asia has been employed.
GHG emissions baseline scenario		This value has been implemented into the model after running it once based on both reference scenarios. Since the difference of them was not significant the value of the second reference scenario has been taken, since this seems more related to the real world.
installation cost solar PV	(IRENA, 2012;Maier, 2015)	For this value of the utility scale c-Si PV system with battery storage has been taken, in order to include the cost required for the battery storage.
O&M cost solar PV	(IRENA, 2012;Maier, 2015)	The average O&M cost of solar PV has been taken and assumed to be similar for Bali.
LCOE of coal, oil and natural gas	(EIA, 2013;Koomey and Hultman, 2007)	An exact value or prediction for these variables could not be found. Therefore the investment cost, O&M cost and fuel costs are found separately and their respective LCOEs are calculated.

The values and units of the variables given in the table above can be found in Appendix B. After inserting all the data into the system dynamics model, the two reference scenarios can already be simulated. In the following section the different policy interventions are introduced which have to be added into the model, in order to be able to run all of the scenarios.

Assumptions

In order to be able to follow up on this work or improve/update the model, it is of high importance to know all of the assumptions which have been taken to construct the model. A list of all the assumptions used while building the SD model can be found in Appendix E.

6.5. Policy Implementation

In this section the possible policy interventions, which can be applied by the main actor, the ministry of energy and mineral resources(ESDM) are given. The understanding and consequences of the policies have been introduced in the previous chapter and will now be followed by an interpretation on how they are implemented into the system dynamics model. This analysis will help ESDM to figure out, which outcome is most profitable for them to follow.

Policy 1: Natural Gas

As already mentioned, this policy increases the capacity of natural gas by decreasing the capacity of oil. In the model this can be achieved by decreasing the capacity of oil based facilities. The equation used to simulate this in the model can be found in Appendix B.

Policy 2: Renewable Energy A

This policy requires a stimulation of the growth rate of the solar PV sector by 24 % from the Ministry of Energy and Mineral Resources. This is simply done by setting the growth rate stimulated by the main actor to 24%. In addition to this, the plans for the second expansion of the coal plants will be cancelled. Meaning there will only be one additional coal expansion occurring in between 2020 and 2030.

Policy 3: Renewable Energy B

For the second renewable energy policy, the growth rate of the solar PV sector is associated to the penetration of the solar PV sector into the total electricity mix. This is achieved by trial and error, while changing the growth rate of the solar PV sector as long until the model results in a 23% penetration of the solar PV sector in the total mix. Similar to policy 2, the plans for the second expansion of the coal plants will be cancelled. In the figure below the difference between policy 2 and 3 is illustrated in a graph. In this figures teh blue line represents the current share of RE in the total mix and the red line indicates the target 2.

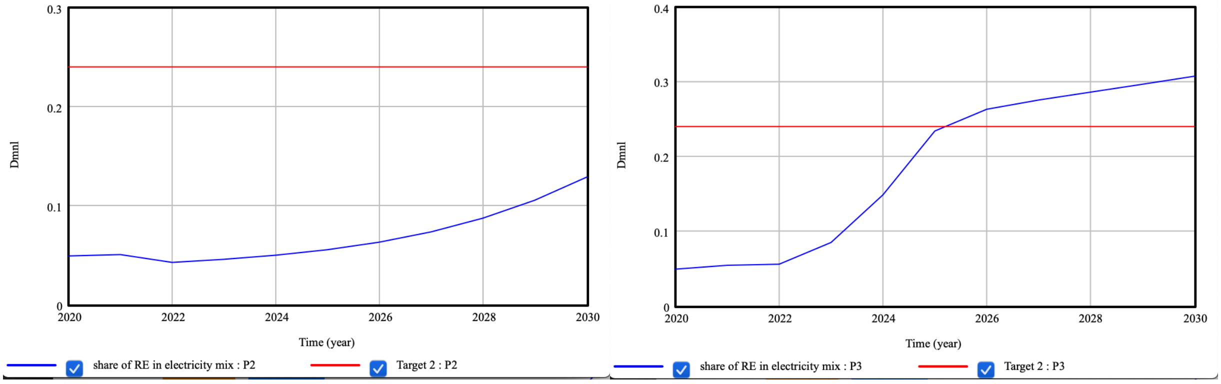


Figure 6.8: Solar PV growth rate policy 2 on the left and policy 3 on the right.

Policy 4: Hybrid

Policy 4 is a combination of policy 1 and 2. If this policy is chosen to be activated, Bali's electricity network will witness an increase in the RE sector and in the natural gas sector.

Policy 5: Fixed Land Cost

In this policy, the ministry of energy and mineral resources will stop the increasing prices for land. As it is explained in the technology awareness mechanism in subsection 6.1.2, the increasing prices of land leads to a decrease in growth rate of the solar PV sector.

This policy essentially shuts down the technology awareness mechanism, which is shown is done by adding a variable called, ” Fixed land prices”. This can be chosen to be 0 or 1 similar to the scenario switches introduced earlier.

Policy 6: Solar PV subsidies

As already mentioned before there are two ways of increasing affinity towards solar PV, ESDM could also decrease the LCOE of solar PV, by giving out subsidies to solar PV projects. According to the international energy agency (IEA, 2011) such subsidies decrease the cost of electricity paid by the consumers and simultaneously increases the benefits of the producers, by lowering production cost.

Policy 7: Tax increase on Fossil Fuel

The affinity towards solar PV can be increased by either lowering the LCOE of solar PV or another method is increasing the LCOE of conventional methods. ESDM can achieve this by increasing the taxes on fossil fuels. In the model this policy can be switch on and off in a similar fashion as the fixed land cost, by setting the variable to 0 or 1.

Policy 8: Adopt minimum GHG emissions

ESDM can set a certain maximum value on greenhouse gases which can be exposed by coal, oil or natural gas power plants. This means that the owners, PLN of these power plants need to upgrade their electricity generation procedure to achieve a lower GHG emissions to capacity output ratio. This can be achieved by regular test checks from ESDM and giving out fines for power plants, which do not meet the new set target. In the model this is included by a reduction of the average GHG emission for coal, diesel and natural gas.

After setting up the conceptual and system dynamics model, it is time to run the simulation and analyse its results. However, before this can be done a verification and validation on the model needs to be executed in order to increase its reliability. Therefore, in the next chapter a verification and validation of the model will follow.

7

Verification & Validation

After the system has been defined and the different scenarios plus all the mechanisms, feedback loops and policies have been introduced it is time to validate and verify the model before running the results. This is required, to convince that the model used for the analysis is actually serving its purpose and simulating a plausible future. Foremost, it has to be recognized that no model is an exact simulation of the reality. As (Sterman, 2000) acclaims: *all models are wrong, because they are simplified, limited versions of reality*. However, he also states that this does not mean that one should not utilize these models. With the right data and valid assumptions the models' depiction of reality can be a valuable tool for decision makers to get a better understanding of the system.

This section will conduct such a verification and validation on the system dynamics model used, to represent the energy transition of the electricity grid in Bali. According to (Sushil 1993), “Failing a test helps to reject a wrong hypothesis, but passing is no guarantee that the model is valid”. Therefore, testing the model with one test is not sufficient, because the test focus on different aspects. In the figure below 7.1 the validation process used to prove the use fullness of the model is shown.

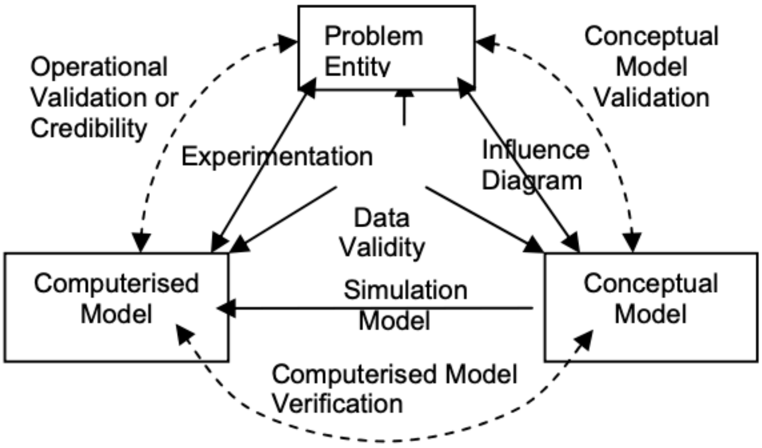


Figure 7.1: Model validation process (Martis, 2006).

Conceptual model validation is used to test that the theories and assumptions representing the conceptual model are correct and that the simulation of the system is ”reasonable”. Computerised model verification checks whether the model implementation represents the conceptual description of the model and the solution to the model (AIAA 1998). Operational validation stands for the analysis of the level of accuracy of the models outputs.

7.1. Model validation & Computerised model verification

Conceptual model validation is a method, which is deployed when a simulation can not be tested directly with an appropriate referent. This is the case in for this simulation, because the model runs from 2020 to 2030, which makes it impossible to compare with historical data. In addition, no similar energy transition has yet occurred in Indonesia. The main concern of model validation is to test if the simulation can support the what it stands for. This can be done by investigating whether the main theories and assumptions elemental for the conceptual model are valid.

During computerised model verification several tests can be used to ensure that the computerised model represents the conceptual model and that it's implementation is done well. First the conceptual model validation test is given, namely, the Boundary Adequacy test. Followed by a Dimensions test, Extreme Condition Tests and Sensitivity Analysis to examine the implementation of the conceptual model.

7.1.1. Boundary Adequacy test

This test will verify that the conceptual model is indeed representing the conception introduced in the literature study and during the system analysis. In other words, this test will check if the model is a valid simulation of the energy transition in Bali.

One way of doing this is to check all of the exogenous and endogenous variables and their feed backs to the model. This test will look at all the exogenous variable of the model and see if they should actually be an endogenous variable. It can be concluded that the vast majority of the variables on this list are exogenous variables in whatever case. However, there are some variable which could also be implemented as endogenous variable. These variables are the following; average lifetime solar PV and LCOE conventional methods.

The average lifetime of solar PV units is assumed to be 25 years, which does not mean that these panels will just stop producing after this time, they will simply start to degrade and to keep the initial efficiency it is better to replace them with new ones. The LCOE of conventional methods could be simulated as an endogenous variable, however since the main target of research is about the expansion of the solar PV sector this variable becomes rather irrelevant because the variables included in this model will only have a very limited affect on it.

Next to this, the model can be checked whether its decision making process is relatable to the real world. In this model, the final decision steps are based on the performance of the scenarios with respect to the targets. These targets are related to the total capacity increase, diversification of the electricity mix, greenhouse gas reduction and total cost. Since the main target of the Balinese electricity network providers and Indonesian government is to reduce its CO2 footprint, target 2 and 3 seem very reasonable. Next, the capacity increase is important in order to avoid a power outage, hence also seems realistic. Finally, the decision will be based on the total cost of the scenarios, which is clearly always an aspect in decision making nowadays.

7.1.2. Dimensions test

Within the software of Vensim there is a feature called Unit Check, which after setting up a model with all of the equations will check if the right hand side is the same as the left hand side. The screenshot below illustrates what the outcome is when applying this test to the system dynamics model. This shows that there is exactly one error, however this error does not mean that the model is wrong. When taking a closer look at the first errors it states that the exponent always has to be dimensionless in Vensim, however when calculating the LCOE the equation clearly states that it is required to calculate the lifetime of the project in the exponent and the lifetime of the project is given in years. This error then also leads to the following 4 warnings. This error and warning messages can be ignored without any trouble.

```
***********************************************
Error in units for the following equation:
annual cost solar PV  =
        ( investment cost solar PV per kW
             * interest rate
             * ( 1
                  + interest rate )
                  ^ average lifetime solar PV systems )
             / ( ( 1
                  + interest rate )
                  ^ ( average lifetime solar PV systems )
                  - 1)
             * kw MW conversion
annual cost solar PV  --> USD/MW
investment cost solar PV per kW  --> USD/kW
interest rate  --> Dmnl
average lifetime solar PV systems  --> year
kw MW conversion  --> kW/MW

Analysis of units error:
Exponent of ^ must be dimensionless
average lifetime solar PV systems
Has Units: year
( 1
     + interest rate )
Has Units: Dimensionless

***********************************************
Warning: units in equation for - electricity demand increase
Lookup -#electricity demand increase#- used with dimensioned argument
 year

***********************************************
Warning: units in equation for - GHG emission baseline scenario
Lookup -#GHG emission baseline scenario#- used with dimensioned argument
 year

***********************************************
Warning: units in equation for - growth rate stimulated by ESDM to meet target

Lookup -#growth rate stimulated by ESDM to meet target#- used with dimensioned argument
 year

***********************************************
Warning: units in equation for - interest rate
Lookup -#interest rate#- used with dimensioned argument
 year
```

Figure 7.2: Dimension test of system dynamics model

7.2. Step size & Integration method

As already mentioned before, the model starts at the beginning of year 2020 and runs the simulations for 10 years, hence until 2030. The units used for time in this model is therefore chosen to be of the unit year. Next to this, it has decided to use the Euler method for the numerical integration. Euler has been chosen because it is a common used and good fit to construct the basis of a complex system. Euler integration assumes that the calculated values stay constant through the time step, which does not seem very likely when compared to the real world. Therefore, this time step has been chosen to be 0.015625 years, in order to decrease the local error, which is proportional to the square of the step size. Another reason why this step size has been chosen is that When running the model with a smaller step size no difference can be noticed on the behaviour of the graphs compared to the 0.015625 years.

7.3. Extreme condition

Nevertheless, it should be noted that the previously introduced sensitivity analysis is not enough to prove the robustness and reliability of the system. First of all, the parameters chosen for this analysis are only modified to a 10% change, however in certain extreme conditions, it is possible that certain parameters will differ by larger margins. Therefore the following section will include an extreme condition test.

For this extreme condition test, plausible hypothesis will be set up, which are thereafter tested by modifying certain parameters to simulate the hypothesis. If the results of this test behave as anticipated under given extreme conditions, then it can be concluded that the model behaves realistic under extreme conditions. For this test the following hypothesis used:

- If LCOE of solar PV is extremely high compared to conventional alternatives, there will not be less solar PV capacity.
- If LCOE of solar PV is extremely low compared to conventional alternatives, there will be an increase in solar PV capacity.
- If the land price for solar farms is increasing more rapidly, the total capacity of solar PV will decrease drastically.
- If the average lifetime of solar panels is decreased, the total capacity of solar PV will decrease.
- If the average lifetime of solar panels is increased, the total capacity of solar PV will increase.

All of these hypothesis are tested separately. Since all of the hypothesis are concerning the development of the solar PV sector, it is logical to test these hypothesis with either scenario 2 or 3. The results of each hypothesis are given in appendix C, these results imply that the model behaves realistic even in extreme conditions.

7.4. Sensitivity Analysis

The resulting graphs of the sensitivity analysis can be found in Appendix D. A sensitivity analysis verifies how the outputs are effected by certain parameters under certain assumptions. This means that this section will show that the sources of uncertainties in the system dynamics model contribute to the model's overall uncertainty. This requires to select certain parameters and determine a specific boundary or range in which they will be examined.

First of all, it has to be noted that this sensitivity analysis will not be conducted for each one of the twelve scenarios. Since the main point of interest is the development of the solar PV sector, this sensitivity analysis will also concentrate on this part. The rest of the model, namely the development of the LNG, coal and oil are mostly defined by step functions, representing the decision to shut down a power plant or build a new one. The only interesting parameter in this sub model, is the time delay required to construct such a facility. The decision on which scenarios will taken for this analysis is based upon the parameters of relevance, which will be given below.

The parameters of interest, whose input value will be modified by +/- 10% are determined by considering their impact on the output values of interest. The output values of interest are the following:

- growth rate solar PV
- share of RE in electricity mix
- Total capacity Bali Grid
- LCOE solar PV

When taking a look at the Vensim model, introduced in chapter 6, the following parameters of interest for the sensitivity analysis have been chosen. All of the following parameters are of exogenous variables which have a significant impact on the output values and performance of the model. Next to this, these parameters are the ones based on assumptions, for which an exact value has not been found. Therefore, by changing the input values of these significant parameter and examining the resulting behaviours, the uncertainty can be reduced and the robustness and reliability of the system can be increased.

- alpha value learning by doing
- initial investment cost solar PV

- average sun hours per year
- initial amount of solar panels in the system
- average delay for solar PV construction
- interest rate

The chosen parameters do not influence the reference scenario nor scenario 1. Therefore, these will not be included in this analysis. Next, since scenario 2, 3, 5, 6, 7 and 8 have a similar build-up, as also scenario 4, 9, 10, 11 and 12, it has been decided that only scenario 2 and 4 will be entering this sensitivity analysis. This can be done, because if the scenarios 2 and 4 demonstrate to reduce uncertainty and increase robustness and reliability, the same will hold for the other scenarios.

Table 7.1: Input parameters for the sensitivity analysis

Parameter	**-10%**	**Initial value**	**+10%**
alpha value learning by doing	0.18	0.2	0.22
initial investment cost solar PV	2,250	2,500	2,750
average sun hours per year	2,025	2,250	2,475
initial solar PV in system	72,000	80,000	88,000
construction delay solar PV	0.45	0.5	0.55

In table 7.1 the parameters used for the sensitivity analysis are given with their respective input values. The parameters are altered with probability function of a random uniform distribution. The minus and plus 10 % of the initial value are taken as minimum and maximum values for this distribution. In the random uniform distribution, numbers between the minimum and maximum values are equally likely to occur, which is suitable for this sensitivity analysis.

In appendix D, the resulting graphs can be found. When taking a closer look at these graphs, it becomes clear that for neither scenario 2 nor 4 the behaviour of the graphs is changing significantly.

7.5. Critical reflection on model

Resulting from this verification and validation it can be concluded that the the model fits its purpose and that it fits well with the energy transition of the electricity network in Bali. Next to this, the model does not include any numerical or dimensional errors. The sensitivity analysis demonstrates that the key variables are robust to changes in parameters within 10 percent range. Next to this, the model behaves as expected in extreme conditions.

This chapter shows that ESDM can make use of this model for the energy transition of the electricity network in Bali. However, it has to be noted that the results have to be critically discussed with the actors because it is based on several assumptions, which can be foud in Appendx E. Only when all the actors involved agree upon these assumptions, a scenario can be applied by ESDM.

8
Results

Having introduced and explained the implementation of all the different mechanisms, feedback loops, variables, policies and equations in the system dynamics model, finally some results can be generated. After the verification and validation chapter it is fair to say that the output of the simulation model will not represent the exact future, however the results will be beneficial to estimate the behaviour of the key variables. First, a comparison and analysis on the five main scenarios is given, followed by an investigation on the effect of the four additional policies. After this, all the scenarios satisfying the requirements are going trough a trade off and compared to one and another. Finally, a conclusion on these results will complete the chapter.

8.1. Target 1: Capacity increase

In this section the five scenarios resulting from activating policy 1 until 4 will be analysed on how they perform compared to the predicted electricity demand. These five scenarios are the outputs after implementing the first 4 policies separately, plus the reference scenario.

1. REF : Reference scenario, no policies
2. S1 : Natural Gas Scenario, policy 1
3. S2 : Renewable Energy A Scenario, policy 2
4. S3 : Renewable Energy 2 Scenario, policy 3
5. S4 : Hybrid Scenario, policy 4

In the following table 8.2, the variables which require different inputs per scenario are given. The switches have to be set according to these values, in order to run the requested scenario.

Table 8.1: Input Data to run five main scenarios

Scenario	REF	S1	S2	S3	S4
Reference scenario switch	1	1	0	0	0
Natural Gas policy switch	0	1	0	0	0
Renewable Energy policy switch	0	0	1	1	0
Renewable Energy policy 2 switch	0	0	0	1	0
Hybrid policy switch	0	0	0	0	1

First these scenarios will be studied in relation towards the first target, capacity increase. This target requires that the capacity of the grid on the islands is always superior to the estimated peak load. In addition to this requirement, a safety margin of 5% has been included to the forecast of the peak load. This safety margin is added, in order to ensure that the grid is able to provide the entire island with electricity even if one power plant needs to shut down due to maintenance or any other external cause. Therefore, the total capacity of the electricity grid has to be superior to this line at any time of the simulation, in order to satisfy this first target. If one scenario does not meet this requirement, it will be considered not good enough. Such a scenario will be taken out and neglected for the rest of the analysis.

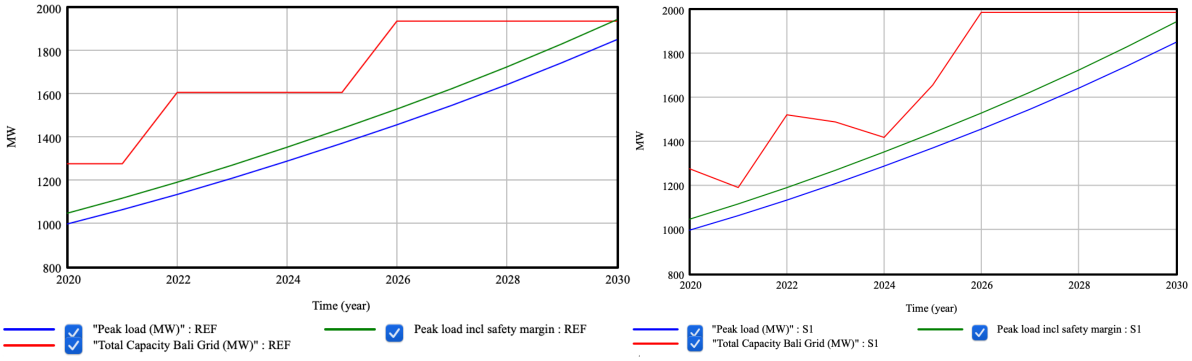


Figure 8.1: Total capacity of the grid in MW compared to peak load forecast. REF on the left and S1 on the right

Figure 8.1 demonstrates the simulation of the total capacity of Bali's electricity grid for the reference scenario on the left and the second scenario following the second policy on the right. The x axis represents the simulation time starting at 2020 and ending at 2030. The y axis represents the capacity in MW. The red line in both graphs is the outcome of the capacity per scenario, the blue line represents the peak load demand following the assumptions made in the energy plan (RUPTL, 2019). The green line represents the peak load including the safety margin. Both scenarios the reference and S1 manage to supply more capacity then the peak load plus safety margin over the entire period of the simulation. In both simulations one can clearly see two steps happening, which represent in both cases the additional development of two new coal powered plants. In the second scenario a decrease in capacity is visible before the first and second step. This is due to the the fact, that the oil powered facilities have to be shut down while they are in maintenance to be transformed into liquefied natural gas engines. From these 2 graphs it also becomes clear that the final capacity of S1 is higher than the reference scenario, this is because the efficiency factor of LNG is higher compared to oil.

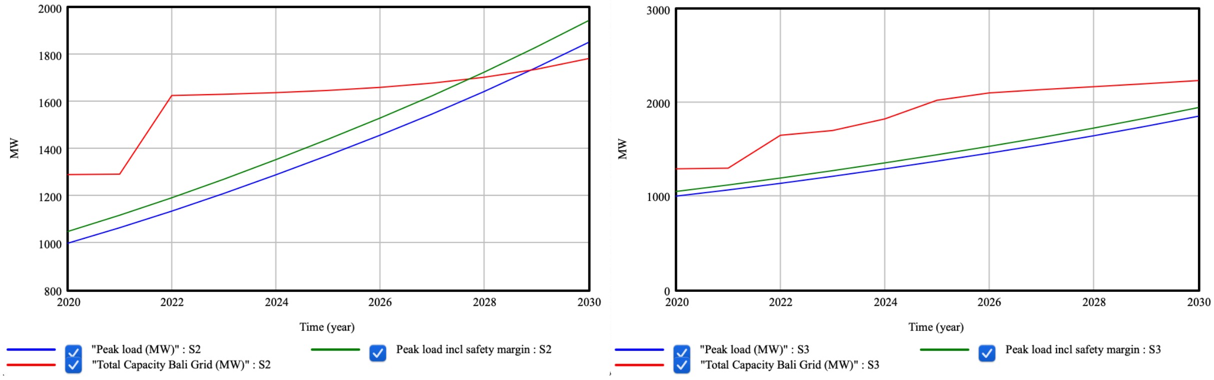


Figure 8.2: Total capacity of the grid in MW compared to peak load forecast. S2 on the left and S3 on the right

Figure 8.2 represents the outcomes of the second and third scenario, where policies 2 and 3 are activated, respectively. The x-axis represent again the time, same as in the previous figure and the blue and green line are also the same as in figure 8.1. The main difference between these two scenarios and the previous ones is that there is only one step function present. This is due to the fact that policy 2 and 3 include the cancellation of a new coal fired power plant in 2025. When activating policy 2 (left figure) there is only a small exponential increase to witness at the end. This is different for policy 3, where more drastic measures lead to a faster expansion of the solar sector.

While scenario 3 satisfies the requirement at all times, this is not the case for scenario 2, where the development in the solar PV sector does not occur fast enough to meet the growing demand. Therefore, scenario 2 can already be eliminated.

Figure 8.3: Total capacity of the grid in MW compared to peak load forecast. Scenario 4

Figure 8.3 represents the total capacity of scenario 4, where P4 is active. The colors of the lines represent again the same as in the previous figures. In this simulation there are again 2 steps present. This is similar to scenario 1, first the total capacity is decreasing because the oil powered plants are replaces by LNG and there are 2 steps which represent the construction of 2 new coal fired power plants. Around the year 2028 there is a slight exponential growth visible, which is caused by the increase in the solar PV sector. However, when taking a look at figure 8.3 the exact same reasoning applies to scenario 4 and therefore also this scenario has to be eliminated.

8.1.1. Additional policies and Technology Evolution

Since both scenarios S2 and S4 did not meet the first requirement, the additional policies will be tested on them as well, resulting in scenario S5 ,S6 ,S7 and S8 and S9, S10, S11 and s12. The table below shows the different inputs required per switch, in order to run the respective simulation scenario. For example, if one wants to run scenario 11, then the policy 4, 5, 6 and 7 need to be activated.

Table 8.2: Input Data to run scenarios

Policies	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**
Policy 2	1	1	1	1	0	0	0	0
Policy 3	0	0	0	0	0	0	0	0
Policy 4	0	0	0	0	1	1	1	1
Policy 5	1	0	0	0	1	0	0	0
Policy 6	1	1	0	0	1	1	0	0
Policy 7	1	1	1	0	1	1	1	0
Policy 8	1	1	1	1	1	1	1	1

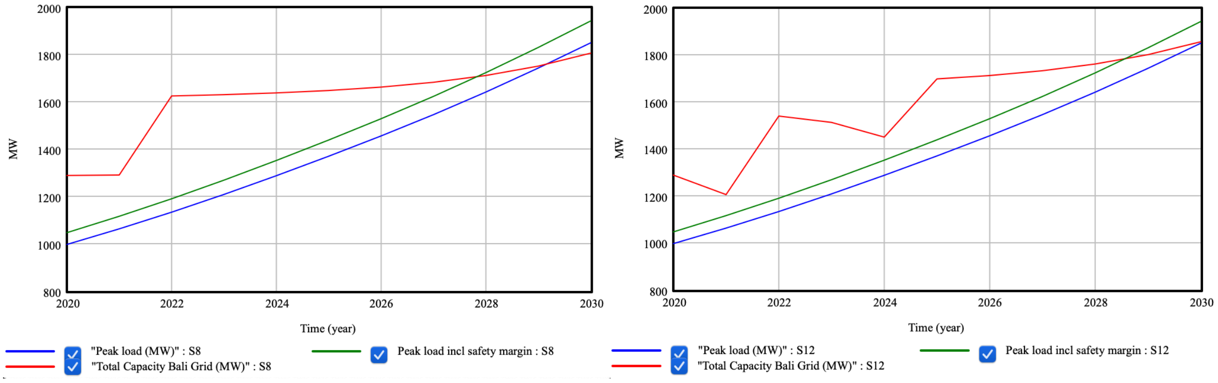


Figure 8.4: Total capacity of the grid in MW compared to peak load forecast. S8 on the left, S12 on the right

Figure 8.4 illustrates Bali's grid capacity evolution for scenario 8 on the left and 12 on the right. These scenarios are very similar to scenario 2 and 4, respectively. Therefore, there is also not a large difference in the behaviour of these lines. The only difference is that in both cases the solar PV sector is increasing in a faster pace, leading to a stronger exponential behaviour. However, when looking at both figures in 8.4 it becomes evident that the additional policies 5, 6, 7 and 8 to only have a very limited impact on the capacity increase and do not manage to meet the first target/requirement. Therefore, they can all be eliminated from further analysis.

To sum up, after analysing the scenarios with respect to the first target only 3 of them are left. Namely, the reference scenario, the 1st and 3rd scenario. However, it is still possible that scenario 8 and 12 can meet the first target, if the model includes the evolution of technology.

Technology Evolution (TE)

The last possibility for scenario S8 and S12 to full fill the first and most important requirement is when including the evolution of the solar photo voltaic cells. These outcomes are given in the figure below 8.5. And indeed, when including the evolution of technology the total capacity of both scenarios S8 and S12 are always superior to the peak load including the safety margin. This is due to the fact, that this evolution in technology sees an increase in efficiency of solar PV cells and a decreases of the GHG emissions while manufacturing them.

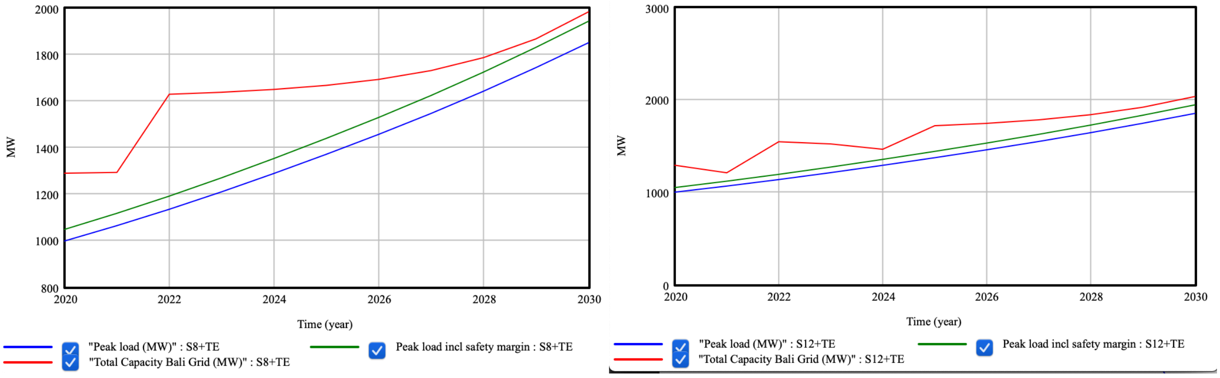


Figure 8.5: Total capacity of the grid in MW compared to peak load forecast. S8+TE on the left, S12+TE on the rigth

After analysing all of the scenarios based on the first target, meeting the increase in electricity demand at any time, only 5 scenarios are left, namely the reference scenario (REF) and S1, S3, S8 + TE and S12 +TE.

8.2. Target 2: Diversification of electricity mix

In this section the electricity mix of the remaining scenarios is given. This is important for ESDM, in order to try to achieve their second target from the national energy policy (NEP, 2014). This target requires a 23% penetration of the renewable sector in the total electricity mix. If the Natural gas scenario (S2) has been chosen, then a 23% penetration of LNG is required. The shares per electricity source have been calculated by dividing the capacity output per year of each sector by the total capacity of the grid in the same year.

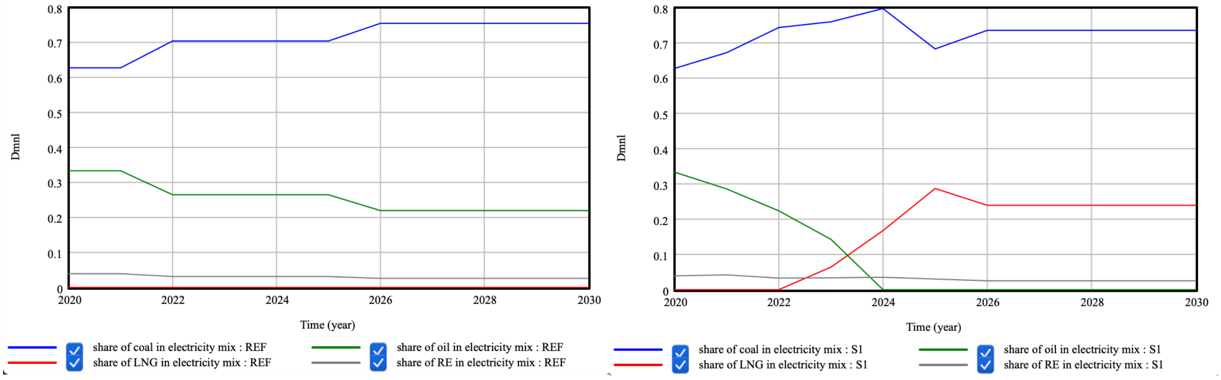


Figure 8.6: Electricity generation mix, reference scenario (left) S1 (right)

In figure 8.6 the electricity generation mix for the REF and S1 scenario are illustrated. For the REF scenario there is no electricity produced by natural gas and the renewable energy sector only provides 4%. In this scenario there is no capacity increase by neither oil, renewable or natural gas. The only change occurring is an increase of the development of coal powered power plants.

In a similar fashion to the REF scenario, the S1 scenario does not include any capacity increase of the renewable energy sector. In addition, also the increase in capacity for power plants running on coal is kept the same as in the reference scenario. In this scenario the power plants running on oil are modified to be able to produce electricity by burning natural gas. This can be seen in the figure on the right by a decrease in the green line representing the share of oil and an increase in the red line, which represents the share of liquefied natural gas. By doing this, the target of 22% penetration by the natural gas sector on the total electricity mix is achieved.

Table 8.3: Electricity mix in 2025 and 2026, Natural gas scenario

Electricity source	**% in 2025**	**% in 2026**
Coal	69	75
Oil	0	0
Natural Gas	27	22
Renewable energy	4	3

However, in figure 8.6 it becomes obvious that there is still a drop in the share of natural gas after 2025, due to the addition of a new coal power plants in the year 2025. Therefore, also the values in the year 2026 will be considered, since this is the year from which onward the electricity mix stays constant. Table 8.3 denotes the exact output values of the variables of interest. This proves that scenario 2 also meets the requirements of the second target.

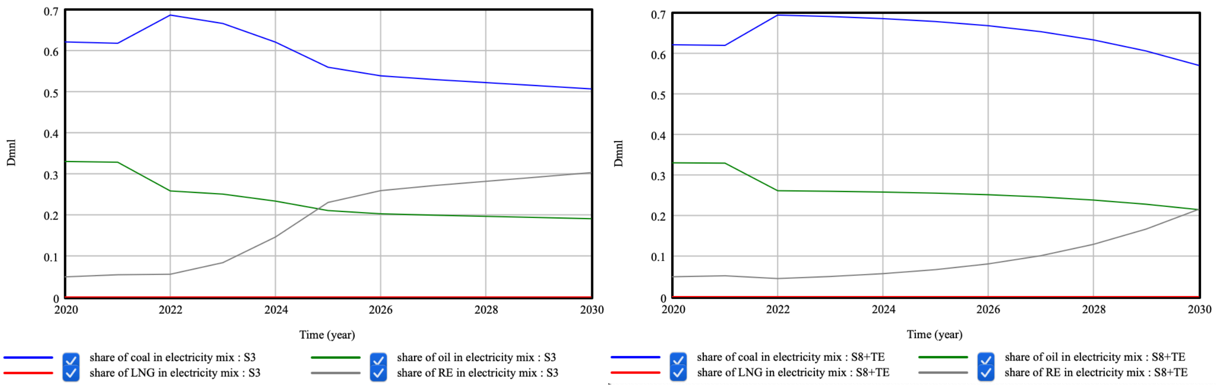


Figure 8.7: Electricity generation mix S3 (left) and S8 + TE (right)

On the left hand side of figure 8.7, the renewable energy scenario B (S3) is shown and on the right hand side you can see the development of the electricity mix of scenario 8 including the technology evolution. In both cases, there is no development to discover of the natural gas sector. Next to this, both scenarios include a raise in the electrification capacity from coal powered plants at the beginning, which causes a drop of the share of oil based electricity generation.

Table 8.4: Electricity mix in 2025 and 2030, S3 and S8 + TE

Electricity source	**% S3 (2025)**	**% S8TE (2025)**	**% S3 (2030)**	**% S8TE (2030)**
Coal	56	67	50	57
Oil	21	26	19	21
Natural Gas	0	0	0	0
Renewable energy	**23**	**7**	31	22

As already mentioned before, policy 3 push ESDM to raise the development of the solar PV sector in order to achieve their target of a 23% penetration of the renewable sector in the total electricity mix by 2025. Therefore, it is clear that this scenario will achieve this second target. However, as Table 8.4 points out, the scenario 8 with technology evolution included does not manage to achieve the required share of 23% by the renewable energy sector. Nevertheless, it should be noted that this scenario achiever 22% by 2030 and does not require as drastic measures as policy 3.

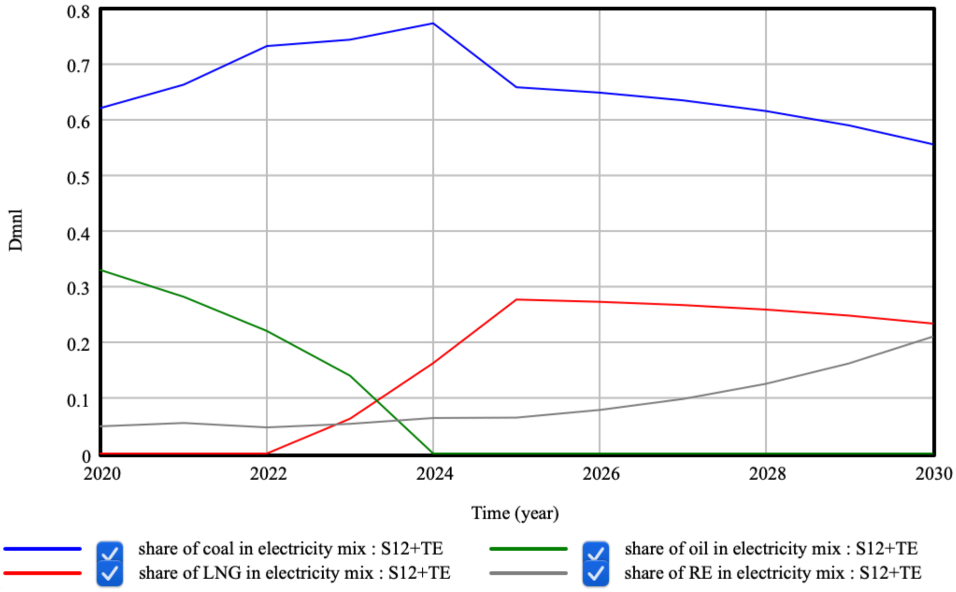


Figure 8.8: Electricity generation mix S12+TE

Figure 8.8 shows the results of the model when running the S12 + TE scenario, in which the renewable and natural gas capacities are being raised. Additionally, also parts of the development of the coal sector is added in this scenario. From this figure, one can see that the renewable share is only increasing at a very low pace at the beginning, which is due to the fact that the natural gas and coal development are occurring at an earlier stage with far more capacity. Again the exact percentages per electricity source for the year 2025 and 2030 are given in the table 8.5. This scenario is nowhere near the required 23% in 2025, however achieves this target at the end of the simulation in 2030, while also the natural gas sector achieves the 23& in 2025. Therefore it is assumed that this scenario successfully achieves target number 2.

Table 8.5: Electricity mix in 2025 and 2030, S12+TE

Electricity source	% in 2025	% in 2026
Coal	66.5	57
Oil	0	0
Natural Gas	27	22
Renewable energy	6.5	21

After investigating the electricity mixes per scenario, it is now time to take a look at the last target, namely the total greenhouse gas reduction compared to the baseline scenario.

8.3. Target 3: Greenhouse gas emission reduction

The ultimate goal of all of the scenarios is to achieve a 11% reduction of the greenhouse gases compared to the reference scenario. In the figure below 8.9 the remaining scenarios are being compared to the baseline scenario. The values given are in percentage and indicate how much lower the total emissions are per year.

First, it has to be noted that these calculations are done in reference to the second baseline scenario as described in chapter 5.

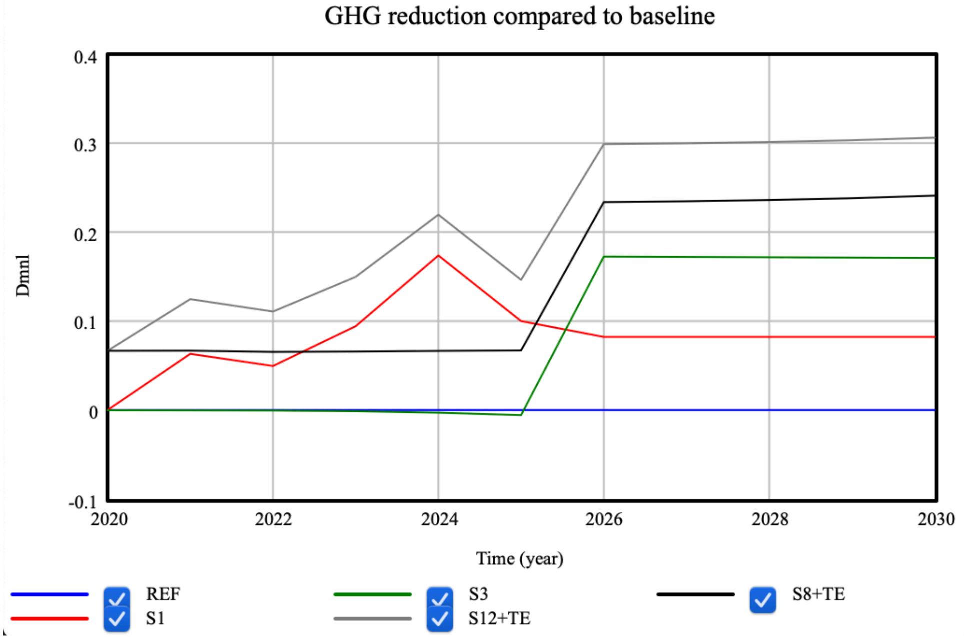


Figure 8.9: GHG reduction compared to baseline scenario

In figure 8.9 the x axis represents again the time starting from 2020 until 2030. The y axis represents the percentage of how much GHG emissions are saved compared to the reference scenario. The most significant ramps and steps in this figure are occurring when an addition power plant is starting it's operation or when power plants are being shut down. For example, for the S8+TE, S12+TE and S3 there is a clear ramp starting in the year 2025 until 2026, this is due to the fact that in these scenarios the additional coal power plant will not be constructed. However, this will happen in scenario S1 and the reference, which is why these lines to not show the same behaviour. This leads to a decrease in the total emissions in comparison to the reference scenario. When taking a close look at this graph it appears that all of the scenarios expect for S1 are achieving the 11% reduction by 2030. The other 3 scenarios all meet this target/requirement. Scenario 12+TE is even reaching a 31% reduction of the GHG emission generated from the electricity network in Bali. In addition, it should be noted that due to policy 8 scenarios S8+TE and S12+TE have an upwards sloping curve at the end. This is because in these scenarios the fossil fuel generators are emitting less GHG compared to the baseline.

Nevertheless, it has to be noted that this representation is not the most ideal way to compare the scenarios, because they do not have the same capacity output and therefore it is only logical that some have a higher percentage. This becomes quite recognizable when taking a look at figure 8.10. This illustration represents the total capacity of the grid per year in MW of each scenario. In 2030 the scenario with the highest output is scenario 3 with 2,250 MW and the scenario with the lowest output is the reference scenario with 1,930 MW. This concludes in a total difference of 320 MW between these two.

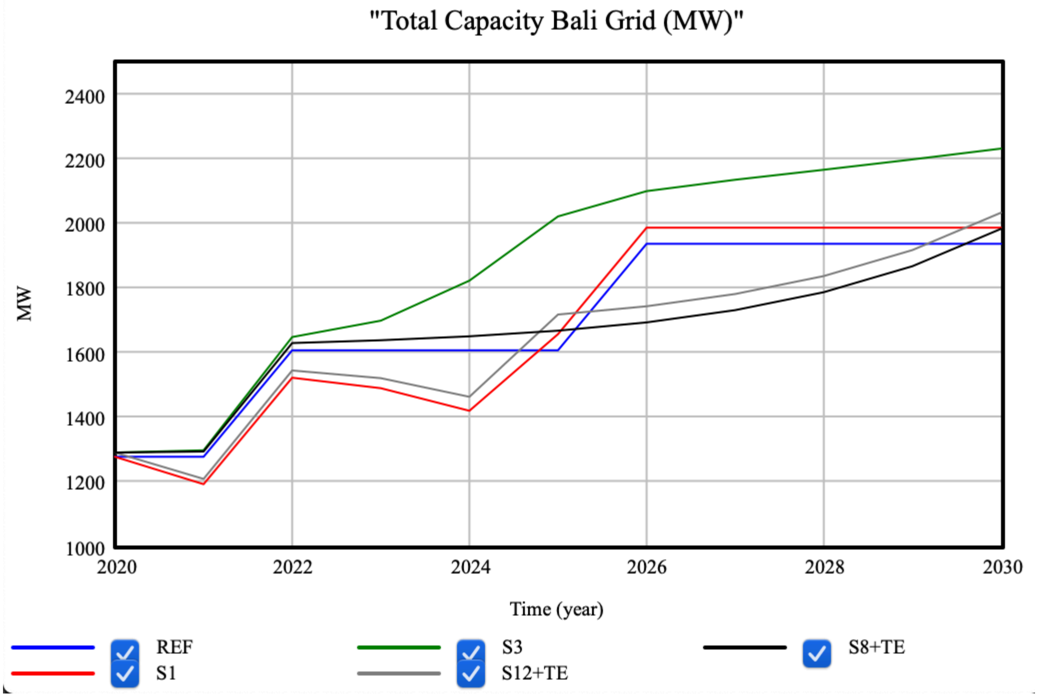


Figure 8.10: Total grid capacity

Consequently, a more representative graph is introduced below. Figure 8.11 calculates the total greenhouse gas emissions per scenario and divides this value by the representative total electricity output, which can be found in the appendix C. This results in the ratio of how much greenhouse gases are being emitted while generating 1 kWh.

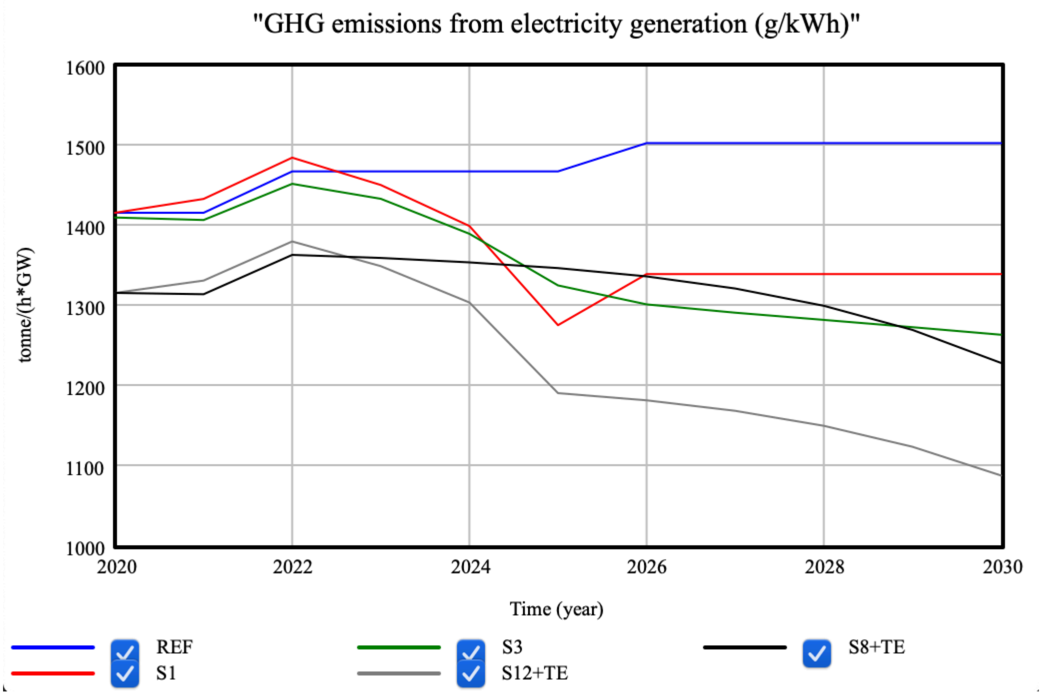


Figure 8.11: GHG emission per kWh

For this reason to get a more accurate and reliable comparison between the scenarios, the values given in the figure above will be multiplied by the total electricity output of the reference scenario. In this way the efficiency of the electricity generation will be determined. For example the total electricity output of the reference scenario in 2030 is 9,800 GWh/year, now this value will be multiplied with the different values per scenario of figure 8.11 for the same year. After finishing these calculations and drawing comparison to the reference scenario new percentages have been determined. The total reduction of GHG emissions compared to the baseline once calculated with their own separate electricity output and with the output of the baseline are given in the table below 8.6.

Table 8.6: Electricity mix in 2025, Renewable Energy scenario 1&2

Scenario	g/kWh (2030)	GHG reduction (model) (%)	GHG reduction w.r.t REF (%)
REF	1,498	0	0
S1	1,340	8	10.5
S3	1,260	17	15.8
S8+TE	1,225	24	18.2
S12+TE	1,080	31	27.9

When doing the calculations for the GHG reduction with respect to the electricity output from the reference scenario the outcome changes significantly. However, the order of the best to worst has not changed. This way of determining the percentage of GHG reduction is only beneficial for the scenario 1.

8.4. Target 4: Cost

All of the targets have been analysed by now except the total cost per scenario. The total cost per scenario includes the initial cost for building a new facility, the operational and maintenance cost of the facility over the 10 year time span and the fuel cost of each energy source. In figure 8.12 the evolution of the total cost per scenario is illustrated. The y-axis indicated the total cost in billion US dollars. Even though, in Indonesia the currency is Rupiah this has been calculated in US dollars for simplicity reasons.

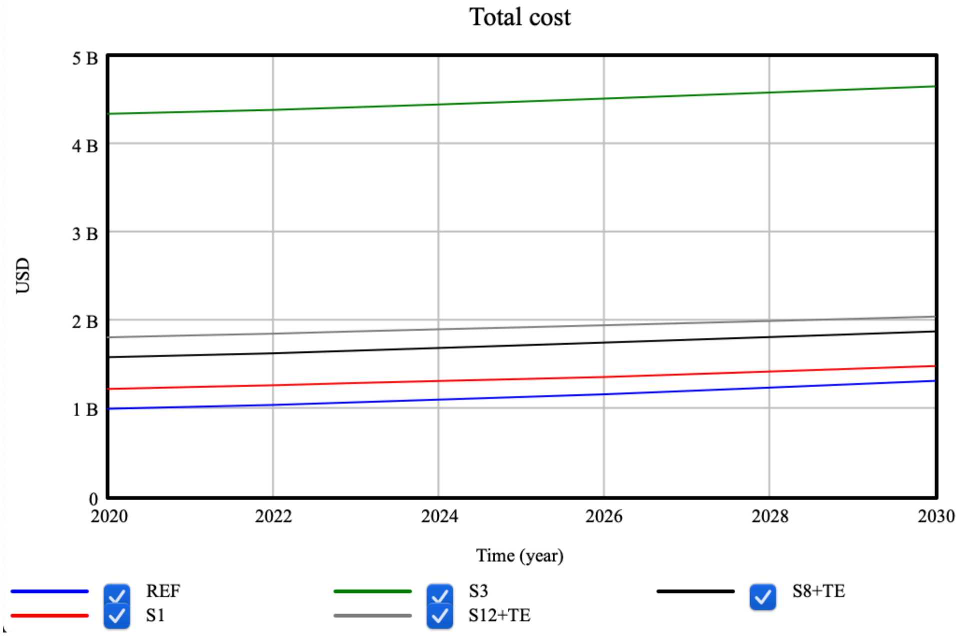


Figure 8.12: Total cost per scenario

Table 8.7 reveals the total cost per scenario in the year 2030, which is considered to be the cost ESDM must be willing to spend to achieve the aforementioned outputs.

Table 8.7: Total cost of the final scenarios

Scenario	**Total Cost in billion USD**	**Total grid capacity (MW)**
REF	1.3	1,950
S1	1.49	1,990
S3	4.6	2,220
S8+TE	1.85	1,990
S12+TE	2.05	2,020

As already foreseeable, the reference scenario would result in the cheapest total cost and every scenario including a development of the solar PV sector will result in a more elevated final cost. Nevertheless, it should be recognized that the slope of the scenarios increasing the solar PV sector is getting smaller at the end. This is not the case for the reference and natural gas scenario. This is due to the fact, that it is cheaper to operate and maintain solar PV farms in comparison to power plants running on coal, oil and liquefied natural gas. Next to this, solar PV farms to not have any fuel cost, which decreases its slope even further. In addition, table 8.7 also indicated the total grid capacity in 2030 per scenario. These values are very similar for every scenario expect scenario 3. One could argue that scenario 3 has more capacity compared to the others and therefore it's cost shouldn't directly be compared to the others. However, the difference in cost is by far higher than the difference of capacity.

8.5. Trade-off table

The following table represents a trade off between the final plausible scenarios. This trade off is constructed, to determine which of the pathways will be recommended to follow for ESDM. Each scenario receives a score from 0 to 10 based on how they perform with respect to the targets. With 0 being the worst and 10 being the best. In addition to this, the 4 targets will be given a weight factor representing their importance.

The main goal of this research is to find a scenario of the future, which decreases the total greenhouse gas emissions from the energy sector. Therefore, target number 3 representing the performance of each scenario regarding the greenhouse gas emissions is given a weight factor of 4. However, the GHG reduction is only use full if Bali enables the capacity of it's grid to be superior to the demand at any time of the simulation. Therefore, target number 1 is given an even higher weigth factor, namely 5. The second target the diversification of the electricity mix will be given a weight factor of only 2, since this is more of a survey target. Finally the cost will be given a weight factor of 4, since this will always play a role in the decision making process for any stakeholder and also for ESDM.

It should be noted that these weight factors and also the scores given per scenario, should be determined by discussing the final scenarios with the key actors. However, since this was not able to achieve during the time of the research this will only help as a recommendation for future work.

Table 8.8: Trade off between final scenarios

Scenarios	T1 (*5)	T2 (*2)	T3 (*4)	T4 (*4)	Final score
REF	7	0	0	9	71
S1	8	8	4	8	104
S3	10	10	6	3	106
S8 + TE	9	6	8	7	117
S12 + TE	9	10	10	6	129

Table 8.8 illustrates the different scores of each scenario per target. These scores have been determined based on the values from the simulations and comparing them to one and another. From this trade off table, the final recommended scenario will be scenario 12 including the technology evolution of the solar PV market.

8.5.1. Sensitivity analysis of trade-off table

In appendix E different table with changing weight factors per target are given. First they are all given the same weight, next each target is given the maximum weight while keeping the other targets at the minimum. And finally one test is done where only the total cost and GHG emissions targets, hence target 3 and 4 are given the maximum weight. This implies that ESDM would try anything whatever the costs are to try and achieve their targets set by the Paris Agreement.
When looking at the final scores of each one of these 6 trade off tables, it is only once that the best scenario is different. This occurs for the case in, which the total cost is given the maximum weight factor. This seems only natural that the scenarios with a increasing development in the solar sector are finishing less good. Nevertheless, even with this scoring method S2 only wins by a margin of 1 point difference compared to S12+TE.

8.6. Conclusion

The result of the different scenarios can be interpreted in very different ways. But first lets conclude on the results included in this chapter. At the very beginning there is one reference scenario, 12 scenarios following the different implementation of the policies and an extra 2 scenarios including the technology evolution of the solar photo voltaic cells. This total of 15 scenarios are being analysed on their performance regarding the 4 target, capacity increase, diversification of the electricity mix, greenhouse gas reduction and the total cost.
The first target is used as an elimination process, because a scenario that does not ensure a grid with enough capacity to meet the demand, is too dangerous to be applied. Thereby, a total of 10 scenarios are being eliminated b target number one. The remaining scenarios are REF, S1, S2, S8+TE and S12+TE.In the next stage these left over scenarios have been measured by means of the second target, the diversification of the electricity mix. Only scenarios S1, S3 and S12+TE accomplish also this target. However, this requirement is not given the same weight of importance as target 1. The main target which this research is trying to attain is the reduction of the total greenhouse gases emitted from the energy sector. This target is achieved by every remaining scenario except the scenario 1 and of course the reference scenario. Finally, the total cost per scenario are announced, resulting in the following order of scenarios REF, S1, S8+TE, S12+TE and S2 from cheapest to most expensive.

9

Conclusion & Reflection

The final chapter will look back and reflect on the work done in this research. First the main research question will be repeated with its sub research questions. The answers to these questions will be picked out of the work and given in this chapter. Afterwards a conclusion on the different scenarios and their performance will be drawn. A trade off of the final scenarios will be done, in order to discover the best scenario and the set of policies required to achieve it. At the end some suggestions for future work will be given, which can help improve the quality of this and future works with a similar basis.

9.1. Answer to research question

The main purpose of this research is to find an answer to this question *What plausible road map can ESDM follow, in order to accelerate the energy transition in Bali, while assuring that the demand is covered, to help Indonesia achieve their targets?* To find the right answer to the main question, the following sub research questions have been set up. And the following list will include these questions with their answers.

Sub research questions

- **How is the current electricity network build up in Bali and what are the factors behind the slow development of renewable sources? (RQ1)**
  The current electricity network in Bali is mostly dominated by fossil fuel, such as coal and oil powered power plants. Coal has already been for a very long time the dominant electricity generation source in Indonesia and Bali. Therefore, the trust in this sources are very high by the local people and investors. In order to reduce risks of a new investment they prefer to invest into technologies which they are familiar with and hence such little investment and growth rate is recorded in the renewable energy sector. Next to this, Bali is a volcanic island which does not have the easiest topography to build wind farms. Its geographical characteristics would be optimal for power plants using geothermal technology. However, the Balinese population is strongly against the construction of such power plants on their volcanoes, because they are sacred in their culture.
  Therefore, solar seems as the right fit for Bali to develop in, if they want to achieve all of their energy targets. However, this sector is still quite underdeveloped at the moment.

- **Which policies may be applied to achieve these targets and what are their influence on the development of Bali's electricity network? (RQ2)**
  After conducting an analysis on the current situation and on similar projects, a total of 15 different scenarios have been constructed. These scenarios result from a set of 8 different policies which the main actor ESDM has the power of applying. Next to this, a total of 4 targets which have been used as a list of requirements are introduced. These targets follow clear goals, which Bali or Indonesia pledged on accomplishing, which are given in the list below.

1. **Capacity increase**
   First and foremost, it is of highest importance that the chosen outcome has at any time of the simulation enough capacity in the electricity grid, to meet the estimated peak load of the same year. An outcome will only be considered plausible when it meets this requirement.
2. **Diversification of electricity mix**
   This target is related to the diversification of the electricity mix. As already tried by the (NEP, 2014). This requires that the renewable sector or the natural gas sector achieves a penetration of 23 % of the total electricity mix by 2025. If a scenario meets all the other requirements except this one it will still be considered plausible.
3. **GHG emission reduction**
   This target is linked to the Paris Agreement pledge of Indonesia to achieve a 11% GHG emission reduction compared to the reference scenario by 2030. Therefore, only outcomes which achieve a reduction of 11% compared to the reference scenario will be considered plausible.
4. **Cost**
   The last one is less of a target and more of an analysis tool. Each scenario will be compared on its total cost over the time span of the model. With the help of this the cheapest scenario which meets all the requirements will be identified.

The following 8 policies are used, in order to try and achieve these targets.

- P1: Natural gas
- P2: Renewable Energy 1, solar PV
- P3: Renewable Energy 2, solar PV
- P4: Hybrid
- P5: Fixed Land Cost
- P6: Solar PV subsidy
- P7: Fossil Fuel Tax
- P8: GHG emission restriction

- **Which policy or combination of policies can help meeting all of the required targets, while ensuring that the capacity increase meets the demand? (RQ3)**

Table 9.1: Scenarios resulting from policy implementation

Scenario	Description
S1	Scenario 1 is the result, when ESDM decides at the beginning (2020) to activate policy 1.
S2	Scenario 2 is the future in which ESDM decides to follow policy 2 from the beginning on.
S3	Scenario 3 results, when ESDM switches on policy 3.
S4	Scenario 4 is the hybrid future, where ESDM determines to follow a development on the renewable and natural gas sector, hence policy 4.
S5	This simulation of the future includes 2 steps, first policy 2 will be activated, followed by policy 5.
S6	This simulation of the future includes 3 steps, first policy 2 will be activated, followed by policy 5 and then policy 6.
S7	This simulation of the future includes 4 steps, first policy 2 will be activated, followed by policy 5, policy 6 and finally policy 7.
S8	This simulation of the future includes 5 steps, first policy 2 will be activated, followed by policy 5, policy 6, policy 7 and finally policy 8.
S9	This simulation of the future includes 2 steps, first policy 4 will be activated, followed by policy 5.
S10	This simulation of the future includes 3 steps, first policy 4 will be activated, followed by policy 5 and then policy 6.
S11	This simulation of the future includes 4 steps, first policy 4 will be activated, followed by policy 5, policy 6 and finally policy 7.
S12	This simulation of the future includes 5 steps, first policy 4 will be activated, followed by policy 5, policy 6, policy 7 and finally policy 8.

A system dynamics model has been used to answer this question. The total 15 scenarios have been simulated in this model including all the feedback loops and stocks and flows representing the complex system of the electricity grid in Bali. After running the scenarios and analysing them with the help of the 4 targets a total of 5 plausible scenarios have been detected. The reference scenario, continuing the current trend of expanding the coal sector, Scenario 1 applying the natural gas policy, scenario 3 applying the renewable energy 2 policy, scenario 8+TE applying the renewable energy 1 policy with all of the additional policies and including an increase in technology by the solar PV sector and scenario 12+TE applying the hybrid policy with all of the additional policies and including an increase in technology by the solar PV sector and scenario are all among the final plausible scenarios.

- **Which set of policies (scenario) are most cost efficient in helping Bali to meet their targets? (RQ4)**
  Finally, since the cost of such a enormous project usually plays a big role the final scenarios have been compared to each other by means of total cost required for installation, operation and maintenance and fuel. The cheapest of the plausible scenarios is the reference scenario, followed by S1 the scenario implementing the natural gas policy.

However, this does not imply that the Ministry of Energy and Mineral Resources representative for Bali should follow the road map of scenario 2. In order, to determine the optimal scenario based on the model a trade off has been done on the final scenarios and this trade off results in scenario S12 + TE being the best road map to follow.

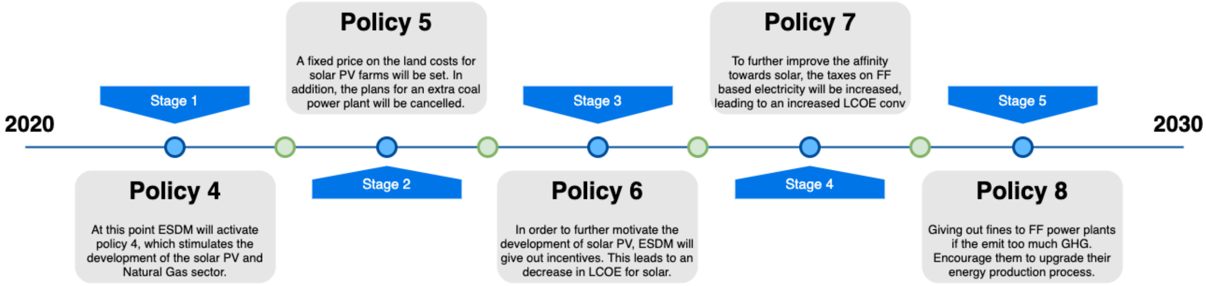


Figure 9.1: Final road map

Figure 9.1 depicts the final road map, which is proposed by the SD model. Starting at 2020, stating the order at which the different policies need to be applied to end up with the same/similar output as the predictions of the model. The blue dots represent a decision making point, where a new policy is being activated. The green dots represent check points at which the actual results should be compared to the models results, in order to prove if the real values are following the trend set by the model.

Actors

The final suggested road map in figure 9.1 also indicates when ESDM should try to work with which actor. In other words, depending on which policy has priority it is also important to know which actor they have to work with closest.

9.2. Conclusion

To conclude system dynamics has been a very use full tool to find a solution to the main research question. The literature review helped to find a knowledge gap, which set up the main research question and its follow up sub questions. The system analysis of the complex system ,representing the electricity network in Bali was of high importance to gather necessary information about all the exogenous and endogenous variables affecting it. From this analysis different mechanisms, feedback loops could be constructed, in order to help building the conceptual model. This lead to the final construction of the system dynamics model, which enable to analyse all the different scenarios with the impact of the different policies. Finally, in the result section these scenarios are filtered with the help of the different targets set by the Indonesian government which are identically taken over for Bali. From this analysis a total of 5 plausible scenarios representing the outcomes of 5 different futures. A trade off has then been introduced to determine which of these 5 is the best scenario leading to the pathway ESDM should follow.

However, the final scenario coming out as the best one is also the one including most policies and also requires an evolution of the solar photo voltaic cells over the next 10 years. Next to this, it has to be noted that the construction of the conceptual model and the system dynamics model includes a lot of assumptions and are therefore to be used with caution, however the sensitivity analysis proves that the change in input variables does not necessary lead to very different results.

9.3. Reflection

In this section a reflection on the work done will be taken, first on the data gathering process, than on the verification and validation methods, on the scenario development and policy implementation and finally on the use of system dynamics.

9.3.1. Data gathering

This proved to be one of the biggest challenges of this research, simply because none of the contacts gave a valid reply with use full data. Therefore, all of the data has been retrieved from online resources, which increases uncertainty, because not all of the papers or websites have been checked on their trustworthiness. However, for most of the values several online resources had similar data, which decreases the uncertainty again.

Nevertheless, it has to be noted that some data could not even be found in online resources and assumptions have been taken. For example, the current amount of solar panels in Bali is unknown. Therefore, this parameter has been used as input for the sensitivity analysis, in order to decrease uncertainty.

9.3.2. Verification and Validation

For the verification and validation the biggest challenges has been that there is no access to historical data, and therefore the model could not be validated with this. However, a different method has been found and the results show that the model is robust to parameter changes and behaves realistically under extreme conditions. Thus, it was possible to move forward with the study to generate useful insights from the model.

9.3.3. Scenario developments & Policy implementation

This part made use of the system dynamics model. This model was created with the purpose of generating different simulations of the future (scenarios), based on implementing different policies. This part has been quite straightforward once the system dynamics model was ready. Vensim proved to be a good fit for this analysis, because it enabled to analyse the behaviour of each key variable. This process was time consuming, but useful for generating insights. The process of generating insights is more of a cognitive work, by comprehending and interpreting the results and tracking back the reasons of these results.

9.3.4. System Dynamics

System dynamics has been as the main tool for analysing the development of the electricity network in Bali. Yet, of course it is possible to analyse it with different methods. Another method could have been agent-based modelling, which is becoming popular among the researchers studying energy transition. Agent-based modelling is a suitable platform for energy transition studies, because it enables the possibility to simulate the autonomous actions of actors, which could easily be the adoption in this case, and assess the effects as a system as a whole. However, agent-based simulation has an actor's perspective, the underlying structures, which are mechanisms in this case are not clear. In agent-based modelling it is more difficult to trace back the chain of events causing the results of the simulation. Besides, agent based modelling is focusing on the micro-level decision making structures of actors, however one of the aims of this study is to reveal the strategic set of actions from governmental perspective.

9.3.5. Replication

Looking back at the system dynamics model and at the methodology used for this research, it has to be noted that it will be quite difficult for somebody to replicate or reuse this research for another island. Even tough, the model is build in a way that the I could reuse it for another island with a few changes. However, this will not be as easy for somebody who never used the software Vensim before. In addition, there are quite some characteristics about this model which are only valid in the case of the electricity network in Bali. Nevertheless, even if it would only be used in the case of Bali, this could already help Indonesia to start a movement into the right direction instead of following the current trend of increasing the fossil fuel industry.

9.3.6. Academic reflection

Building this research took a lengthy process with various challenges in different steps. Before deciding on my research topic, I only had little knowledge on the energy transition on islands. And I can even say that I learned quite a lot during this time, however even after this research there is still a lot to learn about the ever changing energy system and electricity network of islands and in general.

I decided to do my research on this topic, after I had the opportunity to do my internship in Bali. I did not work on the energy transition during the 4 months I was located in Bali, however I realised that I didn't see any windmills, solar panels or geothermal power plants. This started to curb my interest on why an islands such as Bali with such an enormous renewable potential does not invest into renewable technologies. After conducting this research I am still convinced that Bali could follow the likes of Samsoe or El hierro and become one day a 100% renewable island, but I also realised that this process is a lot harder to accomplish once looking at the bigger picture. In my eyes, to improve this research and make it more likely to have an actual impact, it should first be reviewed with shareholders of the electricity network. Unlikely, most probably due to the covid situation, this was impossible to accomplish during the time of the research.

Design Thinking is an iterative process in which it is sought to understand the people, challenge assumptions, and redefine problems in an attempt to identify alternative strategies and solutions that might not be instantly apparent with initial level of understanding. Therefore, this research would clearly profit of an iteration or even if it is done with a different methodology to gain insights from a different perspective.

9.4. Suggestion for future work

This research should only be considered as the first step trying to stimulate the energy transition towards renewable energy in countries such as Indonesia. If there are any attempts to follow up on this research then I would highly suggest to do this in collaboration with some entity which has the power to access to the real data, since a lot of time as been lost during this research trying to contact authors of papers or shareholder of the electricity system in Bali.

The previous has only been a general recommendation to improve the work of this research, however also the model itself could be improved. For example, even if the technical potential of the 4 other renewable energy sources is too low to handle Bali's demand by them self, they could still be included in the model. Next to this, there is maybe a possibility to extract energy with the help of geothermal power plants while still respecting the Balinese culture.

Another suggestion for future work is to include the cost of repairs in the calculations of total cost, as this will lead to a more accurate final result. Next to this, the system dynamics model used for this research only considers the purchase of farmland for solar farms, however more and more farmers start renting their land for solar farms.

Another main contributor to an improved work would be to include the possibility of solar panels on rooftops bought by private owners. In addition to this, there are more and more decentralized power grids arising, which would be another interesting technology to include.

A final recommendation to the follow up work is to consider the possibility of off shore wind and solar farms, because this would raise the technical potential of both technologies by a lot.

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A

Appendix A - Sub models

In this appendix an overview of each sub model can be found. Each design of the sub models as they are constructed in the Vensim software is given here.

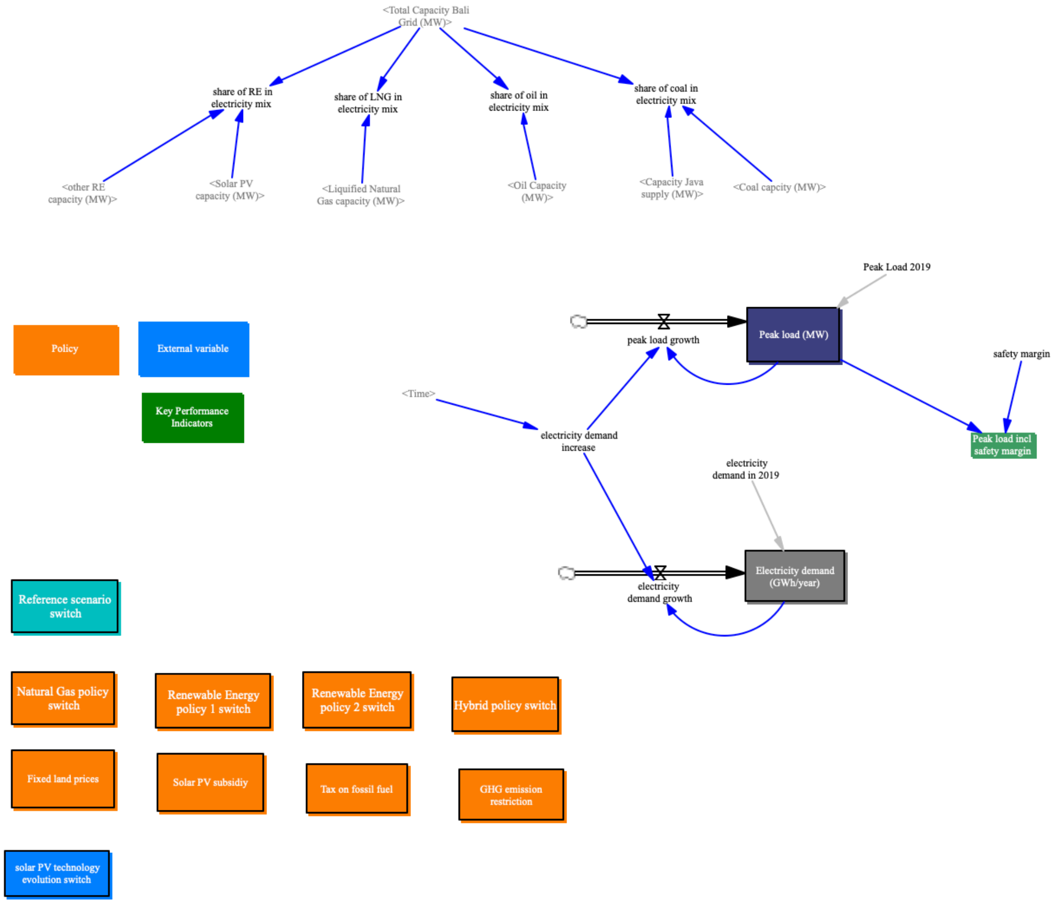

Figure A.1: Sub model 1 overview

In this sub model, the peak load demand is calculated based on the values from (RUPTL, 2019). In addition, this sub model includes a legend explaining the colors used in the model. On the top, the share of each electricity generation on the total mix is calculated at every time step.

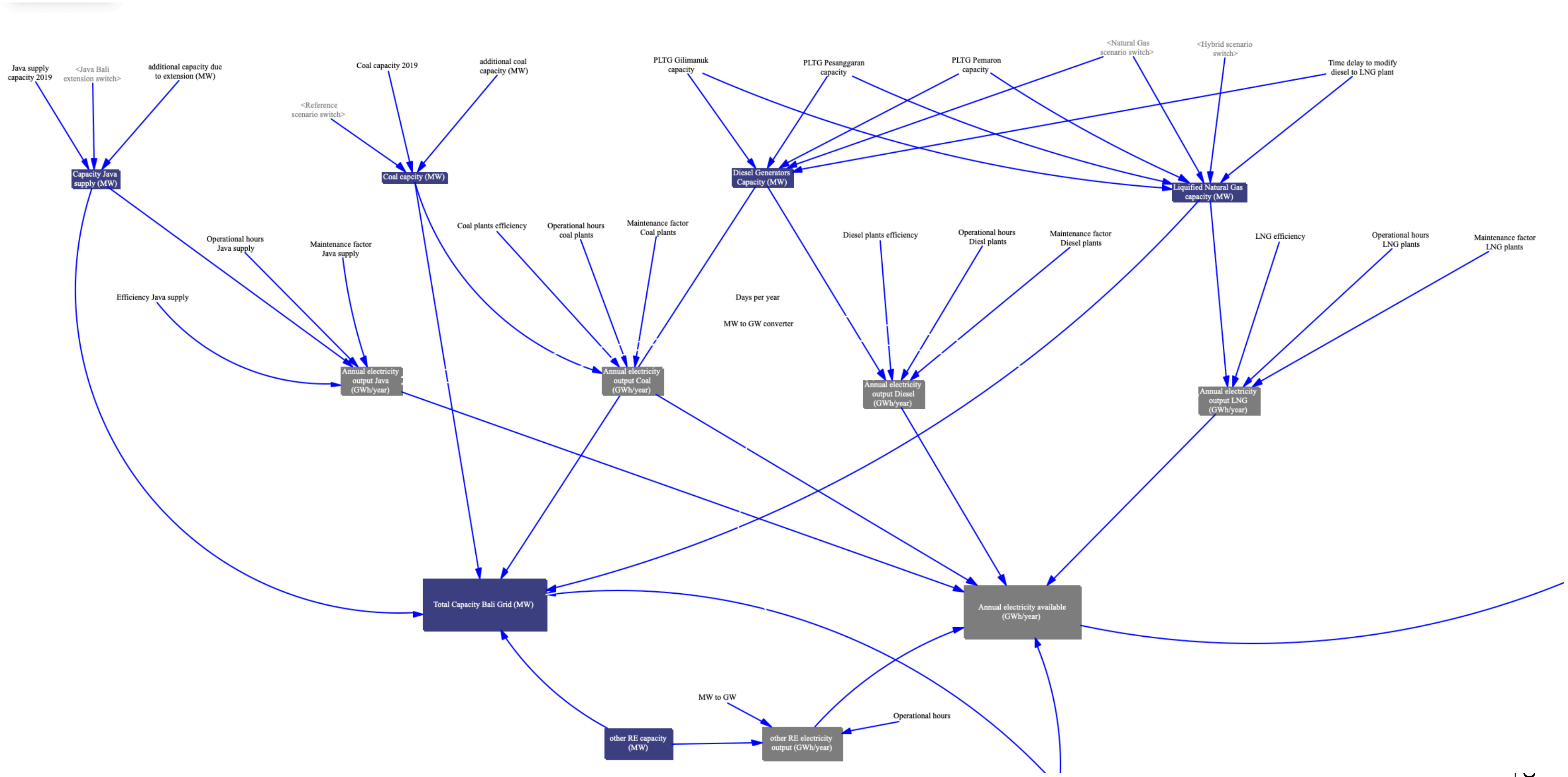

Figure A.2: Sub model 2 overview

Sub model 2 is shown in the figure above, this sub model simply calculated the capacity of the different fossil fuel sources. One can see that the oil and LNG parts are interconnected at the top level, this is due to the fact that in certain scenarios the oil based power plants are rebuild into liquefied gas powered plants. On the bottom of this overview the capacity from other renewable is included, this value is nearly neglectable. However it is added because this is one of the parts which can be further researched on.

Sub model 3 concerns the calculation of the LCOE for the different energy sources. In this overview, the affinity towards solar PV is calculated by comparing the LCOE for solar PV to the LCOE of conventional methods. This affinity is then linked to the growth rate of the solar PV sector.

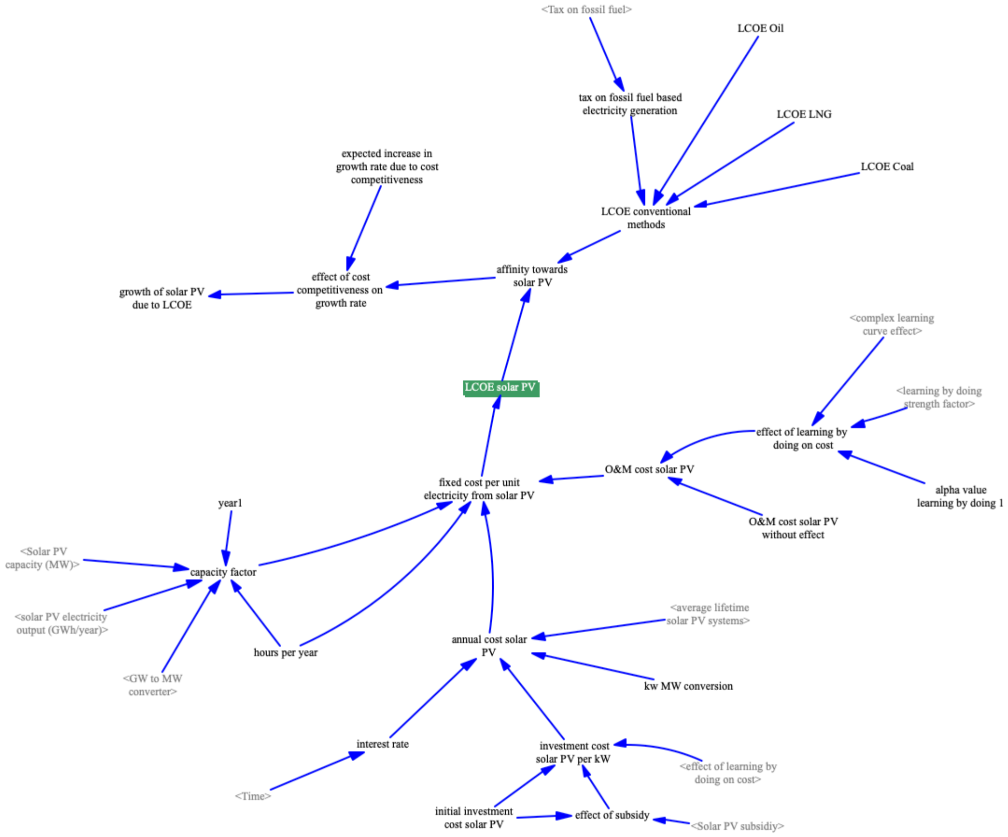

Figure A.3: Sub model 3 overview

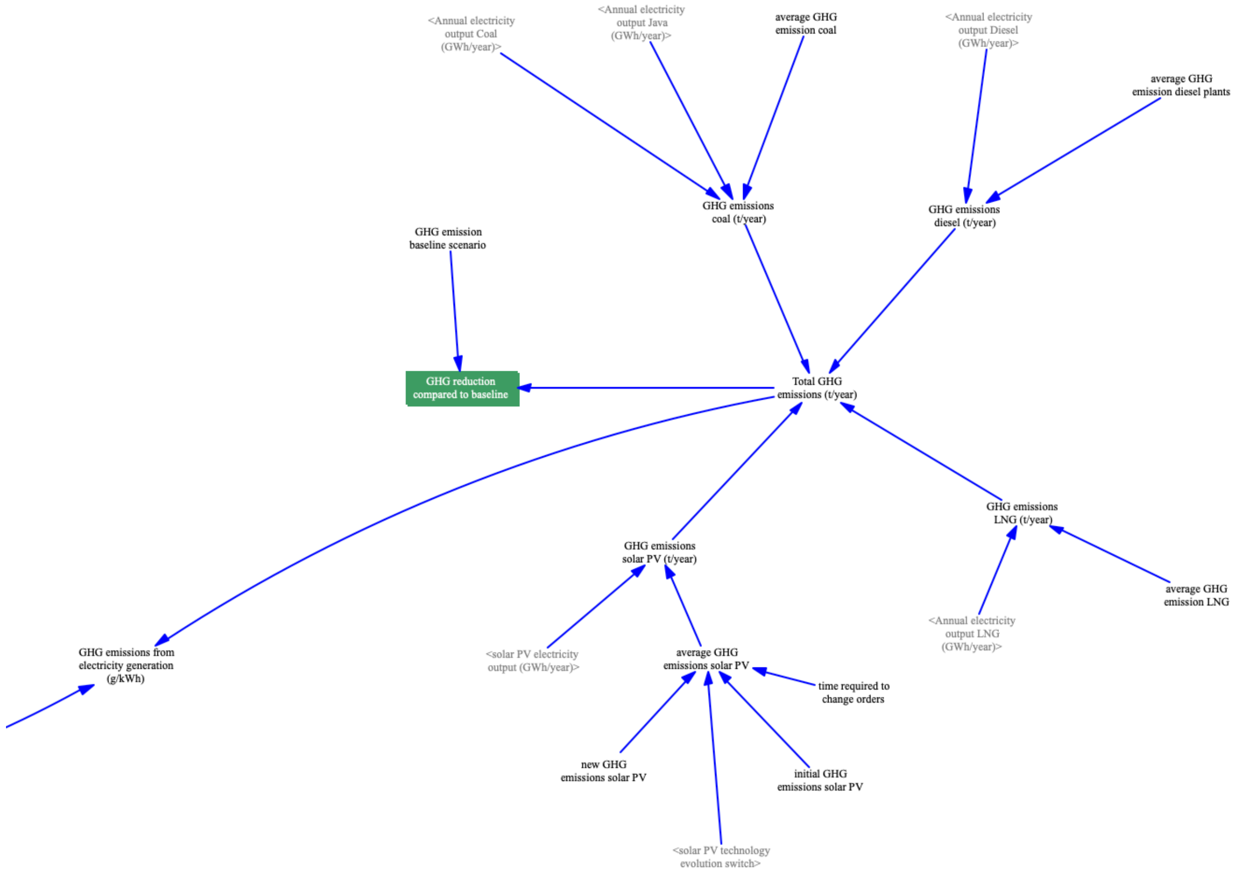

Figure A.4: Sub model 4 overview

In this sub model the total greenhouse gas emissions for generating electricity is calculated per energy source. The total of these GHG emissions is then compared to the emissions of the reference scenario, in order to determine whether a scenario achieves the 11% reduction. In addition, this sub model also calculates the efficiency, namely the gram of CO2 equivalent emissions per kWh of electricity production.

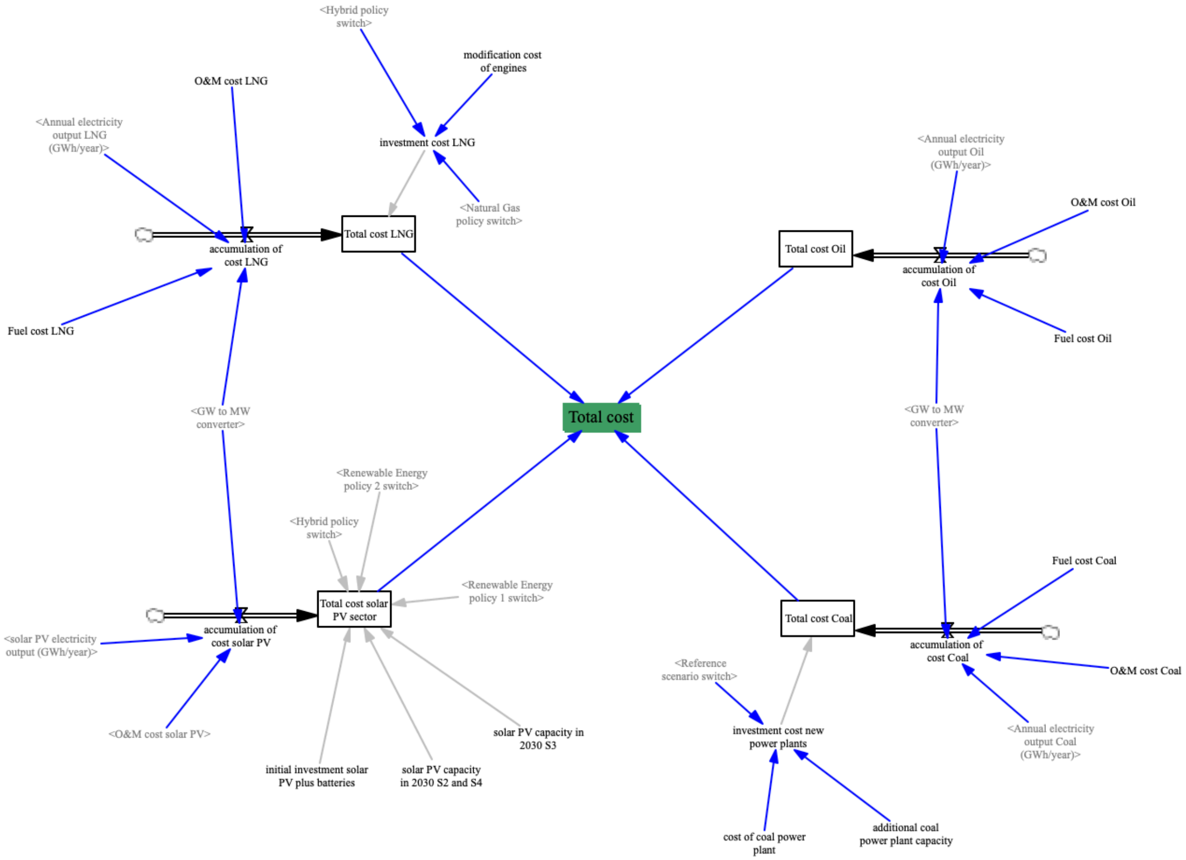

Figure A.5: Sub model 5 overview

At last, the final sub model calculates the total cost of each scenario by taking the total cost to manufacture the power plants and adding up each year the fuel, operational and maintenance costs.

B

Appendix B - All equations SD Model

Table B.1 includes all the equations and units of each variable employed in the system dynamics model.

Table B.1: Variable names, equation and units used in system dynamics model.

Variable name	Equation	Unit
share of RE in electricity mix	(”Solar PV capacity”+”other RE capacity ”)/”Total Capacity Bali Grid”	Dmnl
share of LNG in electricity mix	”Liquified Natural Gas capacity ”/”Total Capacity Bali Grid”	Dmnl
share of oil in electricity mix	”Diesel Generators Capacity”/”Total Capacity Bali Grid ”	Dmnl
share of coal in electricity mix	(”Capacity Java supply”+”Coal capcity ”)/”Total Capacity Bali Grid ”	Dmnl
Peak Load 2019	996.41	MW
electricity demand in 2019	4993	GWh/year
Peak load	INTEG (peak load growth)	MW
Electricity demand	INTEG (electricity demand growth)	GWh/year
electricity demand growth	”Electricity demand”*electricity demand increase	GWh/year/year
peak load growth	electricity demand increase*”Peak load”	MW/year
electricity demand increase	Lookup with Time	Dmnl/year
Java supply capacity 2019	340	MW
additional capacity due to extension	1600	MW
Coal capacity 2019	426	MW
additional coal capacity	330	MW
Time delay to modify diesel to LNG plant	1	year
Capacity Java supply	Java supply capacity 2019 + STEP (” additional capacity due to extension” , 2025) * Java Bali extension switch	MW

Coal capcity	Coal capacity 2019+STEP(”additional coal capacity ” , 2022)+(STEP(”additional coal capacity ” , 2024))*Reference scenario switch	MW
Oil Capacity	(PLTG Gilimanuk capacity + PLTG Pemaron capacity + PLTG Pesanggaran capacity) -(Natural Gas scenario switch)*(STEP(PLTG Pemaron capacity , 2021) +STEP (PLTG Gilimanuk capacity , 2021+Time delay to modify diesel to LNG plant) +STEP(PLTG Pesanggaran capacity, 2021+2*Time delay to modify diesel to LNG plant))	MW
PLTG Gilimanuk capacity	133.8	MW
PLTG Pesanggaran capacity	200	MW
PLTG Pemaron capacity	97.6	MW
Liquified Natural Gas capacity	(STEP(PLTG Pemaron capacity , 2021+Time delay to modify diesel to LNG plant) +STEP(PLTG Gilimanuk capacity , 2021+Time delay to modify diesel to LNG plant*2) +STEP(PLTG Pesanggaran capacity , 2021+Time delay to modify diesel to LNG plant*3)*(1-Hybrid scenario switch))*Natural Gas scenario switch	MW
Coal plants efficiency	0.8	Dmnl
Operational hours coal plants	20	h/day
Maintenance factor Coal	0.8	Dmnl
Diesel plants efficiency	0.6	Dmnl
Operational hours Oil plants	20	h/day
Maintenance factor Oil plants	0.8	Dmnl
LNG efficiency	0.8	Dmnl
Operational hours LNG plants	20	h/day
Maintenance factor LNG plants	0.7	Dmnl
Days per year	365	day/year
MW to GW converter	1/1000	GW/MW
Annual electricity output Java	”Capacity Java supply ”*Days per year * Efficiency Java supply * Maintenance factor Java supply * Operational hours Java supply * MW to GW converter	GWh/year
Annual electricity output Coal	”Coal capcity” * Coal plants efficiency*Days per year * Maintenance factor Coal plants * Operational hours coal plants * MW to GW converter	GWh/year
Annual electricity output Oil	”Oil Capacity” * Days per year*Diesel plants efficiency * Maintenance factor Oil plants * Operational hours Diesl plants * MW to GW converter	GWh/year
Annual electricity output LNG	Days per year * ”Liquified Natural Gas capacity” * LNG efficiency * Maintenance factor LNG plants * Operational hours LNG plants * MW to GW converter	GWh/year
Total Capacity Bali Grid	”Capacity Java supply” + ”Oil Capacity ” + ”Coal capcity” + ”Solar PV capacity” + ”Liquified Natural Gas capacity” + ”other RE capacity”	MW
Annual electricity available	”Annual electricity output Coal ” + ”Annual electricity output Oil ” + ”Annual electricity output Java” + ”solar PV electricity output” + ”Annual electricity output LNG” + ”other RE electricity output”	GWh/year

other RE capacity	50	MW
other RE electricity output	”other RE capacity”*MW to GW*Operational hours	GWh/year
GHG emissions from electricity generation	(”Total GHG emissions ” / ”Annual electricity available”)	tonne/GWh
GHG emission baseline scenario	9.20557e+06 + STEP (2.60557e+06 , 2022) + STEP (2.60561e+06 , 2024)	tonne/year
GHG reduction compared to baseline	((GHG emission baseline scenario - ”Total GHG emissions ”) / GHG emission baseline scenario) * 100	%
average GHG emission coal	1690	tonne/GWh
GHG emissions coal	(”Annual electricity output Coal ” + ”Annual electricity output Java ”) * average GHG emission coal	tonne/year
average GHG emission diesel plants	1200	tonne/GWh
GHG emissions oil	”Annual electricity output Oil (GWh/year)” * average GHG emission diesel plants	tonne/year
average GHG emission LNG	640	GWh/year
GHG emissions LNG	”Annual electricity output LNG (GWh/year)” * average GHG emission LNG	tonne/year
initial GHG emissions solar PV	73	tonne/GWh
new GHG emissions solar PV	45	tonne/GWh
time required to change orders	2	years
average GHG emissions solar PV	initial GHG emissions solar PV - RAMP ((initial GHG emissions solar PV + new GHG emissions solar PV) / time required to change orders , 2020 , 2024) * solar PV technology evolution switch	tonne/GWh
GHG emissions solar PV	average GHG emissions solar PV * ”solar PV electricity output ”	tonne/year
growth rate solar PV	IF THEN ELSE (average expected growth rate by ESDM = 0 , growth rate stimulated by ESDM to meet target , average expected growth rate by ESDM) * effect of learning by doing on growth rate * effect of price increase on growth rate + growth of solar PV due to LCOE	Dmnl/year
effect of learning by doing on growth rate	(impact learning by doing) to the power of (strength of learning by doing 1)	Dmnl
strength of learning by doing 1	LOG(alpha value learning by doing 1 , 2)	Dmnl
alpha value learning by doing 1	1.04	Dmnl
impact learning by doing	learning by doing experience/initial solar PV units	Dmnl
learning by doing experience	INTEG (experience rate)	units
experience rate	decomission of solar PV + solar PV systems ready to use	units/year
initial solar PV units	80,000	units
growth rate stimulated by ESDM to meet target	Lookup with Time	Dmnl/year
average expected growth rate by ESDM	average yearly growth rate by ESDM * Renewable Energy scenario 2 switch	Dmnl/year

average yearly growth rate by ESDM	0.2	Dmnl/year
effect of price increase on growth rate	IF THEN ELSE(Fixed land prices = 1 , Fixed land prices , 1 - price increase of land in percentage)	Dmnl
price increase of land	(”ratio occupied area / available area”) to the power of strength of price increase	Dmnl
strength of price increase	0.6	Dmnl
”ratio occupied area / available area”	Total area required for solar PV / ”Total area available for solar PV”	Dmnl
Total area available for solar PV	”Total potential solar PV” / Solar PV capacity to area converter	m2
Solar PV capacity to area converter	180*	kWh/m2/year
Total potential solar PV	9.8738e + 10	kWh/year
Total area required for solar PV	average size of solar PV unit * solar PV units + average size of solar PV unit * solar PV under construction	m2
average size of solar PV unit	1.8	m2/unit
Total surface area PV panels	solar PV units * average size of solar PV unit	m2
increase in solar PV systems	(solar PV units + solar PV under construction) * growth rate solar PV	units/year
solar PV under construction	INTEG (increase in solar PV systems-solar PV systems ready to use)	units
initial solar PV under construction	1,000	units
solar PV systems ready to use	solar PV under construction/average delay for solar PV construction	units/year
average delay for solar PV construction	0.5	year
solar PV units	INTEG (solar PV systems ready to use-decommission of solar PV)	units
average lifetime solar PV systems	25	year
decomission of solar PV	solar PV units / average lifetime solar PV systems	units/year
average annual solar radiation	1,600	kWh/m2/year
Performance ratio	0.75	Dmnl
solar PV efficiency	0.17 + RAMP(0.015 , 2020 , 2050)*solar PV technology evolution switch	Dmnl
Solar PV area to capacity converter	average annual solar radiation*Performance ratio*solar PV efficiency	kWh/m2/year
solar PV electricity output	(Solar PV area to capacity converter*Total surface area PV panels*kWh to GWh)*Renewable Energy scenario switch	GWh/year
kWh to GWh	1e-06	GWh/kWh
Solar PV capacity	”solar PV electricity output (GWh/year)”/average sun hours per year*GW to MW converter	MW
GW to MW converter	1,000	MW/GW
average sun hours per year	2,250	h/year
monetary bonus for GHG reduction	IF THEN ELSE(GHG reduction compared to baseline>11 , 0.1 , 0)	Dmnl
growth of solar PV due to LCOE	IF THEN ELSE(affinity towards solar PV > 0 , 0.1 , 0) + monetary bonus for GHG reduction	Dmnl

affinity towards solar PV	LCOE conventional methods - LCOE solar PV	Dmnl
LCOE conventional methods	(LCOE Coal+LCOE LNG+LCOE Oil)/3 + (LCOE Coal+LCOE LNG+LCOE Oil)/3 * tax on fossil fuel based electricity generation	USD/MWh
LCOE Coal	55	USD/MWh
LCOE Oil	110	USD/MWh
LCOE LNG	80	USD/MWh
tax on fossil fuel based electricity generation	0.1*Tax on fossil fuel	Dmnl
LCOE solar PV	fixed cost per unit electricity from solar PV	USD/MWh
fixed cost per unit electricity from solar PV	(annual cost solar PV/(hours per year*capacity factor)) + ”O&M cost solar PV”	USD/MWh
capacity factor	0.15	Dmnl
hours per year	8,760	hours
annual cost solar PV	(investment cost solar PV per kW * interest rate * (1 + interest rate) to the power of (average lifetime solar PV systems)) / ((1 + interest rate) to the power of (average lifetime solar PV systems) -1) * kw MW conversion	USD/MW
interest rate	Lookup with Time	Dmnl
investment cost solar PV per kW	3,000 + 1,950 * (1 - effect of learning by doing on cost)	USD/kW
O&M cost solar PV	2.283 + 2.283 * (1 - effect of learning by doing on cost)	USD/MWh
effect of learning by doing on cost	impact learning by doing to the power of (strength of learning by doing) 2	Dmnl
strength of learning by doing 2	LOG(alpha value learning by doing 2 , 2)	Dmnl
alpha value learning by doing 2	1.06	Dmnl

C

Appendix C - Extreme conditions test

In this appendix the results of the extreme condition test are given, along with the concerned hypothesis.

- *If LCOE of solar PV is extremely high compared to conventional alternatives, there will not be less solar PV capacity.*

To test this hypothesis, the LCOE for solar PV in scenario 3 has been multiplied by 3 and compared to the normal scenario 3.

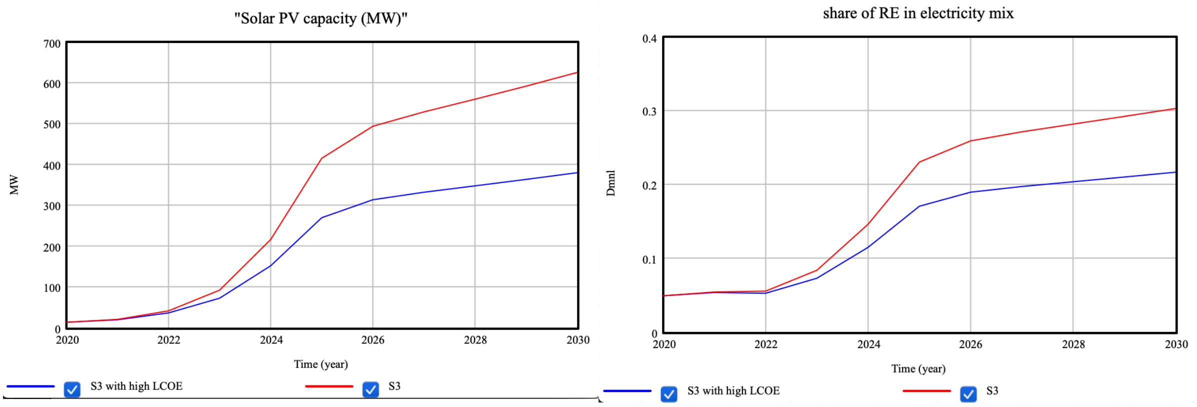

Figure C.1: Solar PV capacity (left) and RE share (right) with elevated LCOE of solar PV

- *If LCOE of solar PV is extremely low compared to conventional alternatives, there will be an increase in solar PV capacity.*

To test this hypothesis, the LCOE for solar PV in scenario 3 has been divided by 3 and compared to the normal scenario 3.

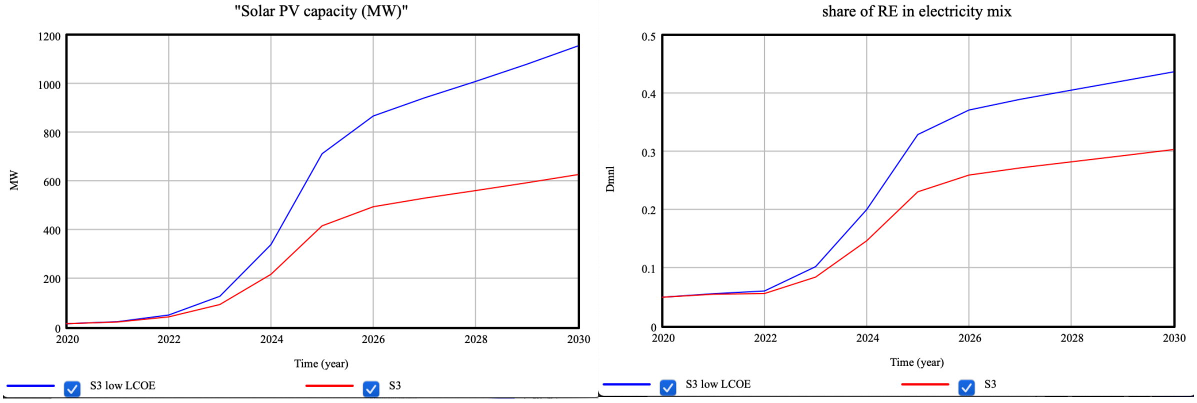

Figure C.2: Solar PV capacity (left) and RE share (right) with decreased LCOE of solar PV

- *If the land price for solar farms is increasing more rapidly, the total capacity of solar PV will decrease drastically.*

For the testing of this hypothesis, the strength of the land price increase parameter had been multiplied by 3 to simulate an increasing price of possible land for solar farms.

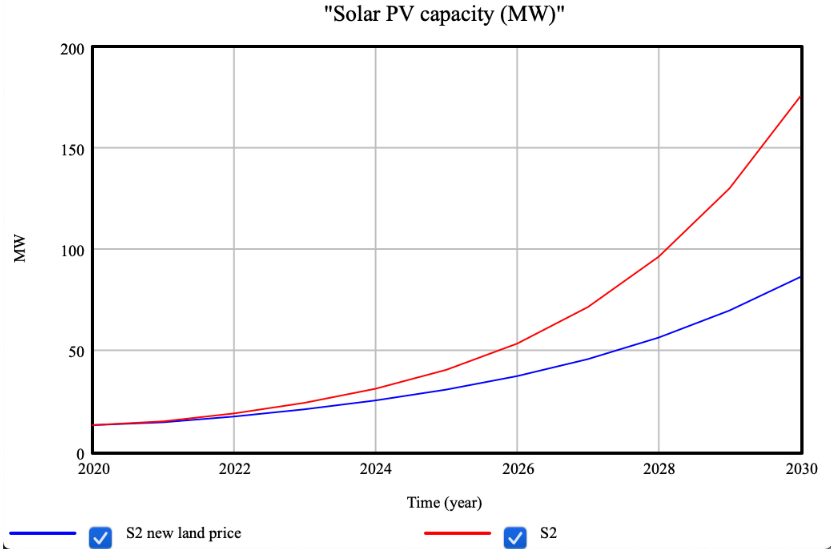

Figure C.3: Solar PV capacity with increased land cost

- *If the average lifetime of solar panels is decreased, the total capacity of solar PV will decrease.*
- *If the average lifetime of solar panels is increased, the total capacity of solar PV will increase.*

Quite straightforwardly, the average lifetime of solar panels has been divided and multiplied by 3 to verify these hypothesis.

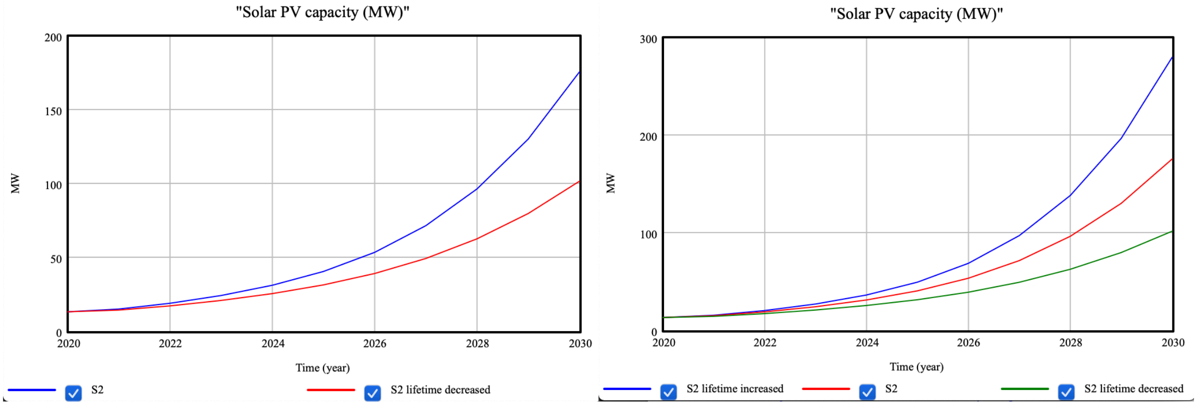

Figure C.4: Solar PV capacity with decreased (left) and increased (right) solar panel lifetime

D

Appendix D - Sensitivity Analysis

In this appendix, the resulting graphs following the sensitivity analysis from the verification and validation chapter are given with a small description. In addition to this, the input variables used per graph are also available in this appendix.

Solar PV growth rate

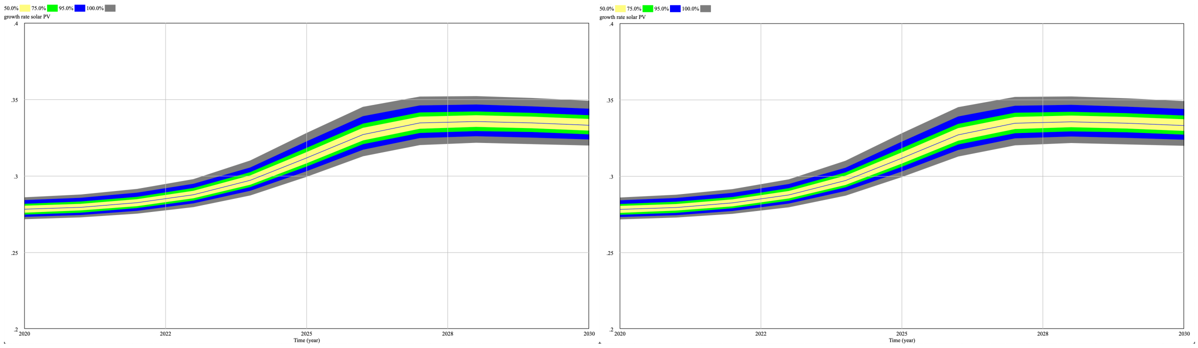

Figure D.1: Solar PV growth rate scenario 2 (left) and 4 (right)

share of RE in electricity mix

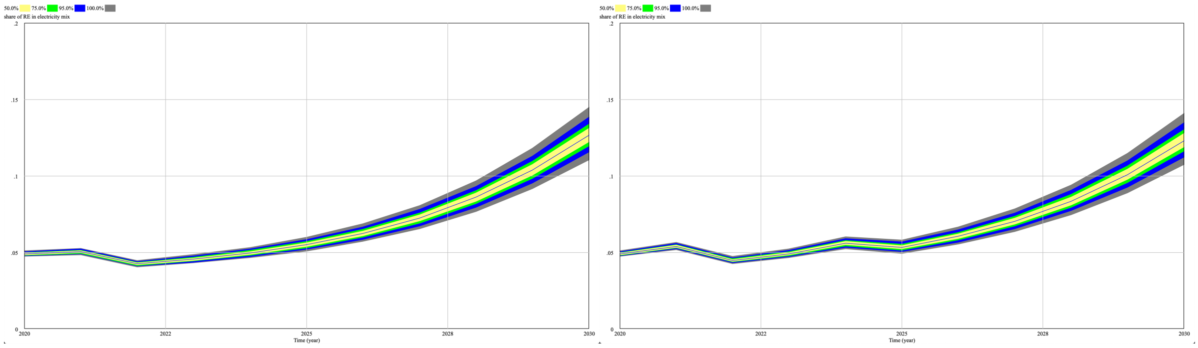

Figure D.2: share of RE in electricity mix scenario 2 (left) and 4 (right)

Total capacity of the Grid

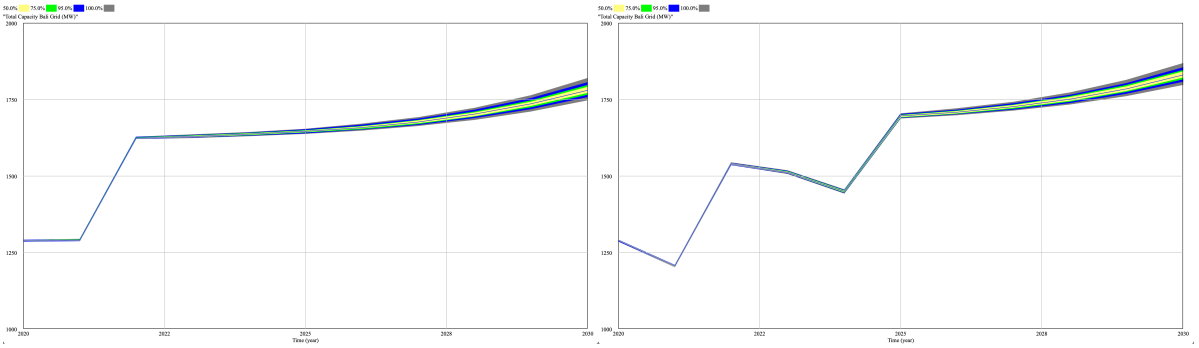

Figure D.3: Total grid capacity scenario 2 (left) and 4 (right)

LCOE solar PV

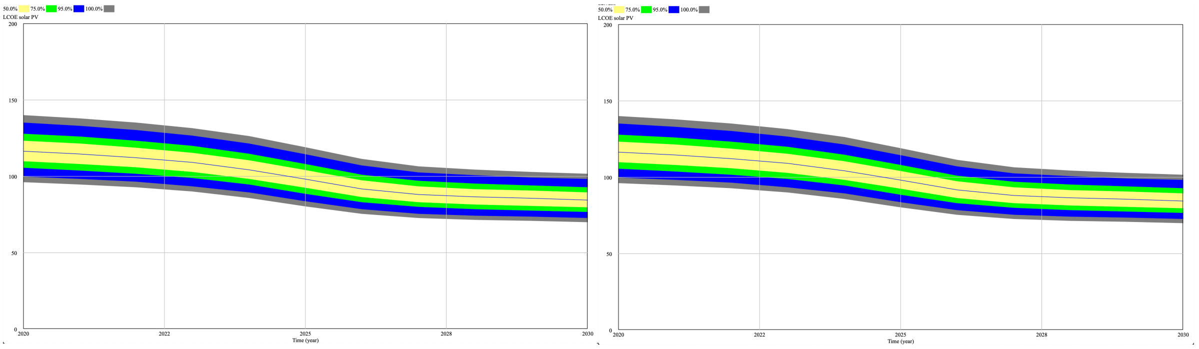

Figure D.4: LCOE solar PV scenario 2 (left) and 4 (right)

E

Appendix E - Assumptions

This appendix includes a list of all of the assumptions used while setting up the system dynamics model.

- Grids capacity should be 10% above peak load demand, to cover for unexpected events. For example if one power plant need to shut down for maintenance or if it is destroyed by a natural disaster.
- In the Paris agreement Indonesia states it will decrease its GHG emissions from the energy sector by 11%. It is assumed that this also counts for an 11% in the electricity sector.
- Development of Geothermal energy in Bali is assumed to be neglected, due to the sacred essence of volcanoes in their culture.
- No development of other RE in the model, since their impact is neglectable compared to solar PV.
- It is assumed that the electricity retrieved from the Java underwater cables is all powered by coal fired plants.
- The 8 policies in the analysis are the only ones acting on the system.
- The development of the fossil fuel sector is expressed in a step function.
- Operational hours of the different fossil fuel powered plants are all the same.
- The time delay to modify the oil powered generators to LNG powered generators is assumed to be 14 months.
- Maintenance factor of the oil and LNG powered power plants are equal.
- Efficiency of the oil and LNG powered power plants are identical.
- Average solar radiation is assumed to be the same every year.
- Initial solar PV under construction is assumed to be 1,000.
- Initial solar PV units in Bali is assumed to be 80,000, because this value equals the MW retrieved from Creutzig et al., 2017.
- It is assumed that the GHG emission related to the manufacturing of the solar Panels is added to the total GHG emission of Bali, even though these panels will most likely not be build in Bali.
- It is assumed that the coal and oil powered plants are currently not producing electricity in the most efficient way, so that improvements are possible.

F

Appendix F - Sensitivity Trade off

In this appendix the sensitivity analysis of the trade off table concerning the final scenarios is given. A total of 6 different tables including different weight distributions are shown.

Table F.1: Weight factors with equal value

Scenarios	T1 (*1)	T2 (*1)	T3 (*1)	T4 (*1)	Final score
REF	7	0	0	9	16
S1	8	8	4	8	28
S3	10	10	6	3	29
S8 + TE	9	6	8	7	30
S12 + TE	9	10	10	6	35

Table F.2: Importance on cost

Scenarios	T1 (*1)	T2 (*1)	T3 (*1)	T4 (*5)	Final score
REF	7	0	0	9	52
S1	8	8	4	8	60
S3	10	10	6	3	41
S8 + TE	9	6	8	7	58
S12 + TE	9	10	10	6	59

Table F.3: Importance on GHG emissions

Scenarios	T1 (*1)	T2 (*1)	T3 (*5)	T4 (*1)	Final score
REF	7	0	0	9	16
S1	8	8	4	8	44
S3	10	10	6	3	53
S8 + TE	9	6	8	7	62
S12 + TE	9	10	10	6	75

Table F.4: Importance on electricity mix diversification

Scenarios	T1 (*1)	T2 (*5)	T3 (*1)	T4 (*1)	Final score
REF	7	0	0	9	16
S1	8	8	4	8	60
S3	10	10	6	3	69
S8 + TE	9	6	8	7	54
S12 + TE	9	10	10	6	75

Table F.5: Importance on grid capacity

Scenarios	T1 (*5)	T2 (*1)	T3 (*1)	T4 (*1)	Final score
REF	7	0	0	9	44
S1	8	8	4	8	60
S3	10	10	6	3	69
S8 + TE	9	6	8	7	66
S12 + TE	9	10	10	6	71

Table F.6: Importance on cost and GHG emissions

Scenarios	T1 (*1)	T2 (*1)	T3 (*5)	T4 (*5)	Final score
REF	7	0	0	9	52
S1	8	8	4	8	76
S3	10	10	6	3	65
S8 + TE	9	6	8	7	90
S12 + TE	9	10	10	6	99