ASSESSMENT OF THE TECHNICAL AND ECONOMIC POTENTIAL OF UTILITY-SCALE SOLAR PV IN INDONESIA AND THE EFFECTS OF POLICY INTERVENTIONS

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EXECUTIVE SUMMARY

Indonesia has set ambitious targets to increase renewable energy in the energy and electricity mix for 2025 and 2050. Solar photovoltaic (PV) is one of the renewable energy technology types that could play an important role in this transition, given the high resource potential compared to other countries and the global declining costs. The Ministry of Energy and Mineral Resource (MoEMR) has recognized the potential of solar energy and has expressed the intention to increase the share in the electricity mix (which currently is less than 1%) by focusing primarily on rooftop solar PV systems. However, utility-scale solar PV power plants could also play an important role, given the economies of scale advantages relative to rooftop systems. Unfortunately, a financial roadblock can be identified for the further development of utility-scale solar PV: the maximum allowed electricity prices that state electricity company Perusahaan Listrik Negara (PLN) pays for electricity produced by a solar power plant, are often lower than the levelized cost of electricity (LCOE). This creates an financially unattractive situation.

This situation calls for insight into the economic potential of utility-scale solar PV and how this can be increased. However, no studies could be found that (1) look at how policies interventions can help to overcome the financial barrier and increase the economic potential and (2) assess the economic potential quantitatively not just in terms of LCOE but also in terms of the potential capacity and electricity generation given the maximum electricity price regulations that are in place. This leads to a knowledge gap which is addressed in this thesis. The main research question is:

What is the technical and economic potential of utility-scale solar PV in Indonesia and what can be recommended in the policy context to increase the economic viability of utility-scale solar PV?

This thesis addresses this question by first assessing the technical and economic potentials of utility-scale solar PV using a geographic information system (GIS)-based modeling approach. A GIS-based modeling approach is widely used in literature to asses potentials of renewable energy technologies and have the benefits of being able to combine, edit and analyze geo-spatial data-sets, which is desirable to asses the potentials on a detailed level (five km² resolution in this research). The second part of the thesis focuses on possible policy interventions and their effect on the economic potential an other relevant system factors, namely social acceptance and domestic solar PV industry growth. This is done following a basic multi-criteria analysis (MCA) method.

The technical potential assessment resulted in an estimation of the potential capacity on a national level between 9 and 53 TW_p. This corresponds with a range in potential electricity generation between 12 and 72 PWh/year. The estimations of the economic potentials are: a potential capacity between 2 and 9 TW_p and a potential electricity generation between 2 and 12 PWh/year. The LCOE is estimated to range between 7,6 and 25,7 US$/KWh, taking into account local parameters such as system output and grid connection costs. Although the economic potential is clearly much smaller than the technical potential, it can still cover the total electricity demand in 2018 in Indonesia of 0,2 PWh/year. The economic potential is estimated to be 10 to 60 times higher. This emphasises that utility-scale solar PV can be a competitive form of renewable energy against fossil fuels in Indonesia.

When the results of the economic potential are studies on a provincial level, a different picture is painted. The potential varies significantly per province: in 12 out of

the 33 provinces, no economic potential was found given the definition and cost estimations used in this research. Among those 12 provinces are some of the provinces with the highest electricity demand. Therefore, it is argued that policy interventions are needed to increase the economic viability of utility-scale solar PV, especially in the provinces where that is needed the most.

After the assessment of the technical and economic potential, the policy analysis was performed. Four policy intervention were identified and analyzed that are expected to increase the economic viability of utility-scale solar PV and could help to overcome the financial barrier: (1) a capacity-based subsidy of 30% of the capital expenditures CAPEX of a new power plant, (2) a price-based subsidy varying in height per province based on current maximum allowed power purchase agreement PPA tariffs, (3) a carbon tax of 35,9 US$ per tonne of carbon dioxide and (4) the lifting of the local content requirement (LCR) regulations that are currently in place. The performance of the identified policy interventions and the base case (business as usual) are explored with four criteria at the basis. The criteria are: (1) economic potential expressed in potential electricity generation [TWh/year], (2) ability to meet provincial demand expressed in number of provinces in which the number of provinces where the economic potential is equal to or larger than 31% of the estimated electricity demand in 2050, (3) domestic industry growth and (5) social acceptance. The last two criteria are assessed qualitatively. The reference point of 31% of the estimated electricity demand in 2050 used in the second criterion is based on the target of the MoEMR to achieve a share of 31% in the electricity mix by 2050.

Several relevant conclusions can be drawn based on the results of the policy analysis. First of all, 'business as usual', is not likely to get very far in overcoming the financial barrier that utility-scale solar PV faces in some provinces. Furthermore, it disregards the potential that utility-scale solar PV has in the Indonesian energy transition, given the relatively low LCOE values compared to other renewable energy technologies. The other analyzed policy options are all effective in achieving more economic potential on both a national and provincial level than in the base case. The policy that stood out of the crowd was the price-based subsidy because of its effectiveness in increasing the economic viability of utility-scale solar PV power plants in the provinces where that is most desirable. The LCR policy is the policy option with the least positive effects. Also, push-back from society can be expected. Overall, it is recommended for policy makers to look further into policy strategies that combine multiple policy interventions and to differentiate per province to be able to provide support where that is needed the most. A starting point for the development of a policy strategy can be the found gaps between the current maximum allowed PPA tariffs and the range of needed tariffs for the economic potential to be equal to or higher than 31% of the estimated electricity demand in 2050. A policy strategy can be further designed and optimized with as an end goal to fill the gaps in the provinces where that is needed. An example could be a combination of a carbon tax, price-based subsidy and an auction scheme, which can together be effective in closing the gap between the maximum allowed tariffs and needed tariffs.

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ACRONYMS

A_i available area size within grid cell i

APAMSI Indonesian Solar Module Manufacturers Association

BPP Biaya Pokok Penyediaan

BPS Badan Pusat Statistik

$CAPEX_{excluding\ GCC}$ capital expenditures, excluding grid connections costs

CAPEX capital expenditures

CI average carbon intensity of electricity in Indonesia

C_{panel} peak power generation capacity per solar PV module

CRF capital recovery factor

CT carbon tax

D distance to nearest connection point

DF connection distance factor

DNI direct normal irradiation

$EG_{average}$ average annual electricity generation

E_i technical potential electricity generation in the available area in grid cell i

$E_{EP,\ total}$ total potential electricity generation in Indonesia (economic potential)

$E_{TP,\ total}$ total potential electricity generation in Indonesia (technical potential)

GCC grid connection costs

GHI global horizontal irradiation

GIS geographical information system

GW_p gigawatt peak

IFC International Finance Cooperation

IPP independent power producer

IRENA International Renewable Energy Agency

ISSD International Institute for Sustainable Development

KPI's key performance indicators

KWh kilowatt hour

KW_p kilowatt peak

L land requirement per installed MW_p solar PV

LCOE levelized cost of electricity

LCR local content requirement

T solar PV system lifetime

MCA multi-criteria analysis

MoEF Ministry of Environment and Forestry

MoEMR Ministry of Energy and Mineral Resources

MoF Ministry of Finance

MoI Ministry of Industry

MWh megawatt hour

MWp megawatt peak

NEP National Energy Policy

OPEX operational expenditure

$\mathbf{P_i}$ technical potential capacity in the available area in grid cell i

PLN Perusahaan Listrik Negara

PPA power purchase agreement

$\mathbf{P_{EP,\,total}}$ total potential capacity in Indonesia (economic potential)

$\mathbf{P_{TP,\,total}}$ total potential capacity in Indonesia (technical potential)

PV photo-voltaic

PVout photo-voltaic power output

PWh petawatt hour

r discount rate

RUEN National Energy General Plan of Indonesia

SDR system degradation rate

TWh terawatt hour

$\mathbf{TW_p}$ terawatt peak

$\mathbf{W_p}$ watt peak

1 INTRODUCTION

In this chapter, the topic of this thesis is introduced. First, a general introduction on the status of renewable energy in Indonesia is given. Then, the role of solar energy is further discussed and subsequently the roadblocks to the development of solar energy. Thereafter, the concept of economic potential is described and research related to this is discussed, leading to a knowledge gap, problem statement and research objectives that are central in this research. Then, the research questions are presented, and the research approach is presented and visualized by a research flow diagram. Finally, the outline of the thesis is given.

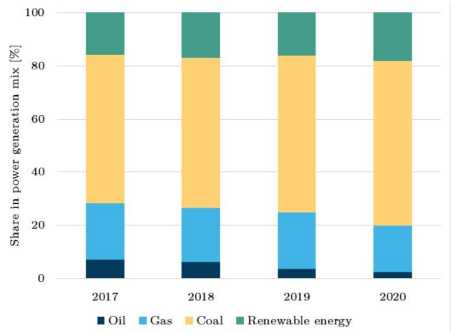
1.1 RENEWABLE ENERGY IN INDONESIA

Indonesia is one of the world´s fastest-growing countries in terms of energy consumption. Within the members of the Association of Southeast Asian Nations, Indonesia is the largest energy user. The country accounted for almost 40% of the total energy use in 2017 [IRENA, 2017]. To limit greenhouse gas emissions, Indonesia has set ambitious targets to increase the use of renewable energy technologies. In the National Energy Policy (NEP) of 2014, the government has set renewable energy targets and expresses that it wants renewable energy technologies to account for 23% of the energy mix in 2025, and 31% in 2050 [Republic of Indonesia, 2014]. The 2025 goal for the share of renewable energy in the power generation mix in 2025 is 25%. The Ministry of Energy and Mineral Resources (MoEMR) is mainly responsible for these goals. Figure 1.2a shows the fuel mix for power generation for the period of 2017 until 2020. As visible, coal is currently the dominating fuel for power generation and its share it still increasing. A growth of renewable energy is also present, but seems to be more stagnant. The share of renewable energy technologies was about 18% in 2020.

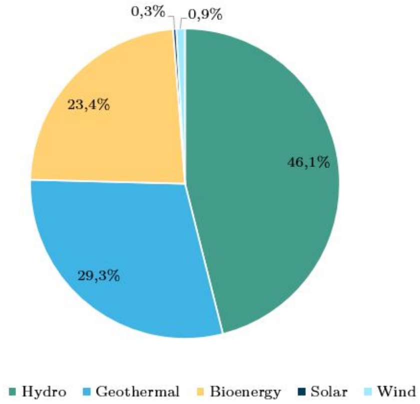
1.2 ROLE OF UTILITY-SCALE SOLAR PV ENERGY

Figure 1.2b shows which types of renewable energy make up the share of 18% in the power generation mix. Solar energy takes up less than 1%, with an estimated installed on-grid capacity of about 124 megawatt peak (MWp), and 61 MWp off-grid. These low numbers might seem strange, considering that most people associate Indonesia with a sun-kissed climate. And indeed, if you look at research on the potential of solar energy in Indonesia, it can be concluded that there is much more potential that has not been utilized yet. In a report on the theoretical potential of solar energy in Indonesia, The World Bank [2017] concludes that Indonesia has favorable potential for solar power generation compared to other countries due to relatively high and stable solar irradiation. This makes Indonesia a possibly interesting location for solar power plants. It is also an interesting renewable energy technology due to declining years over the past decades [IRENA, 2021]. The MoEMR acknowledges the theoretical potential of solar energy. In the National Energy General Plan of Indonesia (RUEN), the ministry has set out strategies to achieve the renewable

Figure 1.1: Share of renewable energy technologies in Indonesia in the power generation mix (based on data retrieved from the MoEMR [2021b]



(a) Development of the share of fuel sources for power generation



(b) Share of renewable energy technologies for renewable power generation in 2020

energy goals set in the 2014 NEP. The RUEN mentions that in 2015, only 0,04% of the estimated theoretical potential of solar energy was being utilized [MoEMR, 2017b]. The MoEMR wants to make more use of this potential and strives to increase it to at least 3% in 2025 and 22% in 2050. This compares to an installed capacity of respectively about 6.000 MWp in 2025 and 46.000 MWp in 2050, which is an increase of 3.400% (2025) and 25.000% (2050) compared to the installed capacity in 2020.

To achieve these targets, the MoEMR wants to focus primarily on the installation of solar PV cells on rooftops of government buildings, housing complexes, apartments and other complexes. Imposing a mandatory utilization of a minimum number of solar cells on roofs of these buildings is one of the policies that is begin considered. There is little policy emphasis on the development of utility-scale solar PV. However, this type of solar energy could also be a way to achieve these targets or even transcend these. Utility-scale solar PV refers to relatively large grid-connected solar PV power plants. An important advantage of this type of solar energy technology compared to rooftop solar, are the economies of scale due to the scale of the installed systems. IRENA [2021] has collected data on rooftop solar PV systems and utility-scale solar PV systems around the world and concludes in its report *Renewable Power Generation Costs 2020* that rooftop solar PV systems in general have significantly higher costs than utility-scale solar PV systems in 2020. Due to the cost benefits relative to rooftop solar, utility-scale solar PV could also be an important possible contributor to generate renewable electricity on a large scale. Even more so when it is taken into account that the state-owned electricity company Perusahaan Listrik Negara (PLN) has expressed its goal to phase out fossil fuel fired power plants by 2050, to stop building new coal fired plants by 2023 and to use more renewable energy in its networks [Rahman, 2021]. Utility-scale solar PV could play a role in filling the gap that phased-out coal-fired plants and other fossil fuel-fired plants leave behind.

1.3 ROADBLOCKS TO SOLAR PV DEVELOPMENT

However, there are some hurdles as to why the development of utility-scale solar PV has not taken off yet. The IISD [2018] has performed 26 interviews with several stakeholders from the solar and wind sector in Indonesia, to find out what the roadblocks are for further development. The ISSD identified four major roadblocks: (1) relatively low electricity prices are paid to renewable power producers compared to the costs (2) project development risks related to regulatory delays and frequent changes in policies are present, (3) there is no recognition of the environmental benefits of renewable energy versus fossil fuels in the electricity prices paid to a power producer, and (4) there is a conflict of interest related to state-owned company PLN: PLN has a monopoly on the electricity distribution and transmission throughout Indonesia, and agrees on power purchase prices for power producers. However, the company also owns the majority of the fossil fuel-fired power plants and has an interest in maintaining the status quo.

Two of the four major roadblocks are related to the relative costs of a solar PV power plant. If the electricity price paid to a power producer is lower than the costs of an installation, it remains financially unattractive to develop one. The price paid to a solar power producer is currently based on the regional and national average production costs of electricity generation as a reference cost [MoEMR, 2017a]. This is called the Biaya Pokok Penyediaan (BPP). This reference price is based on the costs of electricity generated with fossil fuels, given the current power generation mix. Currently, it seems that the reference price is often too high to be able to cover the costs of new utility-scale solar PV installations, creating a financially unattractive situation [IISD, 2018; Maulidia et al., 2019].

1.4 ECONOMIC POTENTIAL OF UTILITY-SCALE SOLAR PV

In Section 1.2, it was discussed that the MoEMR wants to increase the installed capacity of solar energy installations significantly. Utility-scale solar PV power plants could play an important role in this process due to the relative economies of scale compared to rooftop solar PV installations. However, there is a major financial roadblock to further development, as seen in Section 1.3. Therefore, the question arises what the current economic potential of this renewable energy technology is and how more economic potential could be achieved, tackling the financial roadblock and clearing the road to utility-scale solar PV development.

As for the concept of the potential of a renewable energy technology: this can have different meanings. Blok & Nieuwlaar [Blok and Nieuwlaar, 2017] distinguish six types of potential that built upon each other. This typology helps to clarify what is meant when potentials are discussed. The first three types of potential are the theoretical, technical and economic potential. Figure 1.3 visualises the first three types of potential in relation to utility-scale solar PV. As can be seen, the potentials built upon each other. Economic potential refers to the estimated potential that is considered to be economically viable [Blok and Nieuwlaar, 2017]. Financial factors such as the projected projects costs versus the electricity paid to the power producer are taken into consideration. Both technical and economic potential can be expressed in potential electricity generation and potential capacity.

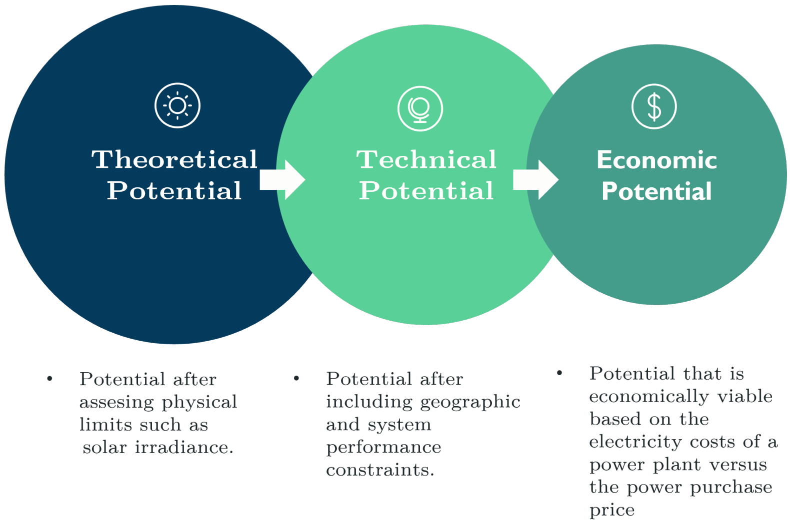


Figure 1.3: Three types of potential for utility-scale solar PV [The World Bank, 2020]

Previously, research has been conducted related to the economic potential of utility-scale solar PV. These studies have estimated the costs of electricity expressed in levelized cost of electricity (LCOE) of utility-scale solar PV in Indonesia. The LCOE is a measure of the average cost of electricity production for a power plant over its lifetime. This measure is commonly used to evaluate the costs of a power plant and to compare different energy generation technologies with each other [McCulloch, 2017]. However, the LCOE alone does not provide insights into whether utility-scale solar PV is actually economically viable. To get those insights, the LCOE needs to be compared with a benchmark such as the expected local electricity tariffs paid to the solar PV power producers. To the authors' best knowledge, there is not a recent study available that assesses the economic potential of utility-scale solar PV for Indonesia expressed in potential electricity generation and capacity, by comparing the LCOE with the expected electricity tariffs paid to power producers. This leaves a knowledge gap to be further researched in this study. Evidently, it has not been researched how policy interventions may influence the economic potential. Section 2.2 elaborates further on the existing literature on the potentials of solar PV in Indonesia.

1.5 PROBLEM STATEMENT & RESEARCH OBJECTIVES

The previous sections have shown that utility-scale solar PV is an interesting renewable energy technology to help in fulfilling renewable energy targets due to the relatively high resource potential compared to other countries, global declining solar PV material costs and the economies of scale compared to rooftop solar PV systems. However, there are roadblocks to overcome. This includes a major financial roadblock. Quantifying the economic potential and exploring the effects of policy interventions on the economic potential could result in valuable insights that may help to rethink the role that utility-scale solar PV could play in the Indonesian energy transition and to give direction for policy design to overcome the financial roadblock. The main research objective of this research is therefore to contribute knowledge on the technical and economic potential of utility-scale solar PV and the effects of several policy interventions on that economic potential, to help rethink the role that utility-scale solar PV can play in meeting the national renewable energy targets as presented in the NEP.

The objective is achieved by first quantifying the technical potential of utility-scale solar PV, which is needed for the next step: quantifying the economic potential. Then, the effects of several policy interventions that are expected to increase the economic potential are explored further.

1.6 RESEARCH QUESTIONS

Based on the knowledge gaps described in Section 1.4, the main research questions and sub-questions of this thesis were formulated. The answers to the questions combined are meant to address the research objectives discussed in Section 1.5. The main research question and sub-questions of this thesis are:

What is the technical and economic potential of utility-scale solar PV in Indonesia and what can be recommended in the policy context to increase the economic viability of utility-scale solar PV?

1. What is the technical potential of utility-scale solar in Indonesia?
2. What is the economic potential of utility-scale solar PV in Indonesia?
3. What are possible policy interventions to increase the economic potential of utility-scale solar PV in Indonesia?
4. How do the policy interventions affect the economic potential and other relevant system factors?

1.7 LINK WITH ENGINEERING AND POLICY ANALYSIS (EPA) PROGRAM

A thesis within the EPA program is required to be related to decision-making in the context of a grand societal challenge while taking the social, economic and/or political context into account. Furthermore, it is analytical in character and modeling or simulation techniques, which can be conceptual, are to be used. This thesis fits the frame of an EPA thesis. First of all, the subject of this thesis is evidently related to the renewable energy transition in Indonesia, which has proven to be a societal challenge. Furthermore, a modeling approach is used to calculate the technical and economic potential of utility-scale solar PV. Finally, given that one of the objectives of this thesis is to inform policy-makers on possible policy interventions related to the financial barrier that utility-scale solar PV seems to face, the thesis is related to decision-making in this context.

1.8 RESEARCH APPROACH

The research approach for this thesis can be split up into three phases: the technical and economic potential analysis, a policy analysis by means of a multi-criteria analysis and a discussion and conclusion phase, in which the results of the first two phases are combined. An overview of the complete research approach can be found in Figure 1.4.

Phase 1 (sub-questions 1 & 2)

To be able to assess the technical and economic potential of utility-scale solar PV, a spatial modeling approach was chosen, given that gaining data from the field is not feasible due to the limited resources of this research. The modeling of the potentials of utility-scale solar PV in Indonesia will be done using a geographical information system (GIS). GIS allows for analyzing and combining spatial data, performing calculations, and presenting results in geographical figures. GIS is often used to analyze data related to renewable energy in a geographical context because of its capability of combining different layers of geographical data Rumbayan et al. [2012]; Choi et al. [2019]. According to Blok and Nieuwlaar [2017], it is also capable of facilitating detailed renewable energy potential assessments. Therefore, a modeling approach using GIS is considered to be appropriate for the assessment of the technical and economic potentials of utility-scale solar PV in Indonesia. In Section 3.1, the GIS-based modeling approach is discussed in more detail.

Phase 2 (sub-questions 3 & 4)

To be able to answer sub-questions 3 and 4, a multi-criteria analysis (MCA) is performed, which forms phase 2: the policy analysis. An MCA is a method that is widely used to assess policies and can be seen as a guided exploration of possible policy interventions and their desirable and undesirable effects [Dodgson et al., 2009]. By following a basic MCA approach, possible policy interventions are identified and their performance on several criteria are assessed. This is in line with sub-questions 3 and 4 and therefore, a MCA is found suitable. In Section 3.1, the MCA method is discussed in more detail.

Phase 3 (main research question)

The final phase of this research consists of a discussion and conclusion on the results from both phase 1 and phase 2. The insights from both the potential analysis and the policy analysis are combined to be able to answer the main research question.

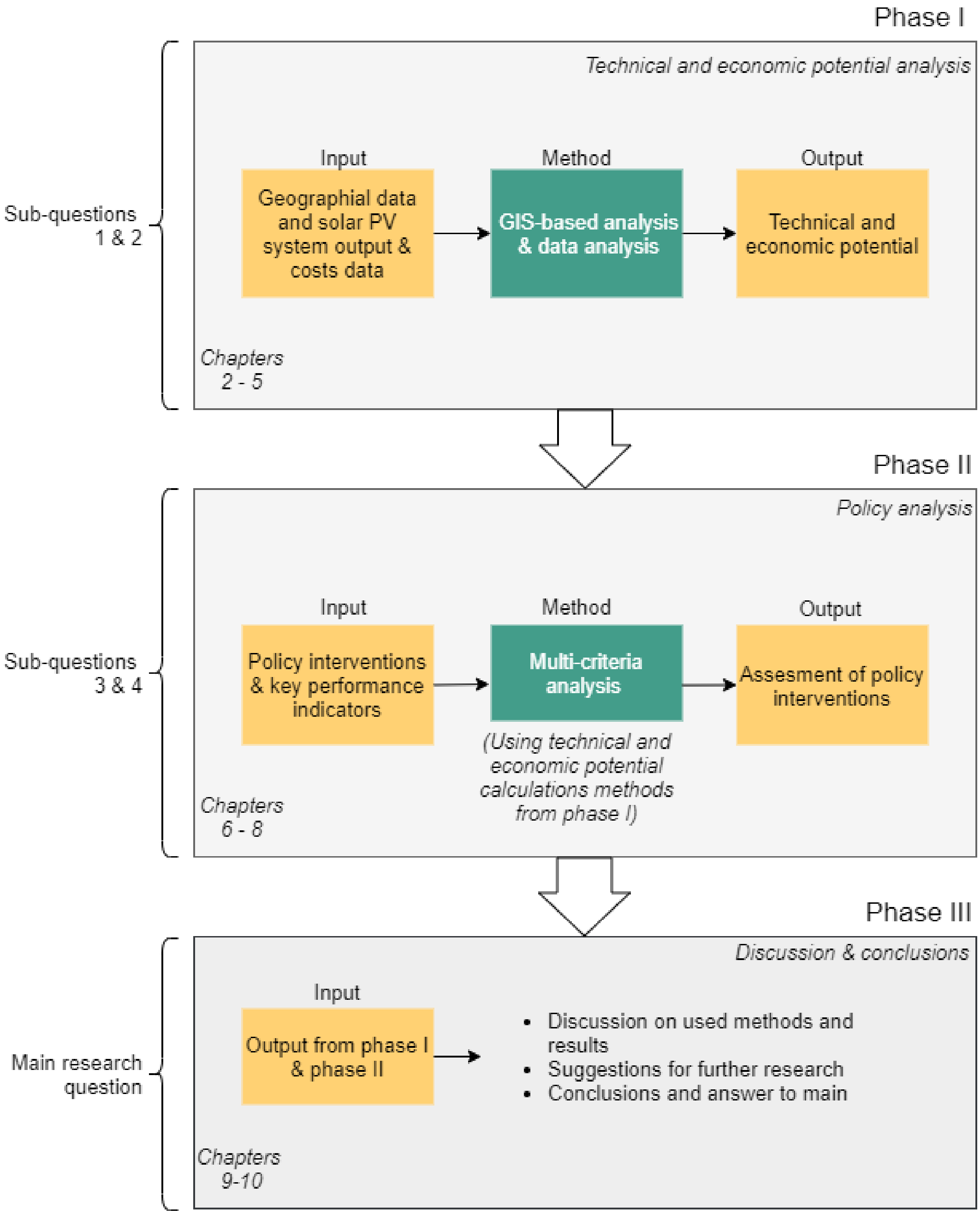


Figure 1.4: Research flow diagram

1.9 THESIS OUTLINE

Part i of this thesis consists of a technical and economic potential analysis. First, a theoretical background is presented in Chapter 2 that discusses relevant concepts and literature related to the technical and economic potential of utility-scale solar PV. Chapter 3 describes the used methods to calculate the technical and economic potential. Chapter 4 and Chapter 5 respectively present the results of the technical and economic potential.

Part ii of this thesis follows, starting with a background on the policy context and the identification of possible policy interventions to help overcome the financial barrier that utility-scale solar PV seems to face in Chapter 6. Chapter 7 follows with the presentation of the MCA method used to asses the identified policy interventions. The results of the MCA are presented in Chapter 8.

Part iii is the final part of this thesis. Chapter 9 includes the discussion of the used methods and results and presents recommendations for further research. Finally, Chapter 10 provides answers to the research questions.

Part I

TECHNICAL AND ECONOMIC POTENTIAL ANALYSIS

2 LITERATURE REVIEW

This chapter provides literature reviews on the relevant concepts related to the technical and economic potentials of utility-scale solar PV. First, a general background of utility-scale solar PV power plants is given in Section 2.1. Then, the existing literature on the resource, technical and economic potentials is discussed in Section 2.2. Section 2.3 discusses the suitability of different land cover types and ground slope for power plant development based on literature. Finally, in Section 2.4, the economic factors related to solar PV power plants are elaborated on.

2.1 ON UTILITY-SCALE SOLAR PV POWER PLANTS

A utility-scale solar PV power plant generates electricity from solar energy on a large scale and is often connected to the main electricity grid of a country. 'Utility-scale' refers to a minimum installed capacity. In this study, a threshold of one MWp is assumed, which is proposed by The World Bank [2020]. The plant generates electricity through fields of solar PV modules. Solar PV modules convert the energy from sunlight directly into current (DC) electricity. Before the electricity is integrated into the electricity grid, is it converted into alternating current (AC) electricity using an inverter [ARENA, nd]. Figure 2.1 presents a schematic drawing of how a typical PV power plant works.

Between utility-scale solar PV power plants, there can be technological differences. The used modules can either be fixed-tilted modules, or sun-tracking modules. While sun-tracking modules can result in a higher energy yield compared to fixed-tilted modules, fixed-tilted modules are the market-dominating technology because of the significantly lower costs [Stein, 2018]. Furthermore, since Indonesia is located around the equator, the positive energy yield effect of sun-tracking modules is expected to be limited [Asiabanpour et al., 2017]. Another difference between solar PV power plants is the PV module technology that is used. Polycrystalline silicon modules and monocrystalline silicon modules are the market-dominating products in the solar module market. Based on efficiency, monocrystalline silicon modules have the advantage [Jiang et al., 2020]. However, polycrystalline silicon modules have an economic advantage with lower costs per module [PVinsights.com, 2021].

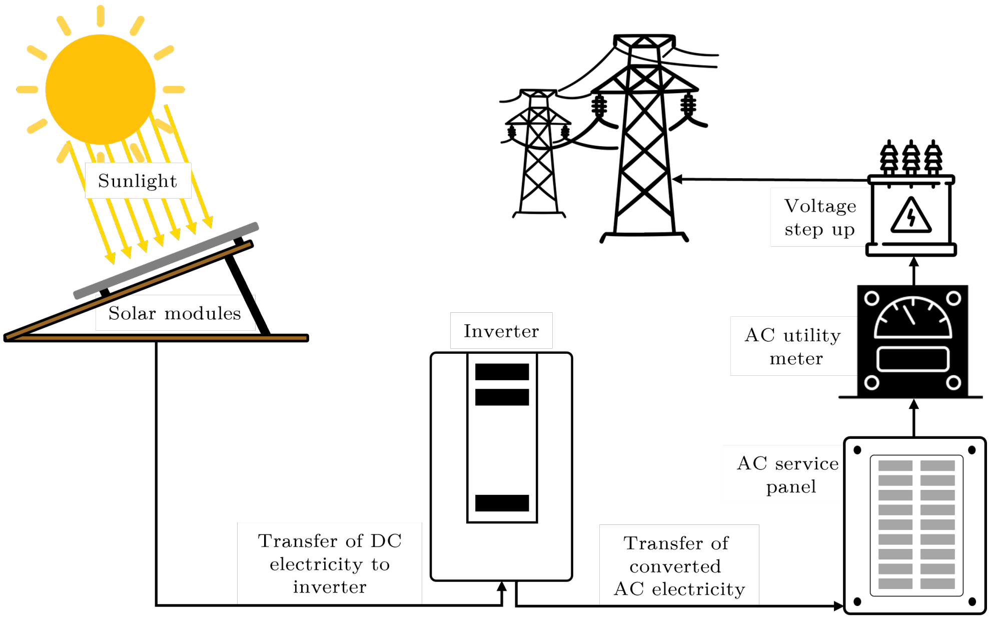


Figure 2.1: Schematic diagram of a typical grid-connected solar PV power plant [Kadem et al., 2018]

2.2 ON THE POTENTIALS

Section 2.2.1 elaborates on the resource potential of solar energy in Indonesia and Section 2.2.2 on the existing literature on the technical and economic potentials of utility-scale solar PV in Indonesia.

2.2.1 Resource potential

The resource potential for solar energy basically means the amount of solar irradiation that reaches the surface annually in a certain area. There are several parameters to measure solar irradiation. The global horizontal irradiation (GHI) refers to the total solar irradiance on a horizontal surface. This is the measure that is most often used for the assessment of the performance of solar PV systems The World Bank [2020]. The studies around this measure generally get their data from institutes like NASA which use ground-based sensors and satellite-based models.

Solargis [2017], as commissioned by the World Bank, has made a global data-set on the GHI publicly available. This data-set suggest that the value of the average daily GHI in Indonesia ranges between 3,9 and 5,78 KWh/m^2. If these numbers are compared to other countries, Indonesia comes out on the high side. In a report on the solar resource potential in Indonesia, The World Bank [2017] concludes that Indonesia has favorable potential for solar energy compared to other countries. This is based on the GHI parameter and the relatively low seasonal variability of the GHI throughout the country, which is favourable for the stability of power generation. In conclusion, the general take on the resource potential of solar energy in Indonesia is quite positive, and there is recent data available on the subject. Figure 2.2 presents an overview of the GHI in Indonesia.

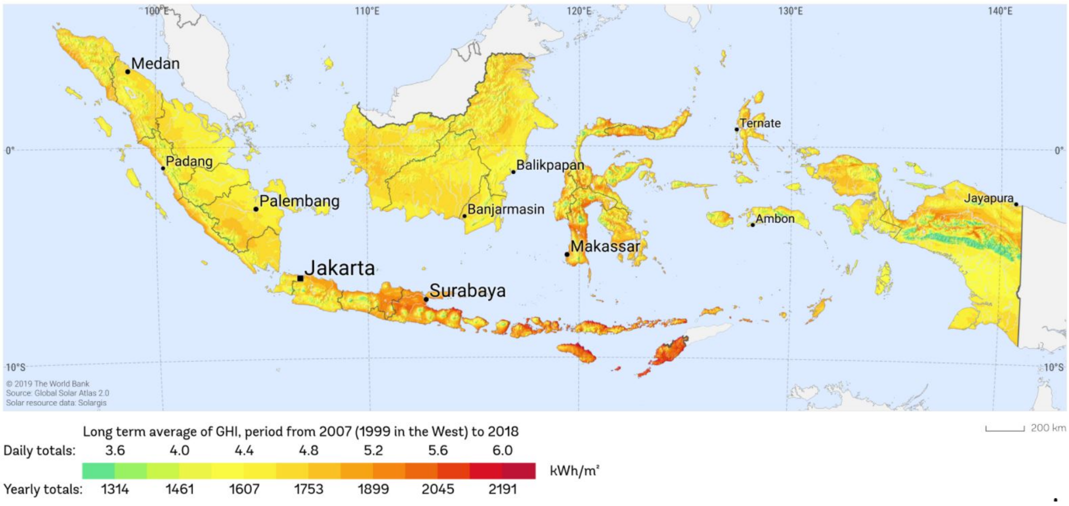


Figure 2.2: Long term GHI averages in Indonesia [Solargis, 2017]

2.2.2 Technical and economic potentials

Research has been performed on the technical and economic potentials of utility-scale solar PV in Indonesia. Studies were identified through a literature search and a literature review on the renewable energy potentials in Indonesia performed by Langer et al. [2021]. An overview of the found studies and the technical and economic potential estimations is presented in Table 2.1. The reported potentials of solar PV by the MoEMR [2017b] are also included at the bottom of the table. The estimations of the MoEMR compared to those found in literature are relatively small, although the MoEMR only mentions forest areas as excluded areas. The estimations of the technical potential found in literature are much larger but also differ from each other. Various site selection criteria are used in each study which affect the outcomes. These site selection criteria are further discussed in Section 2.3.

Although there are multiple studies that report on estimations of the LCOE of utility-scale solar PV in Indonesia, only one estimation on the economic potential was found in literature by Veldhuis and Reinders [2013]. This study compares the LCOE with regional electricity production costs within suitable areas and estimates the economic potential to be 0,4 GW_p. It should be noted that this study estimates the potentials on a provincial level and does not take into account local variances in solar irradiation. Furthermore, some of the estimations used in the study such as the costs are outdated given the fast decline of global solar PV costs [IRENA, 2021].

From the literature review it is concluded there is no study available, to the authors' best knowledge, that includes all of the following: (1) assesses the economic potential for the whole of Indonesia instead of a singular region [Sunarso et al., 2020; Ruiz et al., 2020], (2) assesses the costs of utility-scale solar PV on a more detailed level than national or provincial disregarding local circumstances [IESR, 2021a; Kunaifi et al., 2020; Veldhuis and Reinders, 2013] and (3) compares the LCOE with the expected electricity price paid to the power producer and quantifies the total economic potential in potential capacity and potential electricity generation [Sunarso et al., 2020; IESR, 2021a; Kunaifi et al., 2020; The World Bank, 2020; Silalahi et al., 2021]. The third point is an important one for the following reason: to say something about the economic potential of utility-scale solar PV, an assessment of the LCOE alone is not enough: it needs to be compared to a benchmark such as the electricity price that is expected to be paid to the power producer. When the LCOE is lower in an area than the electricity price paid to a power producer, it can be said that there is economic potential in that area. Given that there are no known studies to the authors' best knowledge that take this into account when assessing the economic potential, a knowledge gap is left that is addressed in this study, as presented in Chapter 1.

Table 2.1: Overview of research on the potentials of ground-mounted utility-scale solar PV in Indonesia; LCOE values not adjusted for inflation

Reference	Analyzed region	Technical potential [GW_p]	Technical potential [TWh/year]	Economic potential [GW_p]	LCOE [US$ct./KWh]
IESR [2021a]	Indonesia	3400 - 20.000	4700 - 27.000	-	5,8 - 10,3
Kunaifi et al. [2020]	Indonesia	73 - 3200	95 - 5180	-	5,9 - 9,5
Veldhuis and Reinders [2013]	Indonesia	27 - 1100	37 - 1492	0,4	15 - 24
Sunarso et al. [2020]	Kalimantan Barat	-	9400	-	4,5 - 5,5
The World Bank [2020]	Indonesia	-	-	-	9 - 13
Silalahi et al. [2021]	Indonesia	-	3300 - 8700	-	-
Ruiz et al. [2020]	Kalimantan Barat	-	9 - 21	-	-
MoEMR [2017b]	*Indonesia*	*0,2*	*0,3*	-	-

2.3 ON-SITE SELECTION CRITERIA

To assess the technical potential of utility-scale solar PV, site selection criteria must be taken into account. Not every area of land is suitable or available for the development of a solar power plant for various reasons. Site selection criteria can be divided into land cover selection criteria on one side and a land slope criteria on the other side. Next, literature on the selection criteria within these two categories will be discussed.

2.3.1 Land cover

Current land cover impacts the suitability of land for solar power plant development. In scientific literature, various site selection criteria for land cover are used. A general consensus on which types of land cover are unsuitable and should not be considered when assessing the technical potential of utility-scale solar PV cannot be found. Table 2.2 shows a literature review of which studies include which land cover selection criteria. It should be noted that different types of land cover categorization, data-sets and methods have been used throughout these studies. For the purpose of consistency, the land cover types have sometimes been translated to the land cover types based on the land cover categorization of the Ministry of Environment and Forestry (MoEF) [2017]. By land cover types based on the land cover categorization of the MoEF, the following is meant: The MoEF has categorized land in 23 types. In Table 2.2, only 13 types of land cover are included. This is based on a re-categorized, based on the relation with a land cover type to the suitability for solar power plant development. For example, there are six types of natural forests categorized by the MoEF. In the re-categorization, they all fall under land cover type 'Natural forests', because no reason could be found to keep these separate. Their relation to the suitability for solar power plant development is pretty much similar. Appendix F shows the land cover types as categorized by the MoEF and the re-categorization used in this study. Also, protected areas are not a land cover type in the categorization of the MoEF, but has been included in the list of land cover types because it is often used as a site selection criteria for solar PV power plants in literature, as is visible in Table 2.2.

Table 2.2: Exclusion criteria of land cover types as used in various studies on the potential of utility-scale solar PV

	Reference	Deng et al. [2015]	IESR [2021a]	Palmer et al. [2019]	Sunarso et al. [2020]	The World Bank [2020]
	Analyzed region	*Global*	*Indonesia*	*UK*	*Province of West-Kalimantan*	*Global*
Land cover type	Agricultural land	X [1]	X [2]	X	X	X [3]
	Airports & harbours		X			
	Bush/shrub	X [1]	X [2]			
	Bare land	X [1]				X
	Bodies of water	X	X	X	X	X
	Dry & shrub-mixed dry agricultural land	X [1]	X [2]			X [3]
	Natural forests	X	X	X	X	X
	Mining areas					
	Plantation forests	X	X [2]		X	X
	Savannah	X [1]				
	Settlement areas	X	X [2]	X	X	X
	Wetland areas		X		X	
	Protected areas	X	X	X	X	X [3]

Based on the literature review presented in Table 2.2, it is clear that there is inconsistency in land cover site selection criteria throughout literature. Next, per land cover type, the reasoning behind the inclusion or exclusion of the land cover type in literature is discussed, sometimes supported with other sources.

Agricultural land

Agricultural land is often considered to be essential for food production and therefore not readily available for solar PV power plant development. However, through land acquisition and land cover conversion, solar PV development might be possible. For example, fish ponds, which fall under agricultural land, can be converted back to land that is appropriate for the mounting of solar PV modules [Tarunamulia et al., 2019]. The consideration of agricultural land for solar PV power plant development was seen in the studies by Deng et al. [2015], IESR [2021a] and The World Bank [2020].

Airports & harbours

Airports & harbours are only specifically mentioned in one study [IESR, 2021a] and excluded there because of limited available space. Although solar PV power plant development has been seen in buffer zones in airport areas, such as those in development in three French airports [Bellini, 2020], these projects cannot be compared with standard utility-scale solar PV projects. Such projects require specialized knowledge and a non-standard setup of the power plant, influencing the costs.

Bush/shrub

According to the categorization of the MoEF (2017), bush/shrub includes dry land areas that are overgrown with various types of mostly low vegetation. These areas can therefore be seen as preferred land for the development of solar PV since it doesn't interfere with economic activities. Bush/shrub is only partially excluded by Deng et al. [2015], by including an availability factor. IESR [2021a] excludes bush/shrub

1 Deng et al. (2015) did not completely rule out these types of land, but took into account an availability factor, ranging between 0,5 and 5%.

2 The IESR (2021a) reviews four different scenario's in their study. The land cover types that reference to this footnote, are the ones that are not included in every scenario.

3 The World Bank (2020) considers agricultural land and protected areas on a different level as the other exclusion criteria. They view these two land cover types as not necessarily limiting factors in every country.

in one out of the four proposed land availability scenarios, only because it makes up a large part of the country's land cover.

Bare land
Bare land is preferred land for the development of solar PV since it doesn't interfere with other types of land use. Bare land is only partially excluded by Deng et al. [2015], by including an availability factor.

Bodies of water
Every reviewed study excluded bodies of water from the development of land-based solar PV power plants. It should be noted that bodies of water might be suited for the development of floating solar PV, but this technology is outside of the scope of this research, which only focuses on land-based solar PV power plant development.

Dry & shrub-mixed dry agricultural land
Dry & shrub-mixed dry agricultural land is usually not covered with vegetation between planting periods. Through land acquisition, solar PV development might be possible. This has previously been seen in two utility-scale ground-mounted solar PV projects in Lombok and Likupang in North Sulawesi. The capacity of these plants are respectively 3 x 7 MWp and 21 MWp [ADB, 2018a,b]. In these projects, parts of the acquired land area were previously categorized as dry agricultural land. In the studied literature, the land cover type is sometimes considered. It is more often considered than agricultural land, given the lesser impact on economic activities if land is acquired for solar PV power plant development

Natural forests
To use this land type for solar PV power plant development, natural forests have to be cut down. It can be viewed as counterproductive to do this for the development of solar PV in light of carbon dioxide reduction goals. This reasoning is seen in every reviewed study. However, it should be noted that although it is not desirable, through land acquisition it might be possible.

Mining areas
Mining areas are open land as a result of mining activities. It is potential land for solar PV development, given the lack of current land use. Silalahi et al. [2021] consider abandoned mining sites to be appropriate for utility-scale solar PV development because of the low environmental and economic impact and refers to two examples of solar PV power plants in former mining areas in Australia and China. It is important to note that the assumption is made that these areas are indeed open land that is currently not being used for mining activities. This is the same interpretation of the land cover data-set by the MoEF as a recent study by the IESR [2021a] has. If some areas are currently being used for mining activities, these areas could be viewed as economically productive areas that should not be interfered with. Another notion is that some parts of abandoned mining sites have to be filled with sand before the area can be occupied with ground-based solar PV modules.

Plantation forests
Man-made plantations are used for food production or other purposes. However, through land acquisition, solar PV development might be possible. This has previously been seen in a ground-mounted solar PV project of 3 x 7 MWp in Lombok [ADB, 2018b]. Part of the land acquired was previously a plantation forest. In the reviewed studies, plantation forests are sometimes included as suitable land for solar PV development. This can be attributed to the discussion of whether is it a good idea to scale down plantation forests to make room for solar PV power plants. On a small scale, this may have a limited effect, but on a larger scale, this can interfere with economic activities and food production.

Savannah
Savannah is open land covered in grass and trees that are spread out sparsely. It is preferred land for the development of solar PV because it does not interfere with much other land use. This reasoning is seen in most of the reviewed studies. Only Deng et al. [2015] partially excludes savannah.

Settlement areas
Residential areas and transmigration areas might be suitable for solar PV development but would require land acquisition and possibly the demolishment of buildings. This has previously been seen for a part of the land that was used for a ground-mounted solar PV project of 3 x 7 MWp in Lombok [ADB, 2018b]. However, using this type of land cover would come with difficult land acquisition issues and concerns on the interference with housing for people. Settlement areas are therefore excluded in every reviewed study, except for the study by the IESR [2021a], which includes settlement areas in one land suitability scenario. Settlement areas are more suitable for rooftop solar PV systems compared to utility-scale solar PV systems, which is a technology that is not assessed in this study.

Wetland areas
Wetland areas are recognized as important ecosystems by the IUCN [nd]. Wetland areas are either covered or saturated with water and are known for their rich ecosystems for biodiversity. The placement of solar PV installations could bring harm to the biodiversity of wetland areas. It also required specified knowledge and mounting of the solar modules. It is therefore not impossible to build a solar power plant in these areas, but it is not preferred, similar to natural forests and protected areas.

Protected areas
Protected areas are nationally protected lands that have a critical environmental or biodiversity concern. The development of solar PV is not preferred and depending on the level of protection and type of protected area, very unlikely. All of the reviewed studies, therefore, exclude protected areas in their land suitability analysis. However, The World Bank [2020] does note that depending on the country and level of protection, solar PV development might be possible in reality.

2.3.2 Ground slope

Ideally, the site of a solar farm is flat or only has a slight slope, according to the developer's guide for solar energy published by the IFC [2015]. If the land is steeper, it can be a limiting factor for the development of solar farms. The shadow effect and higher construction costs are reasons for this. If a utility-scale solar PV installation is built on a steep land area, one solar panel row may cast shadows over the next row. This shadow effect can reduce the energy yield. Concerning the costs: The IFC points out that flat land makes the installation of a solar farm easier and reduces construction cost and construction time.

However, it is not impossible to build a solar farm on land with a moderate or high slope. Structures can be designed for such locations. In those cases, the higher costs must be weighed against the energy and money yield. Because of this dependency on local circumstances, there is no general threshold available for a slope limit in Indonesia or globally. In various studies, various rules of thumbs are used. Table 2.3 shows the ground slope limits used in various studies on the suitability of land for the development of solar PV power plants. Each slope limit is used to determine suitable land for utility-scale solar PV power plant development unless written otherwise in the column *Remarks*. The slope limits range between 2% and 17,6%.

Table 2.3: Slope limits used in studies on site suitability for utility-scale solar PV power plants

Reference	Analyzed region	Slope limit [%]	Remarks
Brewer et al. [2015]	USA	5,42	The limit is based on data of existing solar power plants in the USA.
IESR [2021a]	Indonesia	17,6	
Noorollahi et al. [2016]	Iran	11	
Palmer et al. [2019]	UK	2 - 4,4	The limit is varied and used to select optimal sites.
Sabo et al. [2016]	Malaysia	5	
Sunarso et al. [2020]	Province of West-Kalimantan	5	

Concerning the costs related to the different slope limits: although it is clear that solar power plants built on steeper land require higher construction costs, a relation between the costs and slope limit could not be found in literature. Several interviews with Dutch solar power plant developers and one consultant on solar power plant development in Indonesia could also not provide an estimation for the extra costs because of the dependence on specific local circumstances [anonymous Indonesian industry expert, personal communication, June 25, 2021; Kronos solar employee, personal communication, June 5, 2021; Eneco employee, personal communication, June 11, 2021; Sunvest employee, personal communication, June 6, 2021].

2.3.3 Land buffers

For some land cover types, buffers are appropriate to take into account when developing a utility-scale solar PV power plant. For land cover types settlement areas, natural forests, plantations forests and for the coastline, literature and/or interviews with industry experts point towards the importance of taking into account a buffer for various reasons. For each of these land cover types and for the coastline, it is discussed why a buffer is important and what an appropriate buffer size may be.

Buffer for settlement areas
Indonesia's population is growing and urban development is expected, according to the department of economic and social affairs of the UN [2019]. To avoid causing negative impacts on urban growth, a buffer for settlement areas makes sense to take into account. A former consultant for utility-scale solar PV park developers in Indonesia has confirmed that developers take urban development into account and do not look at sites near settlement areas. This is also done for security reasons: trespassing during construction and afterwards can be more easily avoided when the site is located away from settlement areas. This also limits direct impacts on local communities and the resistance of those communities. Previous studies on site suitability for solar power plants have taken into account a buffer of 500 meters [Watson and Hudson, 2015; Castillo et al., 2016; Uyan, 2013; Palmer et al., 2019].

Buffer for natural and plantation forests
Forests may cast shadows on solar PV modules during the day. Furthermore, debris from nearby forests decreases the power output and increases the need for more cleaning [anonymous Indonesian industry expert, personal communication, June 25, 2021; Eneco employee, personal communication, June 11, 2021]. A buffer for plantation and natural forests thus makes sense. However, no rules of thumb could be found for forest buffer sizes in Indonesia. When building actual solar parks in Indonesia, it is common to take into account a certain buffer, but the sizes depend on local circumstances [anonymous Indonesian industry expert, personal communication, June 25, 2021; D. Silalahi, personal communication, June 12, 2021]. A rule of thumb used in the Netherlands is a buffer of twice the height of nearby trees [Sunvest employee, personal communication, June 6, 2021; Eneco employee, personal communication, June 11, 2021].

Buffer for the coastline
Indonesia has a very extensive coastline. Sand and salt from the ocean that is transported through winds can be an issue for solar parks located near the coast. Wind blown sand may require extra cleaning for solar panels and salt mist degrades the output of the panels [Chudnovsky, 2012; Palmer et al., 2019]. This risk can be mitigated through extra cleaning and using salt mist resistant solar panels. However, in Indonesia, developers avoid building solar parks near the coastline to avoid these issues and the extra costs that come along with it [anonymous Indonesian industry expert, personal communication, June 25, 2021]. A buffer of 300 meters is usually used.

2.4 ECONOMIC FACTORS

Knowledge of the current economics of utility-scale solar PV is important to assess the economic potential in Indonesia. The costs of a utility-scale solar PV power plant can be divided into capital expenditures (CAPEX) and operational expenditure (OPEX). CAPEX refers to the costs of the initial investment for the setup of the power plant. OPEX refers to further annual operation and maintenance costs. Table 2.4 summarizes the costs estimations found in available literature for Indonesia specifically. The year of the CAPEX estimations is included after the value in the CAPEX column. It is important to consider only estimations for Indonesia since costs for materials and services needed for a solar power plant can vary drastically between countries, as can be seen in the global Renewable Cost Database of IRENA [2021], in which costs estimations for various countries are included.

Based on the data collected in Table 2.2 it is clear that there is also a range in costs estimations in literature for Indonesia. The CAPEX ranges between 830 and 1192 US$/$KW_p$ and the OPEX ranges between 1,26 and 1,88 as a percentage of the total CAPEX for each year that the plant is running. For five out of the six reviewed studies, the estimations present costs for a 'utility-scale' solar PV power plant: there is no fixed assumed capacity of the plant. Although there are indications that as the capacity of a plant grows, the average costs get cheaper, no data could be found on the relationship between this. An example of such an indication is the following: according to a report of the consultancy firm Wood Mackenzie [2020] the costs of a 100 MWp single-axis tracker system in the USA were on average 8% lower than the costs of a 10 MWp system in 2020. However, this is only based on solar PV systems in the USA and there is no notion of the costs of other sizes of solar PV power plants.

Table 2.4: Summary of literature review on the economics of utility-scale solar PV power plants in Indonesia

Reference	CAPEX [US$/KW$_p$] *(year of data)*	OPEX [% of CAPEX]	System degradation [%/year]	Discount rate [%]	Plant lifetime [year]	Plant size [MWp]
Directorate General of Electricity [2021]	830 *(2020)*	1,81	0,25 - 0,5	4	35	10
IESR [2019b]	700 - 1200 *(2019)*	-	-	10	-	Utility-scale
The World Bank [2020]	1192 *(2020)*	1,26	0,5 (0,8 in the first year)	10	25	Utility-scale
Donker and Tilburg [2019]	1000 *(2018)*	1,4	-	-	20-25	Utility-scale
Matin et al. [2019]	1060 *(2019)*	1,30	1,0 (1,21 in the first year)	10	25	Utility-scale

About the declining CAPEX and breakdown of the CAPEX
It should be noted that the costs of solar PV systems have been declining sharply over the past decades. International Renewable Energy Agency (IRENA) (2021) estimates that the average global costs of electricity produced with utility-scale solar PV power plants fell by 85% between 2010 and 2020, and that the costs are expected to fall even further in the future. Therefore, to assess the economic potential of utility-scale solar PV, it is essential to look at the most recent cost estimations as possible. Since the OPEX is often expressed as a percentage of the CAPEX, recent data on the CAPEX is most important. The most recent and complete data-set on CAPEX that could be found, is that of IRENA in the previously mentioned Renewable Cost Database (2021). Figure 2.3 shows the breakdown of the estimated CAPEX for 2020 in Indonesia. The components of the CAPEX can be divided into three groups: hardware costs, installations costs and soft costs. Solar modules fall under hardware costs and makeup about 36% of the total CAPEX. In an interview with a former solar PV power plant development consultant, it became clear that the current costs of solar modules compared to 2020 are lower than estimated by IRENA: the former consultant estimated that the average costs of solar modules used in utility-scale solar PV power plants in Indonesia in 2021 are about 320 US$/KW$_p$ [anonymous Indonesian industry expert, personal communication, June 25, 2021].

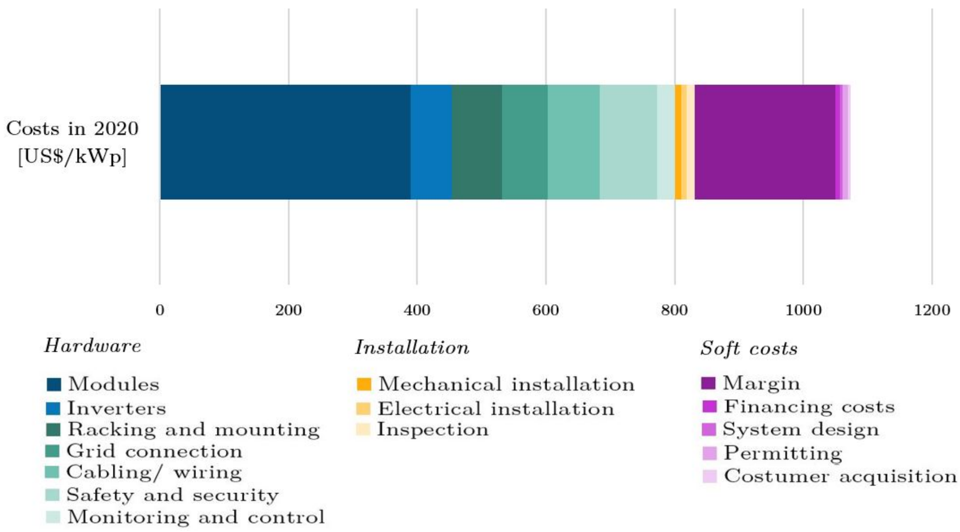


Figure 2.3: Breakdown of the CAPEX estimation by IRENA [2021] of utility-scale solar PV in 2020 in Indonesia

3 METHOD - TECHNICAL AND ECONOMIC POTENTIAL

This chapter elaborates further on the used methods for the technical and economic potential analysis, starting with an explanation of the use of a GIS-based approach for the technical and economic potential calculation methods in Section 3.1. Then, the methods to calculate the technical and economic potential are explained in more detail. These are are separately outlined in Section 3.2 and 3.3. A complete overview of the used data-sets for the technical and economic potential calculations is presented in Section 3.4. The sensitivity analysis of the economic potential is discussed in Section 3.5.

3.1 GIS APPROACH

To assess the technical and economic potential, a GIS-based approach was chosen. A GIS refers to a computer hardware or software system that is designed to, among other things, save, edit, analyze, integrate and visually represent geospatial data. A GIS-based approach is often seen in studies that assess the different layers of potentials of renewable energy technologies including utility-scale solar PV potentials [Sunarso et al., 2020; The World Bank, 2020, 2017; Choi et al., 2019]. Some of the main advantages for using a GIS for solar PV potential assessments are the ability to combine and analyze geospatial data related to solar resource and solar power plant site suitability conditions and the ability to geographically visualize the results [Choi et al., 2019]. In addition, according to Blok and Nieuwlaar [2017], GIS is capable of facilitating detailed energy potential assessments. Therefore, a GIS-based approach is a useful method in this study to asses the technical and economic potential of utility-scale solar PV in Indonesia and to visualize the results. This study uses the GIS software tool QGIS to analyze and edit geospatial data relevant to the technical and economic potential calculations. QGIS is a free and open source GIS [QGIS.org association, nd]. The geospatial data resulting from processes in QGIS, are further analyzed using Python programming.

3.2 TECHNICAL POTENTIAL CALCULATION

The technical potential calculation method consists of three steps: (1) the set-up of land suitability scenarios, (2) technological assumptions of utility-scale solar PV power plants, and (3) the calculations of the technical potential measured in potential capacity and potential electricity generation. Next, each step is further explained.

3.2.1 Set-up of land suitability scenarios

The theoretical background on site selection criteria in Section 2.3.1 showed that there are differences in methods used in literature in the types of land cover that are excluded when assessing the potential of utility-scale solar PV. Therefore, to further analyze the potential, three scenarios are set up which vary in the land cover types that are excluded. The scenarios are based on conclusions on the suitability and availability of land as presented in Section 2.3.1. Table 3.1 presents the land cover exclusions for each scenario. Airports & harbours, bodies of water, natural forests, protected areas, settlement areas and wetland areas are excluded in every scenario, because of their unsuitability for utility-scale solar PV power plant development for various reasons discussed in Section 2.3.1. Although it was mentioned that solar PV power plant development in areas within airports has been seen before, the non-standard set-up requires a more specialized analysis. Next, each scenario is discussed in more detail.

Table 3.1: Land cover exclusion scenarios: an X indicates the exclusion of a land cover type in the scenario

Land cover type	**Scenario 1**	**Scenario 2**	**Scenario 3**
Airports & harbours	X	X	X
Bodies of water	X	X	X
Natural forests	X	X	X
Protected areas	X	X	X
Settlement areas	X	X	X
Wetland	X	X	X
Agricultural land	X	X	
Plantation forests	X	X	
Dry shrub-mixed dry agricultural land	X		
Bush/shrub			
Bare land			
Savannah			
Mining areas			

Scenario 1. This is the most strict scenario in which the most land is excluded. Only preferred land cover types are included. These are: Bush/shrub, Bare Land, Mining Areas and Savannah. These are the land cover types that are never or almost never excluded in literature (see Table 2.2). All other land cover types are excluded. This scenario results in the least interference with economic activities in agricultural areas.

Scenario 2. Next to the land cover types included in Scenario 2, dry & shrub-mixed dry agricultural land is also included. This land cover type is sometimes excluded in literature. This is because solar PV development could be possible on this type of land through land acquisition, and it wouldn't have an equally large impact on the provision of agricultural goods as the inclusion of the land cover types agricultural land or plantation forest have.

Scenario 3. Next to the land cover types included in scenarios 1 and 2, land cover types agricultural land and plantation forests are also included in this scenario. Through land acquisition, solar PV development might be possible. This scenario is the most optimistic scenario in which the least land is excluded based on land cover type. It results in the most interference with economic activities in agricultural areas.

The literature review in section 2.3.2 showed that ground slope can also be a constraint for the development of solar PV power plants. However, there is no general threshold commonly used: In literature, the used slope limit ranges between 2% and 17.6%. Therefore, this study will explore the effect of the exclusion of land because of slope by ranging the slope limit between 2 and 18%. Land will be categorized into five groups, depending on their slope. The further explored slope limits are: 2%, 6%, 10%, 14% and 18%. The number of slope limits was chosen to be able to get insights into the effect of different slope limits on the results while keeping the calculations feasible within the time and resource limitations of this thesis. The slope limits are combined with the three presented land cover scenarios, resulting in a total of fifteen scenarios ranging between 1A to 3E. An overview of the fifteen scenarios is given in Table 3.2. In the next steps of the method, the technical and economic potential will be calculated for each scenario.

Table 3.2: Land suitability scenarios set-up including land cover scenario number and used ground slope limit per scenario

Scenario	Used land cover exclusion scenario	Ground slope limit [%]
1A	1	2
1B	1	6
1C	1	10
1D	1	14
1E	1	18
2A	2	2
2B	2	6
2C	2	10
2D	2	14
2E	2	18
3A	3	2
3B	3	6
3C	3	10
3D	3	14
3E	3	18

Land cover buffers

As seen in the theoretical background on buffers in 2.3.3, buffers are appropriate to take into account for land cover types settlement areas, natural forests, plantations forests and for coastline. Based on the collected literature and interviews with industry experts, buffer sizes were chosen for this study which are presented in Table 3.3. The settlement area buffer size was chosen because it was found as the most frequently used buffer size in literature and it was found suitable for two Indonesian industry experts who were consulted through interviews, of which one wished to remain anonymous (D. Silalahi, personal communication, June 12, 2021; anonymous Indonesian industry expert, personal communication, June 25, 2021). An ocean buffer of 300 meters was chosen based on the suggested value in an interview with an industry expert (anonymous Indonesian industry expert, personal communication, June 25, 2021). For natural forests and plantation forests, due to the lack of buffers size suggestions for Indonesia in literature, the buffer size is based on the rule of thumb of a buffer size twice the height of nearby trees used in the Netherlands to avoid negative effects on the system output due to shadow effects and debris from nearby trees (Kronos solar employee, personal communication, June 5, 2021; Eneco employee, personal communication, June 11, 2021; Sunvest employee, personal communication, June 6, 2021). For Indonesia, it was found that the average tree height of natural forests in Sumatra was 23,5 meters in 2012 [Margono et al., 2012]. Due to the lack of more detailed or recent data on average tree heights for natural and plantation forests in Indonesia, the buffer size is set to 47 (twice 23,5) meters for both these land cover types. It should be noted that tree height varies for each forest and slope also influences the shadow effect. The appropriate buffer for each location is therefore very dependent on local circumstances. Furthermore, the shadow effect is likely to be less present in Indonesia due to the location closer to the equator than in the Netherlands. However, since debris is also a reason for a forests buffer, the buffer is still included.

Table 3.3: Buffer sizes per land type in this research

Land type	**Buffer size [m]**
Settlement area	500
Natural forests	47
Plantation forests	47
Coastline	300

3.2.2 Technological assumptions of utility-scale solar PV power plants

When assessing the technical and economic potential of utility-scale solar PV, it must be clear what type of utility-scale solar PV power plants the potentials are based on and which technology-related factors are assumed. Explanations of the most important technological assumptions follow next. An overview can be found in 3.4.

The PV modules are assumed to be ground-mounted and fixed-tilted.
Ground-mounted and fixed-tilted PV modules were chosen because (1) this is the market-dominating technology that has cost advantages compared to sun tracking modules and (2) the higher energy yield advantage of sun-tracking modules in Indonesia only has a limited effect because of the geographic location near the equator, as was both seen in the theoretical background in Section 2.1.

The PV modules are assumed to be polycrystalline silicon modules.
Although monocrystalline silicon modules are more efficient, as seen in Section 2.1, polycrystalline silicon modules are assumed in this study. These modules have a cost advantage over monocrystalline silicon modules. Furthermore, this type of technology is in line with what is assumed in the data-set on photo-voltaic power output (PVout) (see Section 3.4), which was the most complete, detailed and publicly available data-set on PVout that could be found by the author.

The land requirement of a utility-scale solar PV system is assumed to be 0,011 km²/MWp.
Land requirement refers to how much land is needed for a certain capacity of a power plant. The land requirement of a solar power plant is difficult to determine because of several reasons: (1) the unique local geographic circumstances in each power plant site, (2) the sizes and capacities of solar modules vary per power plant, and (3) land requirement varies per region throughout the world because of the different optimal angles at which fixed-tilted PV modules are placed. Therefore, it was chosen to base the land requirement assumption on three existing seven MWp solar PV power plants in Indonesia located in Lombok, of which the land requirement has been made publicly available by the ADB [2018b]. The land requirement for all three power plants is 0,011 km^2/MWp.

It should be noted, that the PV modules used in the three projects have a capacity of 325 W_p. This differs from the capacity of solar PV modules that are currently commercially available in Indonesia. According to a former consultant of utility-scale solar PV park development in Indonesia, the capacity of domestically produced polycrystalline solar PV modules currently range between 340 and 370 watt peak (W_p). Domestically produced PV modules are mostly used for Indonesian solar PV power plants, because of the local content requirement (LCR) regulations in place, which can be found under Ministry of Industry regulation no. 5/2017. Although the regulation only requires 60% of the value of PV modules to come from domestic sources, in reality usually only domestic PV modules are used. That is because domestically produced solar PV modules already include foreign components, attributing to the foreign value of the PV modules.

It is likely that the size of a 355 W_p PV module is larger than that of a 325 W_p PV module, resulting in a higher land requirement than is assumed in this research. However, this is expected to be partially balanced because of the higher system output when 355 W_p PV modules are used. The effects of the uncertainty of the land requirement on the outcomes of this research are further addressed in the sensitivity analysis in Section 3.5.

A utility-scale solar PV system is assumed to have an annual system degradation of 0,5%.
The electricity output of a utility-scale solar PV power plant degrades over the years. Table 2.4 in the theoretical background showed that estimated system degradation varies throughout literature. In this study, an annual system degradation of 0,5%, which falls within the found in literature and is also used by The World Bank [2020] in a recent study. It also falls within the range of the most recent recommendation in the report Technology Data for the Indonesian Power Sector, published by the Indonesian Directorate General of Electricity in 2021. In this report, it is stated that it is common to assign an annual degradation rate between 0,25 and 0,5% for Indonesian utility-scale solar PV systems.

A utility-scale solar PV system is assumed to have a lifetime of 25 years.
In literature, it is estimated that a utility-scale solar PV system has a lifetime between 20 and 35 years (see Table 2.4). In this study, a lifetime of 25 years is assumed, which is most commonly done in literature.

Table 3.4: Overview of the technological assumptions in this study concerning utility-scale solar PV systems in Indonesia

Technological factor	**Value**	**Unit**
Land requirement of an installed PV system	0,011	km2/MWp
Annual system degradation	0,5	%/year
System lifetime	25	years

3.2.3 Calculation of potential capacity and electricity generation

Now that the land suitability scenarios are set up and the technological assumptions are clear, the technical potential can be calculated. Potentials can be expressed in both potential capacity and potential electricity generation. Both are calculated in this study. The potentials are calculated on a local level (per five km²), provincial and national level, for each scenario. This is done by executing the next process steps for each scenario separately:

1. *Creation of buffers on selected land cover types and ocean*
   Using the buffer geoprocessing tool in the QGIS environment, a buffer is added to the land cover types settlement areas, plantation forests and natural forests, which are located in the land cover data layer [MoEF, 2017]. To include the ocean buffer, a negative buffer is included on the Indonesian land boundary data layer.

2. *Removal of the unsuitable land areas*
   From the land boundary data layer, the unsuitable land areas depending on the scenario are removed, including the buffers. This is done with the clip algorithm in QGIS.

3. *Removal of too small areas for utility-scale solar PV power plant*
   As a result of the removal of unsuitable land areas, isolated areas of land may remain that are too small to be able to develop a solar PV power plant of utility scale. Therefore, areas that cannot fit a one MWp power plant (which is the used threshold for utility-scale in this study, based on the proposed threshold by The World Bank [2020], are removed from the created available land data layer by selecting and removing those areas from the data layer using the select by attribute tool in QGIS. Areas are considered to be too small for a one MWp power plant if the area is smaller than 0,009 km². This is based on the assumed land requirement of 0,009 km² as discussed in Section 3.2.2. The area size of each isolated area is calculated using the add geometry columns algorithm in QGIS. The result of this step is a suitable land vector data layer.

4. *Creation of a data layer with five km² grid cells*
   A vector data layer is created in QGIS with five km² sized grid cells with the land borders of Indonesia as boundaries. To get as detailed results as possible, a high resolution is desirable. After exploration in QGIS, five km² was the lowest resolution that was feasible for this study given the restricted computational power and time.

5. *Overlaying the grid layer with the suitable land vector data layer*
   The five km² grid cell layer is clipped with the suitable land vector data layer using the clip algorithm in QGIS. What remains is a layer with (parts of) grid cells that are considered to be located on suitable land cover.

6. *Execution of the following processes for each grid cell:*
   a) Appointing the average slope [%] to the suitable area as an attribute using the zonal statistics algorithm in QGIS and the slope raster data as input (further discussed in Section 3.4). The zonal statistics algorithm calculates the average value of pixels of the slope raster data within a zone. In this case, the zone is the available area within a grid cell. This step is performed because the resolution of the slope raster data set (approximately one km_2) differs from that of the grid cells (five km²).
   b) Removing the grid cell if the average slope in the available area is equal to or larger than 18% by selecting and deleting those cells using the slope attribute value. This is done because of the unlikeliness of the development of a utility-scale solar PV power plant in such a location and the difficulties that would come with this. This is in line with slope limits used in literature as seen in Table 2.3, 17,6% being the highest slope limit used by a study of the IESR [2021a].
   c) Appointing the average PVout [KWh/KW_p] to the suitable area as an attribute using the zonal statistics algorithm in QGIS and the PVout raster data as input (further discussed in Section 3.4). The zonal statistics algorithm calculates the average value of pixels within a zone. In this case, the zone is the available area in the grid cell. This step is performed because the resolution of the PVout data set (approximately one km²) differs from that of the grid cells (five km²).
   d) Exporting the geospatial data-set to the Jupyter Notebook environment to continue the data analysis using python.

e) Calculating the potential capacity using the land requirement assumption presented in Section 3.2.2 and the size of the remaining available area in the grid cell. This is done using Formula 3.1.

$$\mathrm{P_i}\ [\mathrm{MWp}] = \frac{\mathrm{A_i}\ [km^2]}{\mathrm{L}\ [km^2/\mathrm{MWp}]} \tag{3.1}$$

Where:

$\mathrm{P_i}$ = technical potential capacity in the available area in grid cell i
$\mathrm{A_i}$ = available area size within grid cell i
L = land requirement per installed $\mathrm{MW_p}$ solar PV

f) Calculating the potential electricity generation using the calculated potential capacity and the average PVout value in the available area in the grid cell. See Formula 3.2.

$$\mathrm{E_i}\ [\mathrm{MWh}/year] = \mathrm{P_i}\ [\mathrm{MWp}]\ *\ \mathrm{PVout}\ [\mathrm{MWh/MWp}/year] \tag{3.2}$$

Where:

$\mathrm{E_i}$ = technical potential electricity generation in the available area in grid cell i
$\mathrm{P_i}$ = technical potential capacity in the available area in grid cell i
$\mathrm{PV_{out,i}}$ = average photo-voltaic power output in grid cell i per year

7. *Calculation of the provincial and total potential capacity*
Calculating the total potential capacity by summing the potential capacities of all the grid cells. See Formula 3.3. This is also done for each province separately, to get the potential capacity results per province.

$$\mathrm{P_{TP,\ total}}\ [\mathrm{MWp}] = \sum_{i=1}^{n} \mathrm{P_i}\ [\mathrm{MWp}] \tag{3.3}$$

Where:

$\mathrm{P_{TP,\ total}}$ = total potential capacity in Indonesia (technical potential)
$\mathrm{P_i}$ = technical potential capacity in the available area in grid cell i
n = number of grid cells

8. *Calculation of the provincial and total potential electricity generation*
Calculating the total potential electricity generation by summing the potential capacities of all the grid cells. See Formula 3.4. This is also done for each province separately, to get the potential electricity generation results per province.

$$\mathrm{E_{TP,\ total}}\ [\mathrm{MWh}/year] = \sum_{i=1}^{n} \mathrm{E_i}\ [\mathrm{MWh}/year] \tag{3.4}$$

Where:

$\mathrm{E_{TP,\ total}}$ = total potential electricity generation in Indonesia (technical potential)
$\mathrm{E_i}$ = technical potential electricity generation in the available area in grid cell i
n = number of grid cells

3.2.4 Presentation and visualisation of technical potential results

The technical potential is expressed in two measures: potential electricity generation and potential capacity. The results for each scenario and each measure are presented in tables and maps. In the tables, the numeric results on both a provincial and national level are presented. The available areas in each scenario are visualized in maps made in the QGIS software.

3.3 ECONOMIC POTENTIAL CALCULATION

The economic potential is measured in this study by calculating the LCOE for each grid cell and comparing that to the maximum allowable electricity purchase price for electricity produced by solar power plants in Indonesia that PLN pays to a power producer. This benchmark is further referred to as the power purchase agreement (PPA) tariff in this study. If the PPA tariff is equal to or higher than the LCOE in an area, there is assumed to be economic potential in that area for utility-scale solar PV power plant development. The area is called an economically viable area. The economic potential is quantified by aggregating the potential electricity generation and the potential capacity in the economically viable areas. Similar to the technical potential, the economic potential is therefore expressed in two measures. To complete the calculation of these measures, the following three steps are followed: LCOE calculation set-up (1) economic assumptions of utility-scale solar PV power plants and (3) calculation of potential capacity and electricity generation in areas that are considered economically viable. Next, each step is further explained.

3.3.1 LCOE calculation set-up

There are many different methods to calculate the LCOE of renewable energy technologies such as utility-scale solar PV [Visser and Held, 2014]. A simplified calculation method adapted to utility-scale solar PV technology is used in this research and is presented in Formula 3.5. The LCOE is calculated separately for each available area within a grid cell in each scenario and it represents the LCOE of a utility-scale solar PV power plant in that area.

$$\mathrm{LCOE} = \frac{\mathrm{CRF} * \mathrm{CAPEX} + \mathrm{OPEX}}{\mathrm{EG}_{\mathrm{average}}} \tag{3.5}$$

Where:

$$\begin{aligned}
\mathrm{CAPEX} &= \text{capital expenditures [US\$]} \\
\mathrm{OPEX} &= \text{operational expenditure [US\$/year]} \\
\mathrm{CRF} &= \text{capital recovery factor [-]} \\
\mathrm{EG}_{\mathrm{average}} &= \text{average annual electricity generation [KWh/year]}
\end{aligned}$$

For the input variable $\mathrm{EG}_{\mathrm{average}}$ the annual system degradation rate has to be taken into account. This technological assumption was explained in Section 3.2.2. The input value of the variable $\mathrm{EG}_{\mathrm{average}}$ is calculated using Formula 3.6.

$$\mathrm{EG}_{\mathrm{average}} = \frac{\sum_{t=0}^{\mathrm{T}-1}((1-\mathrm{SDR})^{t} * \mathrm{E_i})}{\mathrm{T}} \tag{3.6}$$

Where:

$$\begin{aligned} EG_{average} &= \text{average annual electricity generation [KWh]} \\ E_i &= \text{potential electricity generation in the available area within grid cell i [KWh]} \\ SDR &= \text{system degradation rate [\%]} \end{aligned}$$

Another variable that is used to calculate the LCOE, is the capital recovery factor (CRF). This is a ratio that is used to include present values of costs over the years. The CRF is calculated using Formula 3.7. The variables discount rate *r* and system lifetime *T* determine the CRF. The discount rate is a rate that is used to calculate the present value of future cash flows.

$$CRF = \frac{r}{1-(1+r)^{-T}} \tag{3.7}$$

Where:

$$\begin{aligned} CRF &= \text{capital recovery factor [-]} \\ r &= \text{discount rate [\%]} \\ T &= \text{solar PV system lifetime [years]} \end{aligned}$$

The CAPEX variable can be calculated with Formula 3.8. There is a distinction made between grid connection costs and other costs because grid connection costs vary per power plant depending on the distance to the nearest connection point. The further away a power plant is located, the more expensive the grid connection gets. More explanation on the grid connection costs and the included connection distance factor in the formula can be found in Section 3.3.2.

$$CAPEX = CAPEX_{\text{excluding GCC}} + GCC * D * DF \tag{3.8}$$

Where:

$$\begin{aligned} CAPEX &= \text{capital expenditures [US\$]} \\ GCC &= \text{grid connection costs [US\$/KW}_p\text{/km]} \\ D &= \text{distance to nearest connection point [km]} \\ DF &= \text{connection distance factor [-]} \end{aligned}$$

3.3.2 Economic parameter assumptions

To execute the LCOE calculation as presented in Section 3.3.1, more assumptions on economic parameters are needed next to the technological assumptions presented in Section 3.2.2. First of all, an important notion is that the LCOE does not refer to a utility-scale solar PV power plant with a fixed capacity size, such as a 50 MWp, but to a utility-scale solar PV power plant in general. This choice was made because most of the economic parameter estimations that are publicly available refer to utility-scale solar PV power plants in general, as was seen in Table 2.4 and discussed in Section 2.4. Next, the other assumptions for each economic parameter that is input for the LCOE calculation are explained and summarized in Table 3.5.

The discount rate r is assumed to be 9%.
The discount rate ranges in literature between 4 and 10%, as was seen in Table 2.4. This research considers 9%. This is the discount rate that is generally being used by the ADB [2020] for energy sector projects in Indonesia, in lack of official Indonesian data.

The CAPEX excluding grid connection costs is 1041 US$/KW$_p$
Estimations on the CAPEX for utility-scale solar PV plants vary in literature between 700 and 1200 US$/KW$_p$ for Indonesia, as can be seen in Table 2.4. In Section 2.4, the importance of using recent data due to the fast declining costs of solar PV power plant components such as the PV modules was discussed. For all cost components of the CAPEX except the solar PV module cost component, 2020 data published by IRENA [2021] was used, because this was the most complete and recent data-set that could be found with a detailed breakdown of the costs. For the solar PV module cost component, more recent data was found through an interview with a former solar PV power plant development consultant (anonymous Indonesian industry expert, personal communication, June 25, 2021). The former consultant estimates that in 2021, the solar PV module costs are 320 US$/KW$_p$. This is also assumed in this research. Taking into account the inflation rate between 2020 and 2021, the CAPEX of the entire system excluding grid connection is assumed to be 1041 US$/KW$_p$. For the inflation rate, the latest US government data as published by the Board of Governors of the Federal Reserve System [2021] was used. More details on the calculation of the CAPEX can be found in Appendix A.

Grid connection costs are assumed to be 4,42 US$/KW$_p$/km.
Grid connection costs are part of the CAPEX of the entire system, as seen in Formula 3.8. Grid connection costs are calculated for each grid cell based on the distance to the nearest connection point. A connection point in this study is defined as medium or high voltage substations as published by the MoEMR [2021a] and national, provincial and regional capitals, as published by the UN OCHA [2016]. That substations are assumed to be grid connection points is evident. National, provincial or regional capitals are also included because they are considered to be electricity demand centers. Although this does not necessarily mean that a substation is located there, and possibly a substation should be built there to be able to connect the solar power plant to the grid, capitals are still included. This is because the results of the economic potential analysis could show areas in which the LCOE is relatively low, and where it would therefore make sense for PLN to explore the possibility of investing in new substations if there are no substations located nearby but a demand center is.

As for the costs of grid connections to the nearest connection point, no recent data in terms of costs per kilometer could be found in literature for Indonesia. According to a former consultant for utility-scale solar development in Indonesia, grid connections costs for a 10 MWp power plant are estimated to be 44.236 US$/km in 2021 (anonymous Indonesian industry expert, personal communication, June 25, 2021). In absence of more detailed values for grid connections costs per kilometer, this value was taken to calculate the costs in US$/KW$_p$/km by dividing the total costs by 10.000 KW$_p$. This results in an assumption of grid connection costs of 4,42 US$/KW$_p$/km. This calculation assumes that the costs are linear per KW$_p$ and per km. In reality, this is expected to be different, because of fixed costs for every separate grid connection and the differences in costs for low, medium and high voltage cables. The size and voltage of the cables are dependent on the capacity size of the utility-scale solar PV power plant.

For the length of the cables for grid connection, the distance between the center of an area in a grid cell and the nearest connection point is calculated in the GIS-environment. However, in reality, cables are usually not placed in straight lines from power plants to connection points because of land ownership issues, ground characteristics and other factors. Therefore, a connection distance factor was included. The distance to the nearest substation or city, is multiplied by this factor, to better represent the true cable distance. The factor is set at 1,5 and will be varied in the sensitivity analysis discussed in Section 3.5.

The electricity price paid to a power producer is assumed to be equal to the maximum allowable PPA in a region.
In Indonesia, the PPA tariff paid for renewable energy sources to power producers is based on the BPP. When PLN is negotiating with an independent power producer (IPP) about the PPA tariff paid to the IPP, the BPP serves as a baseline. This regulation falls under the Ministry of Energy and Mineral Resources [2017a]. The national and regional BPPs are used to determine the maximum allowable PPA in a region. If the BPP in a region is lower than the national BPP, the PPA tariff can be up to 100% of the regional BPP. If the BPP in a region is higher than the national BPP, the PPA tariff can be up to 85% of the regional BPP In this research, to be able to compare the LCOE with the local PPA tariff, it is assumed that the tariffs are not up to these percentages, but exactly these percentages. This is a simplification of reality.

The BPP ranges regionally between 6,91 and 21,34 US$ct./KWh. The national BPP is 7,85 US$ct./KWh. A complete list of the BPP values per region can be found in Appendix B.

Overview of economic parameter assumptions
The assumptions for the economic parameters used as input for the LCOE calculation formula are summarized in Table 3.5. The sensitivity of the LCOE for each economic parameter will be explored in the sensitivity analysis, which is further explained in Section 3.5.

Table 3.5: Economic parameter assumptions

Parameter	Value	Unit
CAPEX	1041	US$/$KW_p$
OPEX	1,44	% of CAPEX/year
Discount rate	9	%
System degradation rate	0,5	%/year
Solar PV system lifetime	25	year
Grid connection costs	4,42	US$/$KW_p$/km
Connection distance factor	1,5	-

3.3.3 Calculation of potential capacity and electricity generation in economically viable areas

Now that the LCOE calculation method and the economic parameter assumptions are clear, the economic potential can be calculated. Similar to the technical potential, the economic potential is expressed in both potential capacity as well as potential electricity generation. The potentials are calculated on a provincial and national level, for each scenario. This is done by executing the next process steps for each scenario separately:

1. *Calculation of the distance to the nearest connection point for each grid cell*
   The distance to the nearest connection point for each grid cell is calculated with the distance to nearest hub algorithm in the QGIS environment. The distance is calculated between the nearest connection point and the center of the available area in the grid cell. The center of each grid cell is calculated using the polygon centroids algorithm.

2. *Assigning of the maximum PPA tariff to each grid cell.*
   Depending on the region of the nearest connection point and the corresponding BPP, a maximum PPA tariff is assigned to each grid cell. This is done by

transferring the BPP region of the connection point as an attribute to the grid cell when the distance to nearest hub algorithm is carried out. Then, based on the BPP, the maximum PPA is calculated for each grid cell, following the method explained in Section 3.3.2. The BPP regions are manually added to the connection points in QGIS. A problem that arises is that the boundaries of the BPP regions are not always clear in the overview of the MoEMR [2017a]. Therefore, it is sometimes not clear to what BPP region a capital or substation belongs to. In those cases, a BPP region is assigned based on the nearest known BPP region by the author using google maps.

3. *Calculation of the CAPEX for each grid cell.*
The CAPEX and grid connection costs related assumption and the distance to the nearest connection point of each grid cell are used as input for Formula 3.8 and the CAPEX is calculated for each grid cell in US$/$KW_p$. That figure is multiplied by the potential capacity in the available area in the grid cell, which was previously done in the technical potential calculation as can be seen in Formula 3.1.

4. *Calculation of the LCOE for each grid cell.*
Using Formulas 3.5 and 3.6, the LCOE is calculated for each grid cell. The result is the LCOE expressed in US$ct./KWh.

5. *Determining if a grid cell is an economically viable area for utility-scale solar PV development.*
In this study, an area is considered to be economically viable for utility-scale solar PV power plant development, if the assumed PPA tariff is higher than the calculated LCOE. This is easily checked for each grid cell and results in a binary result: if the area is assumed to be economically viable or not.

6. *Calculation of provincial and total potential capacity in economically viable areas*
The total potential capacity is calculated by summing the potential capacities of all the grid cells that are considered to be economically viable. See Formula 3.9. This is also calculated for each of the provinces separately. The final numbers on potential capacity are expressed in PWh/year.

$$\mathrm{P_{EP,\ total}}[\mathrm{MWp}] = \sum_{i=1}^{n} \mathrm{P_i}\ [\mathrm{MWp}] \tag{3.9}$$

Where:

$$\begin{aligned} \mathrm{P_{EP,\ total}} &= \text{total potential capacity in Indonesia (economic potential)} \\ \mathrm{P_i} &= \text{technical potential capacity in the available area in grid cell i} \\ n &= \text{Number of grid cells that are considered to be} \\ &\quad\ \text{economically viable for utility-scale solar PV development} \end{aligned}$$

7. *Calculation of provincial and total potential electricity generation in economically viable areas.*
The total potential electricity generation is calculated by summing the potential electricity generation of all the grid cells that are considered to be economically viable. See Formula 3.10. This is also calculated for each of the provinces separately. The final numbers on potential electricity generation are expressed in PWh/year.

$$\mathrm{E_{EP,\ total}}[\mathrm{MWh}/year] = \sum_{i=1}^{n} \mathrm{E_i}\ [\mathrm{MWh}/year] \tag{3.10}$$

Where:

$$E_{\mathrm{EP,\,total}} = \text{total potential electricity generation in Indonesia (economic potential)}$$
$$E_{\mathrm{i}} = \text{technical potential electricity generation in the available area in grid cell i}$$
$$n = \text{Number of grid cells that are considered to be economically viable for utility-scale solar PV development}$$

3.3.4 Presentation and visualisation of economic potential results

The results on economic potential are threefold: there are results on the LCOE, the potential electricity generation and the potential capacity of utility-scale solar PV in Indonesia. The results are presented by means of tables, graphs and geographic maps. The tables and graphs are created in the Jupyter Notebook environment using python. The geographic maps are created in QGIS.

The LCOE values are plotted into maps for each scenario using colours for different LCOE value categories. These maps help visualize the locations of relatively low and high LCOE results within Indonesia.

The results on the potential electricity generation and potential capacity are numerically shown in tables per scenario on both a provincial and national level. Furthermore, maps are created that show which part of the areas have technical potential but are not considered to be economically viable. These maps help visualize in which areas in Indonesia there is expected to be economic potential for utility-scale solar PV.

3.4 USED DATA-SETS & DATA PRE-PROCESSING

An overview of the geospatial data-sets that are used in this research for the calculation of the technical and economic potential presented in the previous sections, can be found in Table 3.6. Next, each data set and the pre-processing of the data set, if relevant, is discussed in more detail.

Table 3.6: Data-sets used for the GIS modeling of the technical and economic potential of utility-scale solar PV power plants in Indonesia

Data	Spatial Resolution	Year of data	Source
Administrative country & province borders	Polygon vector layer	2021	BPS [2020a]
Ground slope	30 arcsec. (approx 1 km)	2020	Derived from terrain elevation data-set from the Global Solar Atlas [2020]
Photo-voltaic power potential	30 arsec. (approx. 1 km)	2019	Solargis [2019]
Land cover	Polygon vector layer	2017	MoEF [2017]
Protected areas	Polygon vector layer	2021	UNEP-WCMC [2021]
National, provincial & regency capitals	Point layer	2016	UN OCHA [2016]
Power substations kV >70	Point layer	2021	MoEMR [2021a]

3.4.1 Administrative country & province borders

Since only land falls into the scope of this research, data layers on the land and province borders of Indonesia were retrieved. The data layers of Badan Pusat Statistik (BPS), the governmental statistics institute of Indonesia, are used [2020a]. The data layers are updated each year.

3.4.2 Ground slope

Ground slope is one of the geographic constraints to determine the suitability and availability of land for utility-scale solar PV development. A data layer of the slope is therefore included. The ground slope is calculated with the slope algorithm in QGIS using a raster data-set on land elevation above sea level from the Global Solar Atlas [2020]. The resolution of the data-set is approximately one km².

3.4.3 Photo-voltaic power potential

The output of utility-scale solar PV power plants differs based on factors such as the solar radiation in a specific area. To include the effect of solar radiation and other relevant factors that impact the output of a PV system, a PVout data-set is used. The PVout data-set was obtained from the Solargis [2019] and is based on long term daily solar irradiance averages measured with satellite data. PVout represents the potential electricity generation of a one KW_p solar PV plant over a year. The unit is KWh $/KW_p$ /year. Solar irradiation, air temperature, terrain, losses in energy conversion in the PV modules and in other components of the PV system have been taken into account. The resolution of the data-set is approximately one km². The data-set assumes a ground-mounted solar PV system with polycrystalline silicon PV modules. These are the same assumptions that are used for the PV systems in this research.

3.4.4 Land cover

As land often already has a purpose, land-use restrictions for solar PV development are appropriate. To assess land cover, a data-set from the Indonesian MoEF is used [2017]. The purpose of this data set is to publish official data from the government on land cover for Indonesia in the year 2017. The data-set was chosen because it comes from an official Indonesian government source. The data set divides land cover into 23 categories. Based on their relation to solar PV development, they are redivided into 12 categories, as was substantiated in Section 2.3.1 (protected areas are separately handled because of the different data source). The renaming of some of the polygons belonging to certain land cover types was done in QGIS by selecting these polygons based on attribute value and changing the attribute value in the attribute table manually.

3.4.5 Protected areas

Next to the land cover categories based on the MoEF categorization, protected areas are also included as a land cover type in this research. Protected areas include, among other things, national parks, wildlife reserves and nature reserves. The data on protected areas is retrieved from the World Database of Protected Areas [2021], since protected areas are not included in the land cover data-set from the MoEF. The data is updated on a monthly basis, and the protected areas in Indonesia that are included are verified through authoritative sources from the Indonesian government.

3.4.6 National, provincial & regency capitals

The national, provincial and regional capitals are retrieved from a data-set of the UN OCHA [2016]. A point represents a capital. These capitals act as connection points in this research. In QGIS, each capitals gets assigned a BPP region based on the BPP data from the MoEMR [2017a] and the location of the capital. This is done by manually selecting capitals in a BPP region and attributing the region as an attribute.

In some regions, no explicit BPP is listed. For the capitals located in those regions, the BPP of the nearest listed BPP region was assigned.

3.4.7 Power substations

The power substation data-set is retrieved from the MoEMR geoportal [2021a]. A point represents a power substation. The power substations act as connection points in this research. Only medium and high voltage substations are relevant for connecting a utility-scale solar PV power plant to the grid. Therefore, substations with a voltage below 70 kV are removed from the data-set in QGIS using the select and delete by attribute tool.

3.5 SENSITIVITY ANALYSIS

A sensitivity analysis is performed to show how variation in the technical and economic input parameters alter the outcomes. A sensitivity analysis is performed for the LCOE by varying some of the input parameters by +/- 20%, while keeping the other parameters constant. The input parameters discount rate, CAPEX, OPEX, system degradation rate, solar PV system lifetime, grid connection costs, connection distance factor and PVout are assessed. These are all input parameters for the LCOE calculation method as can be seen in Section 3.3. The sensitivity analysis is performed in scenario 3E. This is the least restrictive scenario when it comes to site selection criteria.

A separate sensitivity analysis for the CAPEX input parameter is also performed by varying the CAPEX between 0 and -90%. This is done because the CAPEX has been declining globally for decades (as discussed in Section 2.4) and there are predictions that it will decline even further. IRENA [2019] projects the CAPEX to drop globally between 31 and 72% by 2030 and between 60 and 86% by 2050 compared to the CAPEX in 2019. The declining costs are attributed to technological improvements and economies of scale.

4 TECHNICAL POTENTIAL RESULTS

In this chapter, the results of the GIS-based technical potential analysis of utility-scale solar PV in Indonesia are presented. First, a general exploration of the land cover types and slope in Indonesia is presented in Section 4.1. Then, the results per scenario are presented in tables and visualised in geographic maps, which are made in QGIS. The results on a national level are presented in Section 4.2 and on a provincial level in Section 4.3. Conclusions on the technical potential analysis results are drawn in Section 4.4. Finally, the technical potential results on a national level are compared with estimations found in literature in the validation in Section 4.5.

4.1 EXPLORATION OF LAND COVER TYPES AND GROUND SLOPE LIMITS

Land cover types
Table 4.1 shows the land cover type distribution in Indonesia based on the land cover and protected areas data-sets [MoEF, 2017; UNEP-WCMC, 2021]. The largest part of the country's landmass (46,5%) consists of natural forests. About 18% of the landmass is covered with dry & shrub-mixed dry agricultural land. Out of the entire landmass, 15% is located in protected areas. Of all protected areas, about 78% overlaps with natural forests.

Table 4.1: Land cover of Indonesia's landmass, sorted on area size

Land cover type	Area size [km²]	Percentage of land mass [%]
Natural forest	888.423	46,5
Dry & shrub-mixed dry agricultural land	343.256	18,0
Agricultural land	242.484	12,7
Bush/shrub	152.698	8,0
Wetland area	94.087	4,9
Bodies of water	37.680	2,0
Settlement area	35.768	1,9
Bare land	35.420	1,9
Savannah	46.283	1,4
Mining area	69.283	0,4
Airports & harbours	221	0,01
Out of which protected area	*291.767*	*15*

Ground slope limits
Table 4.2 shows the effect of different slope limits on the suitability of land for solar PV power plant development, not taking into account any other land cover site selection criteria. Using the most strict slope limit of 2%, up to 53% of Indonesia's landmass remains available for solar PV development. When the least strict slope limit of 18% is used, up to 94% of the landmass can be used. This shows that it is

important to address different slope limits for the calculations of the technical and economic potentials

Table 4.2: Suitable landmass for utility-scale solar PV power plant development based on the criteria ground slope limit only; figures are rounded to the nearest integer

	Suitable area	
Slope limit [%]	*Area [km²]*	*Percentage of total land mass [%]*
18	1.769.460	94
14	1.706.597	90
10	1.451.957	77
6	1.272.521	67
2	998.063	53

4.2 RESULTS PER SCENARIO ON A NATIONAL LEVEL

Table 4.3 shows the estimated technical potential for utility-scale solar PV in Indonesia for each scenario. The technical potential is expressed in both capacity [TW_p] and electricity generation [PWh/year]. The potential capacity in Indonesia ranges between 9 and 53 TW_p. The electricity generation ranges between 12 and 72 PWh/year. The potential is the lowest in scenario 1A and the highest in scenario 3E. This makes sense since scenario 1A is the scenario with the most strict site selection criteria and scenario 3E is the least strict. See Table 3.2 for an overview of the site selection criteria for each scenario. From these results, it becomes clear that both the land cover exclusion criteria, as well as the slope limits, have a significant impact on the estimated technical potential of utility-scale solar PV in Indonesia.

Table 4.3: National technical potential and capacity factor results for each scenario; figures on the potentials are rounded to the nearest integer

Scenario	**Potential capacity [TW_p]**	**Potential electricity generation [PWh/year]**	**Capacity factor [%]**
1A	9	12	15
1B	12	16	15
1C	14	19	16
1D	14	20	16
1E	14	20	16
2A	20	27	15
2B	29	39	16
2C	33	45	16
2D	35	47	15
2E	35	48	16
3A	35	48	16
3B	46	62	16
3C	51	69	16
3D	53	72	16
3E	53	72	16

The capacity factor in Table 4.3 refers to the ratio between the capacity and the actual expected electricity generation of a utility-scale solar PV system. It ranges between 15 and 16% depending on the scenario. That the capacity factor does not vary much per scenario, can be attributed to the following: although there are local exceptions, the capacity factor throughout Indonesia does not vary drastically. A basic descriptive statistics analysis of the generated data in the Python environment showed that in 50% of the suitable land in the least strict scenario, the capacity factor ranges between 15 and 15%. 25% has a lower capacity factor and the other 25% has a higher capacity factor. These statistics remain the same in the other scenarios. This means that more strict criteria do not lead to significantly more exclusions of areas with relatively high or low photo-voltaic power output compared to the average in Indonesia.

4.3 RESULTS PER SCENARIO ON A PROVINCIAL LEVEL

Table 4.4 shows the estimated technical potential for each Indonesian province expressed in both potential capacity and potential electricity generation. Only the results of scenario 1A (most restrictive) and scenario 3E (least restrictive) are shown because this shows in which range the potentials are estimated to be. The table is sorted based on the potential capacity value in scenario 1A from low to high. The provincial demand per province is also included in the table. In the least restrictive scenario, the technical potential expressed in electricity generation is can cover the electricity demand in every province. This is not the case for every province in the least restrictive scenario: In seven provinces, the technical potential is lower than the electricity demand in 2018. These provinces area: Bali, Daerah Istemewa Yogyakarta, Jawa Barat, Sulawesi Utara, Jawa Tengah, Banten and Jawa Timur. What stands out from these results is that these are also some of the provinces with the highest electricity demand in the country. Banten, Jawa Barat, Jawa Tengah and Jawa Timur (all located on Java) together account for about 66% of the total electricity demand and are all found with the top 10 rows of the table.

Table 4.4: Provincial technical potential results for the most restrictive scenario 1A and the least restrictive scenario 3E; figures on the potentials and demand are rounded to the nearest integer

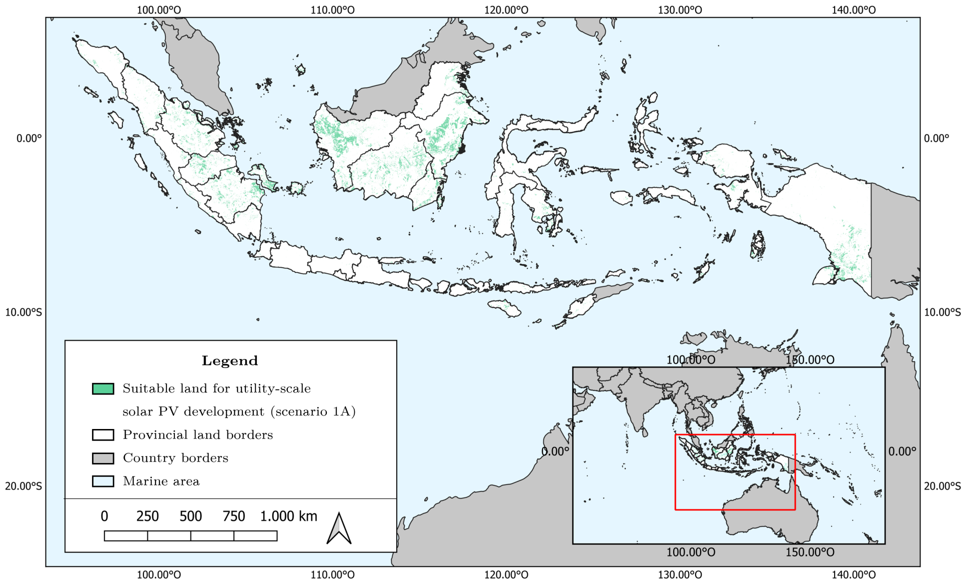
Province	Potential capacity [GW$_p$]		Potential electricity generation [TWh/year]		Electricity demand in 2018 [TWh/year][1]
	Scenario 1A	Scenario 3E	Scenario 1A	Scenario 3E	
Bali	<1	83	<1	120	5
Daerah Istimewa Yogyakarta	<1	101	<1	151	3
Gorontalo	<1	244	1	363	<1
Jawa Barat	<1	1172	1	1597	53
Sulawesi Utara	1	405	1	579	2
Jawa Tengah	2	928	3	1311	24
Banten [2]	2	344	3	455	57
Nusa Tenggara Barat	4	412	6	657	2
Jawa Timur	4	1583	7	2342	36
Sulawesi Barat	7	406	10	575	<1
Maluku Utara	22	625	31	889	<1
Sulawesi Tengah	34	1158	50	1635	1
Sulawesi Selatan	34	1747	52	2539	5
Bengkulu	44	866	64	1206	<1
Lampung	45	1098	62	1478	4
Sumatera Barat	55	1433	75	1926	4
Aceh	85	892	118	1229	3
Nusa Tenggara Timur	87	1537	144	2480	<1
Kepulauan Riau	106	259	139	340	3
Maluku	118	846	165	1202	<1
Sulawesi Tenggara	160	987	229	1403	<1
Kalimantan Utara	165	665	224	911	<1
Papua Barat	165	376	226	514	<1
Sumatera Utara	185	4027	252	5377	10
Kalimantan Selatan	275	1832	361	2409	3
Kepulauan Bangka Belitung	355	907	466	1185	1
Jambi	377	2509	488	3246	1
Riau	466	4914	603	6383	4
Sumatera Selatan	674	4500	896	6034	6
Papua	913	1563	1193	2060	<1
Kalimantan Tengah	1025	4298	1363	5746	1
Kalimantan Barat	1577	6191	2129	8292	2
Kalimantan Timur	1686	4085	2214	5351	4

Figure 4.1 includes geographic maps that show the locations of the land that is considered suitable for scenario 1A, 2c and 3E. 1A is the most restrictive scenario, 3E is the least restrictive scenario, and 2C is in between based on the potential results as presented in Table 4.3. The large differences in estimated technical potential per scenario are visible on a national level. On a provincial level, the maps show that the varying of the site selection criteria affects all provinces. This is supported by the numerical results in Table 4.4, which showed that each province is sensitive for the site selection criteria.

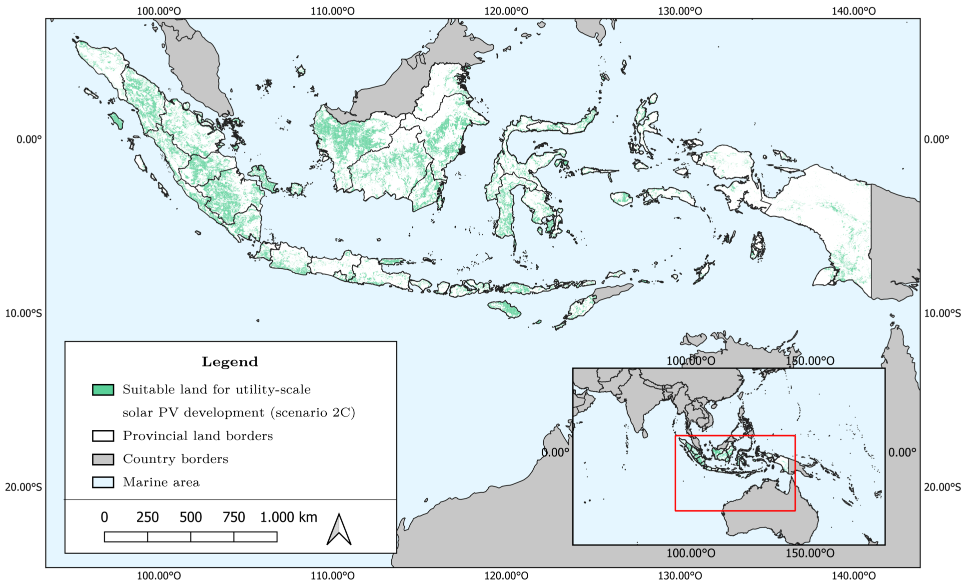
1 The electricity demand in 2018 was retrieved from the statistical yearbook of BPS [2020b], which provides data on the distributed electricity per province in 2018. The electricity demand is assumed to be equal to this.

2 The electricity demand of the special province of DKI Jakarta was added to that of the neighbouring province of Banten, as well as the potential figures. This has been done because the Jakarta province is the smallest province of Indonesia in terms of land area and mainly exists of the settlement area land cover type, but it has the third-highest electricity demand (33 TWh/year).

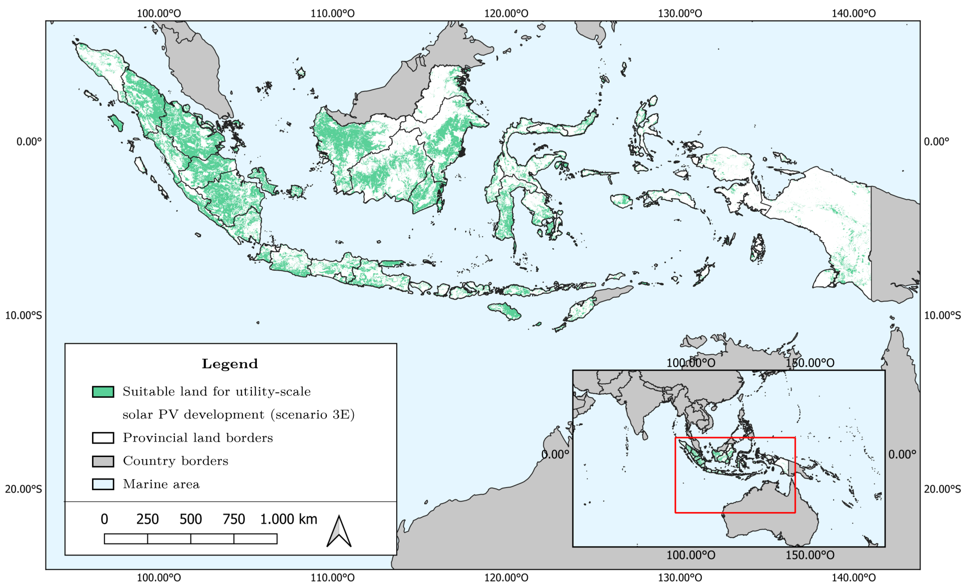
Figure 4.1: Suitable land for utility-scale solar PV development in scenario 1A, 2C and 3E



(a) Scenario 1A



(b) Scenario 2C



(c) Scenario 3E

4.4 CONCLUSION ON TECHNICAL POTENTIAL RESULTS

Depending on the scenario, the technical potential of utility-scale solar PV in Indonesia is estimated to range between 9 and 53 TW_p. This range results in an estimated electricity generation between 12 and 72 PWh/year. The large differences per scenario show the importance of including or excluding land cover types and the choice of slope limit for the outcomes of the potentials. Although there are large differences in the outcomes, the calculated potentials can still completely cover the total electricity demand in 2018 in Indonesia of 0,2 PWh/year (rounded to one decimal) in every scenario. The capacity factor is calculated to range between 15 and 16% on average per scenario. This means that the varying site selection criteria do not specifically affect exceptionally low or high irradiation areas.

On a provincial level in the least strict scenario, the potential electricity generation is higher than the electricity demand in 2018 in every province. However, this is not the case for the most strict scenario: seven provinces cannot cover the electricity demand in 2018 with the calculated potential electricity generation. Banten, Jawa Barat, Jawa Tengah and Jawa Timur, which together account for about 60% of the electricity demand in 2018, all belong to these seven provinces. This means that if utility-scale solar PV were to play a large role in fulfilling the electricity demand in those provinces, less preferable land such as land which has a ground slope higher than 2% or some form of agricultural land should be considered for the development of the power plants.

Overall, the technical potential results show that utility-scale solar PV can be developed in all provinces to some extent (without taking economic factors into account). This underlines the potential that utility-scale solar PV as a renewable energy technology has for Indonesia and the role that it could play in the energy transition. The technical potential is able to cover the 2018 electricity demand in most provinces. Exceptions are for some of the provinces with the highest electricity demand, which have the lowest range in potentials. In those provinces, less preferable land should be considered for utility-scale solar PV power plant development if it were to play a large role in meeting the electricity demand. The next chapter focuses on which areas with technical potential also have economic potential.

4.5 VALIDATION OF TECHNICAL POTENTIAL RESULTS

For the validation of the technical potential, the results expressed in electricity generation and capacity on a national level are compared with results found in other studies. An overview of the estimations in literature is presented in Table 4.5.

Table 4.5: Estimations of the technical potential of Indonesia on a national level found in literature

	Technical potential	
Reference	**Capacity** [TW_p]	**Electricity generation** [PWh/year]
This study	9 - 53	12-72
IESR [2021a]	3 - 20	5 - 27
Kunaifi et al. [2020]	0,07 - 3	0,1 - 5
Silalahi et al. [2021]	-	4 - 9

Silalahi et al. [2021] estimate a lower range in electricity generation than in this study, which can be explained by the focus of this study on solely agricultural land with low crops and abandoned mining sites for ground-mounted utility-scale solar PV projects to keep interference with economic activities and the environmental impact to a minimum. Whereas this study also looks at other land cover types.

The IESR [2021a] use a similar approach with several land exclusion scenarios. Also, the same data-set on land cover is used [MoEF, 2017]. However, the high estimate in this study for the technical potentials is more than twice the high estimate in this study. This can be explained by the differences in assumption for the value of the land requirement. The land requirement is assumed to be 0,011 km^2/MWp in this research, whereas the land requirement used by the IESR is 0,024 km^2/MWp. This directly affects the technical potential results. The land requirement used by the IESR can be seen as a conservative estimation, given that three existing solar PV power plants in Lombok all have a land requirement of 0,011 km^2/MWp.

Finally, Kunaifi et al. [2020] estimate a much lower range compared to this research. This can be attributed to the inclusion of provincial demand as a limiting factor (the potential may not exceed this in the low estimate), which is not assessed in this research. Furthermore, the used method excludes rural areas completely based on the assumption that no electricity grid is located in those areas. For urban cores, suburbs and villages, land availability factors are considered. Combined, these methodological differences lead to a lower estimation of the size of the land that is available for utility-scale solar PV development, resulting in differences in technical potential estimations.

5 ECONOMIC POTENTIAL RESULTS

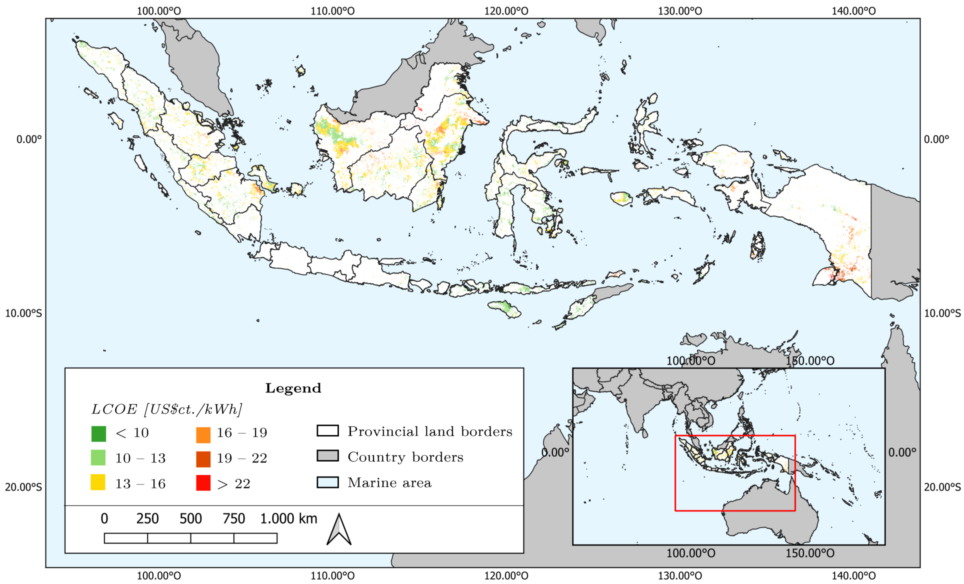
In this chapter, the results of the GIS-based economic potential analysis of utility-scale solar PV in Indonesia are presented. The main results on the economic potential are twofold: first, the results of the LCOE calculation are presented in Section 5.1. Then, the results on the economic potential expressed in both potential capacity and potential electricity generation are presented on a national and provincial level in respectively Section 5.2 and Section 5.3. The results of the sensitivity analysis on the LCOE are presented in Section 5.4. Finally, conclusions on the results are drawn in Section 5.5. A validation of the results on the LCOE can be found in Section 5.6.

5.1 LCOE

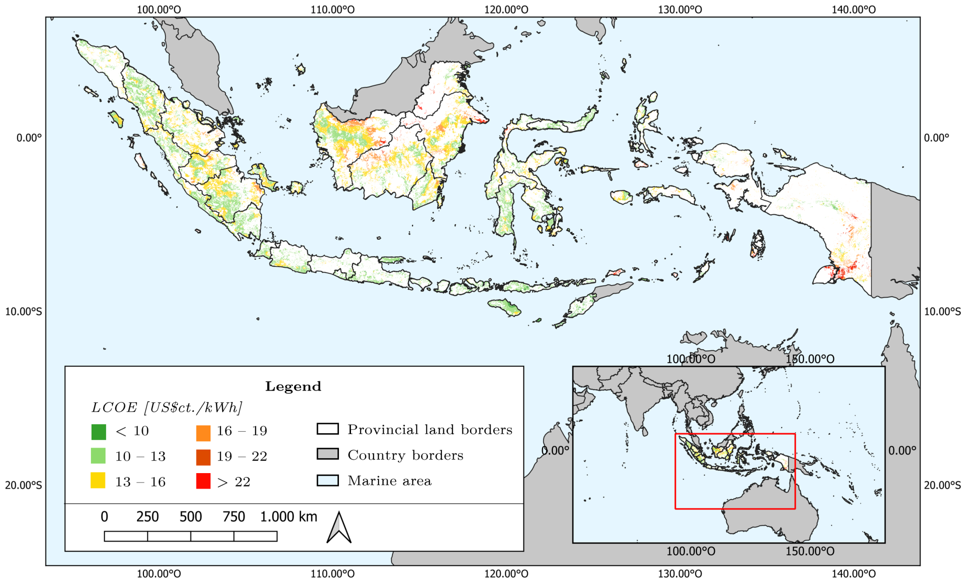
The calculated LCOE for utility-scale solar PV ranges on a national level between 7,4 and 24,9 US$ct./KWh. Figure 5.1 shows the LCOE distribution across Indonesia in geographical maps for scenarios 1A, 2C and 3E. A descriptive statistics analysis in the python analysis showed that in all three scenarios, the average LCOE is 12 US$ct./KWh and 75% of the suitable land has an LCOE lower than 13 US$ct./KWh (values rounded to the nearest integer). This indicates that the site selection criteria do not heavily affect areas with relatively high or low LCOE values.

On a provincial level, the average LCOE varies between 9,3 US$ct./KWh (Nusa Tenggara Timur) and 14,2 US$ct./KWh (Papua). These minimum and maximum values were found in scenario 1A. A complete list of the average LCOE values per province in scenario 1A, 2C and 3E can be found in Appendix E. It is important to note that similar to the average LCOE on a national level, the average LCOE does not vary much per scenario.

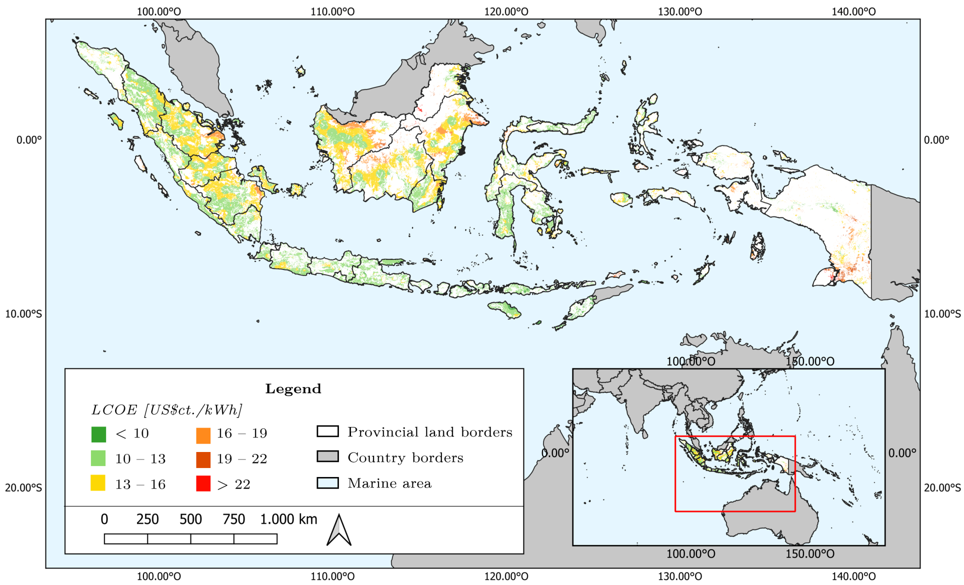
Figure 5.1: Distribution of LCOE results for utility-scale solar PV in scenario 1A, 2C and 3E



(a) Scenario 1A



(b) Scenario 2C



(c) Scenario 3E

5.2 RESULTS PER SCENARIO ON A NATIONAL LEVEL

As explained in the economic potential calculation method in Section 3.3, it is determined for each available area within a grid cell whether there is economic potential based on a comparison between the estimated LCOE and the assumed PPA tariff. The total economic potential is calculated by summing the potential capacities and potential electricity generation of the areas that are considered to be part of the economic potential, based on the definition used in this research. The economic potential is expressed in both potential capacity [TW_p] and potential electricity generation [PWh/year]. Table 5.1 shows the results of the economic potential analysis of utility-scale solar PV power plants in Indonesia. The capacity factor is 15% in every scenario. The potential capacity ranges between 2 and 9 TW_p. The potential electricity generation varies between 2 and 12 PWh/year.

The results are significantly different from the estimated technical potential. The minimum estimated potential capacity for the technical potential is 9 TW_p, whereas the maximum estimated capacity for the economic potential is also 9 TW_p. The same goes for the potential electricity generation. The minimum estimated potential capacity for the technical potential is 12 TW_p, whereas the maximum estimated capacity for the economic potential is also 12 TW_p. The difference is visualized in a graph that shows the ranges of both the technical and economic potential expressed in potential electricity generation in Figure 5.3. Although the estimated economic potential is smaller than the technical potential, the potential can still cover the total electricity demand in 2018 in Indonesia of 0,2 PWh/year (rounded to one decimal) in every scenario.

Table 5.1: National economic potential and capacity factor results for each scenario; figures are rounded to the nearest integer

Scenario	Potential capacity [TWp]	Potential electricity generation [PWh/year]	Capacity factor [%]
1A	2	2	15
1B	3	3	15
1C	3	4	15
1D	4	5	15
1E	4	5	15
2A	3	4	15
2B	5	7	15
2C	7	10	15
2D	8	10	15
2E	8	10	15
3A	3	4	15
3B	6	8	15
3C	8	11	15
3D	9	12	15
3E	9	12	15

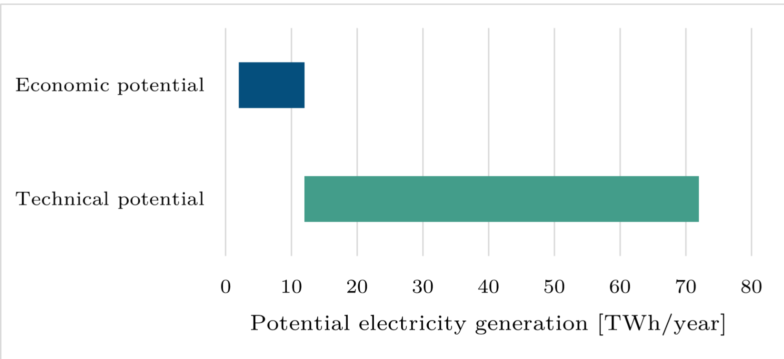


Figure 5.3: Estimations of the range of economic potential next to the estimated technical potential range expressed in electricity generation [TWh/year]

5.3 RESULTS PER SCENARIO ON A PROVINCIAL LEVEL

Table 5.2 shows the estimated economic potential expressed in potential capacity and potential electricity generation per province. The table is first sorted on potential capacity in scenario 1A from low to high, and then sorted based on the 2018 electricity demand from high to low. Although previous results on a national level showed that the estimated potential range was able to cover the electricity demand in 2018, that is different on a provincial level.

The results in Table 5.2 show that in 12 provinces, no economic potential was found in any scenario. Among these 12 provinces are three provinces with a relatively high electricity demand compared to the other provinces: Banten, Jawa Barat and Jawa Tengah. These three provinces combined accounted for 49% of the electricity demand in 2018. It should be noted that the average LCOE values in these provinces are not particularly high, as can be seen in the provincial LCOE results in Appendix E. All three provinces have an average LCOE value equal to or lower than 11 US$ct./KWh, which is lower than the national average of 12 US$ct./KWh. The lack of economic potential can be attributed to the relatively low maximum PPA tariffs in these provinces. This situation poses an issue for utility-scale solar PV development in the provinces where renewable energy technology development is arguably needed in light of the goals of the MoEMR and the high electricity demand.

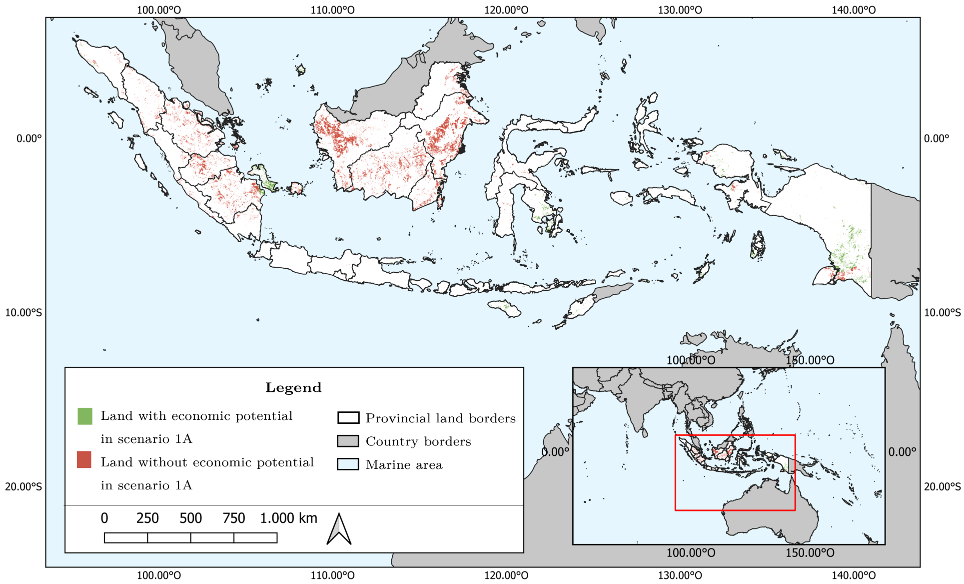
Table 5.2: Provincial economic potential results for the most restrictive scenario 1A and the least restrictive scenario 3E next to the 2018 electricity demand; figures are rounded to the nearest integer

Province	**Potential capacity [GWp]**		**Potential electricity generation [TWh/year]**		**Electricity demand in 2018 [TWh/year]**[1]
	Scenario 1A	Scenario 3E	Scenario 3E	Scenario 3E	
Banten[2]	0	0	0	0	57
Jawa Barat	0	0	0	0	53
Jawa Tengah	0	0	0	0	24
Bali	0	0	0	0	5
Lampung	0	0	0	0	4
Kalimantan Timur	0	0	0	0	4
Daerah Istimewa Yogyakarta	0	0	0	0	3
Kalimantan Barat	0	0	0	0	2
Jambi	0	0	0	0	1
Bengkulu	0	0	0	0	<1
Sulawesi Barat	0	0	0	0	<1
Kalimantan Utara	0	0	0	0	<1
Kalimantan Selatan	0	6	0	7	3
Riau	0	2	1	3	4
Gorontalo	1	230	1	320	<1
Kalimantan Tengah	1	10	1	13	1
Sulawesi Utara	1	392	1	527	2
Sulawesi Selatan	2	51	3	73	5
Sumatera Barat	3	49	3	60	4
Jawa Timur	3	324	5	457	36
Nusa Tenggara Barat	4	413	6	616	2
Sumatera Utara	13	319	16	387	10
Sulawesi Tengah	15	613	21	808	1
Aceh	18	90	24	118	3
Maluku Utara	20	576	27	770	<1
Kepulauan Riau	38	80	47	98	3
Sumatera Selatan	66	100	82	124	6
Papua Barat	67	192	88	250	<1
Nusa Tenggara Timur	88	1537	136	2325	1
Maluku	113	790	149	1052	<1
Sulawesi Tenggara	159	945	214	1262	<1
Kepulauan Bangka Belitung	266	658	327	807	1
Papua	629	1191	763	1471	<1
Total	*1508*	*8567*	*1915*	*11549*	*239*

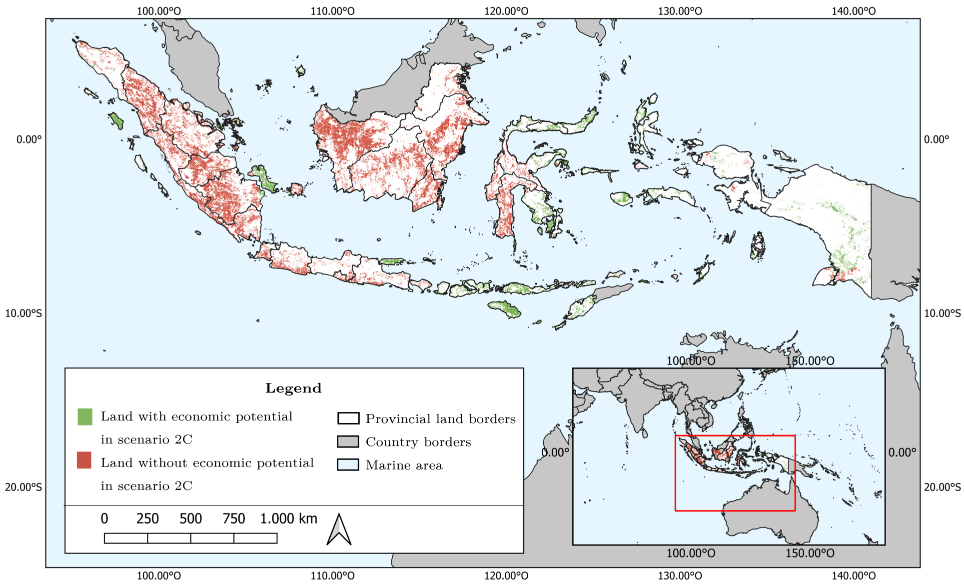
Figure 5.4 visualizes how areas with assumed economic potential for utility-scale solar PV development, according to the definition used in this research, are distributed over the provinces. Again, the results are shown for scenarios 1A, 2C and

3E. The maps show clearly that the majority of the land that is considered to be part of the technical potential does not have economic potential given the currently estimated LCOE and assumed PPA tariffs. Most of the economic potential can be found in the eastern part of Indonesia and on several small islands around the archipelago. There is a lack of economic potential in some of the provinces where the electricity demand is relatively high compared to other provinces.

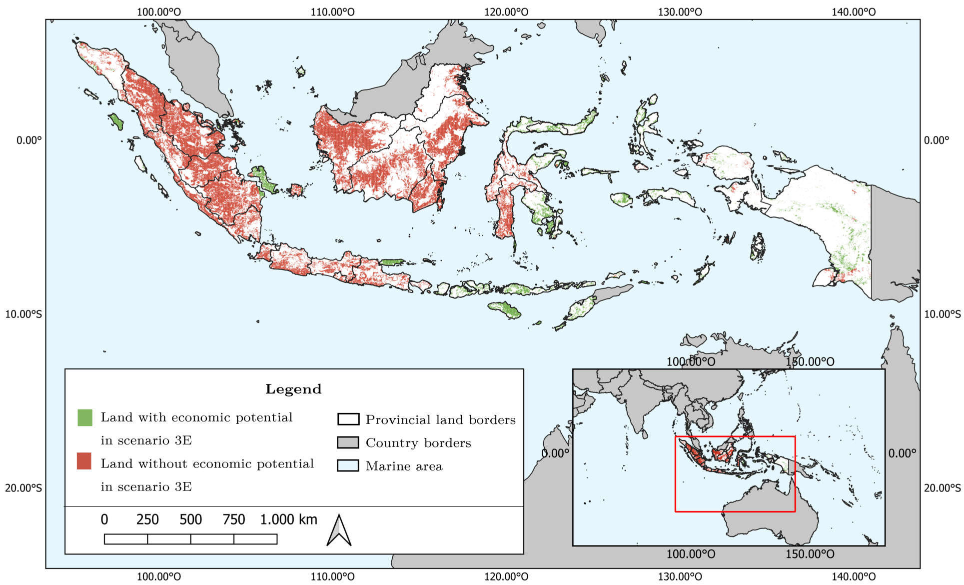
Figure 5.4: Distribution of economic potential for utility-scale solar PV in scenario 1A, 2C and 3E



(a) Scenario 1A



(b) Scenario 2C



(c) Scenario 3E

5.4 SENSITIVITY ANALYSIS OF LCOE

Two sensitivity analyses were performed: one general and one specifically for the CAPEX input parameter. In the next two sub-sections, the results are discussed.

5.4.1 General

The sensitivity of the LCOE for its input parameters was analyzed by varying them with +/- 20%. The numerical results are presented in Table 5.3 and visualized in Figure 5.6. The data is sorted based on the sensitivity of each input parameter. The results show that the LCOE is most sensitive to the following three input parameters: PVout, CAPEX and the discount rate.

The LCOE is most sensitive to the input parameter PVout. This input parameter presents the electricity generation output that a solar PV system of a given capacity has. According to the technical report on the used PVout data-set [2019], the data-set has an uncertainty that ranges between 6 and 42% due to several uncertain factors in the simulation model. The two most uncertain factors are losses due to external shading and losses due to dirt and soiling. It should be noted that the uncertainty of external shading is partly mitigated in this research because of the inclusion of buffers to both settlement areas with buildings that may cause shading and forests with trees that may cause shading. Without the uncertainty of the losses due to external shading, the uncertainty ranges between 6 and 36%. Given that the PVout data-set includes uncertain factors and that the LCOE is relatively sensitive to this input parameter, the local LCOE values may vary in reality compared to the results in this study. The remaining uncertain factors influencing the PVout data can be mitigated by performing local analyses when researching potential areas for utility-scale solar PV power plant development.

Next to PVout, the CAPEX and the discount rate are factors for which the LCOE is relatively sensitive. The sensitivity for the CAPEX parameter is further discussed Section 5.4.2. As for the discount rate: this input parameter rate has considerable influence because utility-scale solar PV projects by nature are capital-intensive but have no fuel costs throughout the years (only the annual OPEX). It should be noted that there is much discussion on appropriate values for the discount rate for renewable energy technologies such as solar PV. From a purely financial point of view, often high discount rates up to 10% are used for developing countries such as Indonesia [Steffen, 2020]. However, these discount rates have been criticized because they do not take into account the social costs of carbon emissions and the long term beneficial effects on future generations of renewable energy technologies. The sensitivity analysis shows that if a lower discount rate would be considered from a social-economic point of view, the LCOE goes down significantly. A decrease of the discount rate from 9 to 7,2 (20%), could lead to a decrease in the average LCOE from 12 to 10 US$ct./KWh (12%). Furthermore, a lower discount rate from a financial point of view can be achieved when low-interest loans are agreed on to finance the project.

Table 5.3: Results of the sensitivity analysis of input parameters on the average LCOE; figures are rounded to the nearest integer

Input parameter	LCOE average [US$ct./KWh]		Percentage change compared to LCOE in the base case [%]	
	-20%	+20%	-20%	+20%
PVout	15	10	25	-17
CAPEX	10	14	-16	16
Discount rate	10	13	-12	13
Solar PV system lifetime	12	11	5	-3
Grid connection costs	11	12	-4	4
Connection distance factor	11	12	-4	4
OPEX	11	12	-2	2
System degradation rate	12	12	-1	1

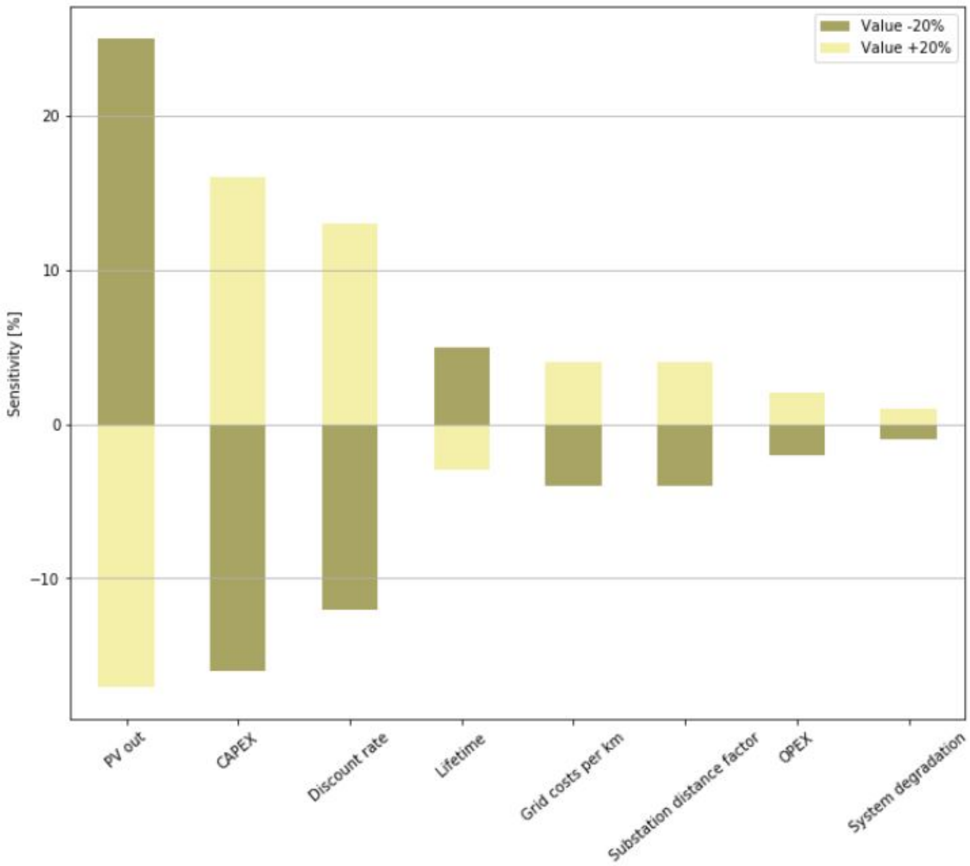


Figure 5.6: Sensitivity of the input parameters on the average LCOE

5.4.2 CAPEX

Due to the expectations of declining utility-scale solar PV investment costs up to 90% by 2050 as discussed in Section 3.5, a separate sensitivity analysis was performed for the input parameter CAPEX. The input value of the CAPEX was varied with -30, -60 and -90%. The results are presented in Table 5.4 and rounded to the nearest integer.

The results show that if the CAPEX keeps declining in the future decades, the LCOE can be reduced up to 73% and can become as low as 3 US$ct./KWh (with a 90% decrease of the CAPEX value). The current average LCOE is 12 US$ct./KWh. Also with a more modest decrease in the CAPEX of 30%, which is almost equal to the minimum expectation of 31% of IRENA [2019] by 2030, the LCOE decreases with 25% to 9 US$ct./KWh. These results are promising for the economic potential of utility-scale solar PV in the future and the cost competitiveness of utility-scale solar PV compared to fossil fuel-based power plants.

Table 5.4: Results of the sensitivity analysis the CAPEX on the average LCOE

CAPEX value varied	LCOE average [US$ct./KWh]	Percentage change compared to LCOE in base case [%]
-30%	9	-25
-60%	6	-49
-90%	3	-73

5.5 CONCLUSION ON ECONOMIC POTENTIAL RESULTS

The found LCOE of utility-scale solar PV in Indonesia ranges between 7,6 and 25,7 US$ct./KWh, with an average of 12 US$ct./KWh. Depending on the scenario, the economic potential is estimated to be somewhere in the range of 2 to 9 TW_p. The corresponding potential electricity generation is estimated to range between 2 and 12 PWh/year. It is clear that only a small part of the areas that have technical potential, also have economic potential: the estimated technical potential capacity ranges between 9 and 53 TW_p and the estimated electricity generation between 12 and 72 PWh/year.

The economic potential on a national level is not spread out equally over the country: it differs significantly per province. In 12 out of the 33 provinces, no economic potential could be found with the used definition of economic potential and the values of the input parameters in this study. Some of these provinces have a relatively high electricity demand, which creates an undesirable situation. This is for example the case for Jawa Barat, Jawa Tengah and Banten, which together account for about 49% of the national electricity demand. The reason for the complete lack of economic potential in these provinces can be attributed to the relatively low assumed PPA tariffs in these provinces compared to the other provinces. The assumed PPA tariffs are low in these provinces, because of the low BPP figures. This creates an undesirable situation: in some of the provinces where the transition to renewable energy technologies is arguably needed the most because of the large share in electricity demand, utility-scale solar PV is currently financially unattractive. The financial barrier for utility-scale solar PV development is the largest in these provinces. These provinces, therefore, deserve the attention of policymakers. On a positive note, economic potential was found in the other 21 provinces. In 18 out of those 21 provinces, the found economic potential is equal to or larger than the provincial electricity demand in 2018. This shows that there are currently opportunities for utility-scale solar PV power plant development in these provinces in Indonesia.

The results of the sensitivity analysis showed that the LCOE is most sensitive to the PVout, CAPEX and discount rate. Given that the CAPEX is expected to decline further in the next decades, the LCOE is also likely to decline. This results in lower future LCOE values and possibly more economic potential of utility-scale solar PV in Indonesia. As for the discount rate: if lower rates are used than the 9% used in this research to include low-carbon benefits for future generations of solar PV or to represent lower interest loan rates, the LCOE also decreases. The uncertainty of the PVout input parameter and the sensitivity of the LCOE for the parameter underlines the importance of a detailed analysis of an area before developing a utility-scale solar PV power plant.

5.6 VALIDATION OF ECONOMIC POTENTIAL RESULTS

As presented in Table 2.1, only one study has previously assessed the economic potential of utility-scale solar PV in Indonesia expressed in potential capacity. Veldhuis and Reinders [2013] estimate the potential capacity on a national level to be 0,4 GW_p. This is much lower than the range of 2 to 9 TW_p found in this research. However, the results of the study are outdated due to the decrease in solar PV system costs over the past years globally and in Indonesia [IRENA, 2021]. The used CAPEX value is about four times higher than the CAPEX value (excluding grid connection costs) used in this study.

Due to the lack of further studies on the economic potential of utility-scale solar PV in Indonesia expressed in potential electricity generation and capacity, further validation of the results remains limited to a validation of the LCOE. Next, the found LCOE values are validated by comparing them with values found in other recent studies on the LCOE in Indonesia and with values found for existing utility-scale solar PV projects in Indonesia.

LCOE comparison with literature

Previously, research has been performed on the LCOE of utility-scale solar PV in Indonesia. The results are listed in Table 5.5 in US$ct./KWh and are corrected for inflation up to September 2021. As can be seen, the estimated ranges of LCOE differ per study but are in the same order size.

The IESR [2019a] estimates a range that is partially within the range calculated in this study. That the high estimate is lower than the high estimate in this study, can be explained by the fact that the IESR does not take local circumstances into consideration, such as grid connection costs based on distance to a connection point and local system output data. The IESR estimates the LCOE on average for the whole of Indonesia, using national cost estimations. The system output is assumed on a provincial level, instead of on a more detailed level (5 km^2) as is done in this research. This results in fewer outliers of the calculated LCOE. The low estimate of the IESR is about 16% lower than the estimate in this study. This can be attributed to the CAPEX assumption used to calculate the lower limit of the range in that study. The assumed CAPEX including grid connection costs is 742 US$/$KW_p$ converted to 2021 US$. This is about 29% lower than the assumed CAPEX in this study, excluding grid connection costs. The sensitivity analysis showed that a decrease of the CAPEX of 20% can already lead to a 16% decrease in the LCOE, explaining the different results.

The differences in range in results with the study of The World Bank [2020] and Kunaifi et al. [2020] can also be attributed to the use of global and/or national assumptions, instead of local assumptions based on for example expected local system output and local grid connection costs. The World Bank mentions that they use rough input values and disregards local intricacies, due to the impossibility to asses those from a global perspective. Kunaifi et al. [2020] use provincial assumptions, also disregarding local circumstances. This results in a smaller range with fewer outliers.

The range in LCOE found by Sunarso et al. [2020] can only be compared to the range in LCOE in the province of Kalimantan Barat found in this study, which is 9,2 to 18,4 US$ct./KWh. The range found by Sunarso et al. is much lower. No direct indications can be given why that is the case. The assumed CAPEX values are very close to each other and local grid connections costs are included in both methods. However, it should be mentioned that the study does not provide information on what the input values are for the calculation of the CRF. The study works with an assumption on the annual real interest rate to represent the discount rate, but the value is not mentioned. Given that the LCOE is quite sensitive to the discount rate, this information is important to have to further discuss the differences between the results.

Table 5.5: Estimations of the LCOE for utility-scale solar PV for Indonesia found in literature and adjusted for inflation up to September 2021

Reference	**Analyzed region**	**Estimation of LCOE [US$ct./KWh] in 2021**	
		Low estimate	*High estimate*
This study	Indonesia	7,4	24,9
IESR [2019b]	Indonesia	6,2	11
Kunaifi et al. [2020]	Indonesia	6,3	10
Sunarso et al. [2020]	Kalimantan Barat	4,8	5,8
The World Bank [2020]	Indonesia	9,5	13,8

LCOE comparison with existing projects

Besides comparing the estimations of LCOE to other estimations in literature, validation can also take place by looking at the final costs of existing utility-scale solar PV power plants in Indonesia. Unfortunately, there is no public data available on LCOE values for ground-mounted solar PV projects, to the authors' best knowledge. However, some auction bid prices for floating solar PV projects have been published. These bid prices are also interesting because of a comparison by The World Bank [2021b] on differences in costs between ground-mounted and floating solar PV projects, showed that the LCOE values do not differ significantly from each other. According to a recent report by the IESR [2021b], the tariffs agreed on in a PPA with PLN in 2020 for a floating solar PV power plant of 145 MWp in the Cirata Reservoir in West Java, was 5,81 US$ct./KWh. Furthermore, the report states that in 2020, two other floating PV projects had price bids of respectively 3,74 US$ct./KWh and 3,68 US$ct./KWh. These tariff are all lower than the minimum LCOE value of 7,4 US$ct./KWh found in this study.

Desk research on the economics behind the power plant in the Cirata Reservoir of which the location and some specs are known did not result in direct indications as to why the agreed PPA tariff is so low. There are no reports on exceptionally low CAPEX or low interests loans resulting in a low discount rate. As for the PVout in the area: an analysis of the data in the GIS-environment shows that although the average PVout in the Cirata reservoir is higher than the average PVout in Indonesia, it still results in an estimated LCOE around 9 US$ct./KWh using the calculation method of this study. The analysis also showed that when a lower discount rate of 3% is assumed, the LCOE in the area could drop to 5,6 US$ct./KWh. A lower discount rate could be the case if low-interest loans are agreed on with financiers of the project. However, this cannot be assumed without more information on the project and the reasons for the low LCOE remain unclear.

Part II

POLICY ANALYSIS

6 POLICY CONTEXT

This chapter aims to provide contextual background on the current policy landscape related to utility-scale solar PV and to identify possible policy interventions to enlarge the economic potential of utility-scale solar PV development in Indonesia. First, context is provided on the relevant stakeholders surrounding utility-scale solar PV in Section 6.1 as background information. In Section 6.2, the current policy landscape of utility-scale solar PV in Indonesia is discussed. Finally, optional policy interventions to increase the economic potential of utility-scale solar PV are discussed in Section 6.3.5.

6.1 STAKEHOLDER CONTEXT

Identifying stakeholders surrounding utility-scale solar PV in Indonesia and understanding their roles, interests and interrelations, can help in the designing process of policies meant to enlarge the economic potential of utility-scale solar PV and in understanding the effects of policies on the stakeholders in policy consideration. Enserink et al. [2010] confirm that a stakeholder analysis can be of support when designing and recommending policies and that it is likely to improve the process of a policy analysis. Therefore, a concise stakeholder analysis is conducted. The next paragraphs elaborate on the results. First, the involved stakeholders relevant to the utility-scale solar PV industry in Indonesia are identified and their roles and objectives are discussed in Section 6.1.1. Then, the formal relations among the stakeholders are discussed in Section 6.1.2.

6.1.1 Identification of involved stakeholders

The stakeholders have been identified by desk research. The involved stakeholders were identified by asking the question: "Who influences or is influenced by the utility-scale solar PV industry in Indonesia?". The most relevant found stakeholders are categorized into four groups: institutional, industrial and financial stakeholders, and consumers. Next, each stakeholders' role and interests are discussed. It should be noted that only the key stakeholders are included and discussed. The list is non-exhaustive.

Institutional stakeholders
The MoEMR, Ministry of Finance (MoF) and local government institutions are the identified relevant institutional stakeholders.

Ministry of Energy and Mineral Resources
The MoEMR sets the national renewable energy targets and regulates the electricity sector related to policies such as the maximum allowed PPA tariffs for renewable energy technologies including utility-scale solar PV power plants, as further discussed as part of the current policy landscape in Section 6.2. Based on the renewable energy targets, the MoEMR decides on policies related to the electricity sector. This stakeholder is therefore a crucial stakeholder in the utility-scale solar PV system. The MoEMR also needs to pre-approve of power plant development plans before construction. The interest of the MoEMR is to meet the renewable energy targets, but

also to keep electricity affordable for consumers and to ensure the financial health of state-owned electricity company PLN [ADB, 2020]. PLN is supervised by the MoEMR.

Ministry of Finance
The MoF approves of and implements subsidies, investments, tax regulations and other monetary policies in the electricity sector including the energy sector. The Ministry controls the government budget and provides recommendations for these monetary policies. The main interest of the MoF is to ensure financial health of the country in general [MoF, 2021]. The MoF is an important stakeholder because it is able to advise on and create monetary policies that could increase the economic potential of utility-scale solar PV.

Ministry of Industry
The Ministry of Industry (MoI) is responsible for regulations related to the industrial side of the utility-scale solar PV sector. For example, the Ministry sets LCR regulations, as further discussed as part of the current policy landscape in Section 6.2. The Ministry's interests are strong and globally competitive industries based on innovation and technology [MoI, 2021].

Local government institutions
Local government institutions are the regional and provincial institutional stakeholders that have the power to issue or deny licenses and permits for the development of utility-scale solar PV power plants and other power plants. These institutions are essential for successful utility-scale solar PV power plant development.

Industry stakeholders
The industry stakeholders are the state electricity company PLN, IPP's of utility-scale solar PV energy and Indonesian solar power plant component manufacturers.

State electricity company PLN
PLN produces the majority of electricity in Indonesia and has a monopoly on the national electricity distribution, as mandated by the government. Furthermore, all renewable energy projects must be procured by PLN. Tariffs paid to IPP's of renewable energy are agreed on in PPA's and are based on the regional and national BPP figures, as is further discussed as part of the current policy landscape in Section 6.2. It is evident that PLN has power when it comes to the development of utility-scale solar PV power plants. PLN is a state-owned company and falls under the supervision of the MoEMR. The company is dependent on the energy regulations set by the MoEF, energy-related subsidies received by the MoF, industry regulations set by the MoI and licensees and permits for local power plant development given by local government institutions.

The interests of PLN are the provision of stable and affordable electricity for consumers, making a profit and contributing to the renewable energy targets and other targets set by the government [PLN, 2021]. This poses struggles for PLN. Given that current coal electricity generation prices are quite low and coal is a stable source of power generation, this fuel has many advantages for PLN in light of their goals. Renewable energy technologies often can only offer electricity at higher prices, as is for example the case for solar PV in some of the more inhabited provinces, as was seen in Chapter 5. Maintaining the status quo of only a limited share of renewable energy technologies in the electricity mix is therefore of interest to PLN [ADB, 2020]. However, this directly conflicts with the electricity mix targets set by the MoEMR. Although PLN does not determine tariff regulations in place in Indonesia, PLN has to agree on every new power plant and has the final say on the tariffs paid to the power plants. It is therefore a key stakeholder with internal struggles and an interest in keeping the status quo.

Independent power producers
Next to PLN, IPP's can also produce electricity in Indonesia and operate a power plant. IPP's can develop and operate utility-scale solar PV power plants. The distribution of the generated electricity to consumers is most of the time the job of electricity infrastructure monopolist PLN. In exceptional situations, IPP's can play a role on a local scale in this. IPP's agree on electricity tariffs paid in a PPA by PLN to the IPP during the lifetime of the power plant. The main interests of IPP's in the utility-scale solar PV sector are to generate renewable electricity and to make profits out of that. IPP's are dependent on the regulations set by the institutional stakeholders and the approval of and agreements with PLN and local government institutions when developing a utility-scale power plant. IPP's themselves have no direct influence on policymaking.

Indonesian solar power plant component manufacturers
There are ten companies in Indonesia that produce solar PV modules and other components needed to develop a utility-scale solar PV power plant. These companies are represented by the Indonesian Solar Module Manufacturers Association (APAMSI). The current estimated production capacity of solar PV modules based on data from the APAMSI is 515 MWp/year [Consulate General of the Republic of Indonesia - USA, 2021]. Utility-scale solar PV power plant developers are dependent on these companies given the current LCR regulation, which mandates that the majority of the used solar modules must be from domestic sources. The solar PV module prices of these companies impact the costs of a solar PV power plant. The interests of the companies themselves are to make profits and to able to provide solar PV modules at affordable prices. Sector growth is also an important interest for the companies, to be able to achieve economies of scale to get the solar PV module prices down.

Financial stakeholders
Financial stakeholders are considered to be private investors and banks that are able to finance PLN and IPP's in the development of utility-scale solar PV projects. These financial stakeholders have cost benefits interests and want to minimize financial risks for themselves. They also influence the interest rates that IPP's have to pay on loans. This can impact the discount rate and therefore the LCOE of a power plant significantly, as was seen in the sensitivity analysis in Section 5.4. Examples of banks that could help in financing the development of solar PV power plants are the Asian Development Bank and the Indonesian Bank. Financial investors can be both foreign or domestic. Examples of foreign investors in the solar PV sector in Indonesia are the Japanese multinational financial services company Sumitomo Mitsui Banking Corporation, European investment bank Societe Generale and the multinational financial services company Standard Chartered Bank. These three companies have closed a deal in August of 2021 on the financing of a 145 MWp floating solar PV power plant in Java Barat [IPP Journal, 2021].

Electricity consumers
Under electricity consumers fall residential and industrial consumers. These stakeholders consume electricity and pay a price for this to PLN. The main interests of electricity consumers are access to reliable electricity and affordable electricity prices. A part of the electricity consumers also has an outspoken interest in more renewable energy in the electricity mix, given the current attention for the global energy transition. Furthermore, an increase in renewable energy is also of interest to all and future electricity consumers because of the positive health effects and the negative effects of climate change.

6.1.2 Formal relations

Figure 6.1 presents a map of the most important formal relations between the stakeholders identified in the previous paragraph. The map is meant to give context on stakeholder relations in the utility-scale solar PV system and is a simplified version of the reality. Informal relations are not included. It is clear that the stakeholders who could develop utility-scale solar PV power plants, which are IPP's and PLN, are dependent on regulations from various institutional stakeholders. Furthermore, PLN plays a central role because of its monopolist position in the electricity network and the power to make PPA agreements with IPP's. IPP's are highly dependent on PLN.

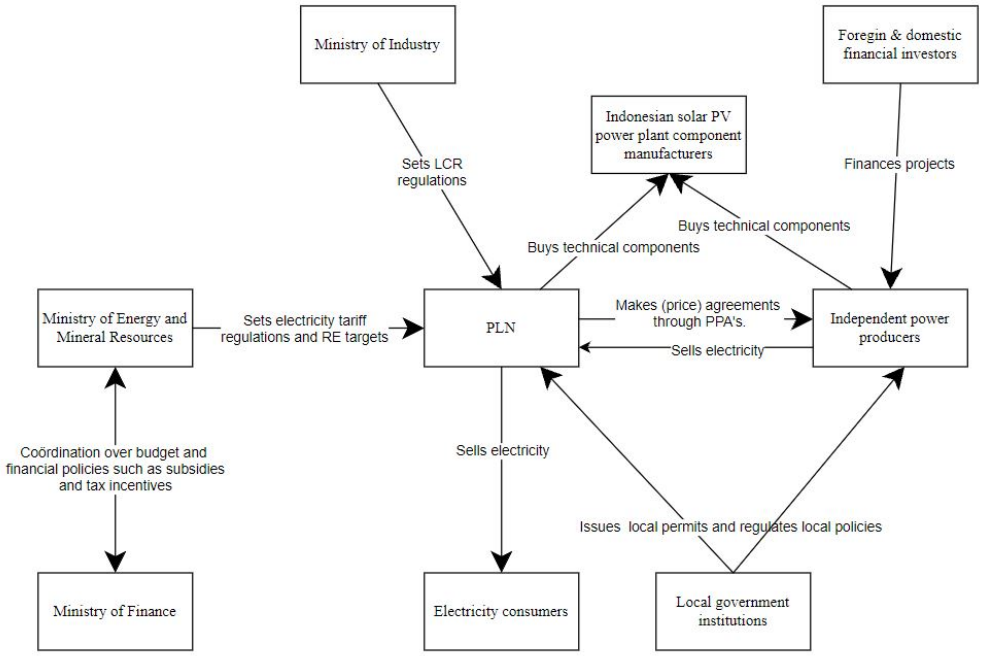


Figure 6.1: A schematic overview of the formal relations between the identified key stakeholders in the utility-scale solar PV development system in Indonesia (authors' diagram)

6.2 CURRENT POLICY LANDSCAPE

There are many regulations related to utility-scale solar PV power plants in Indonesia. Given that this research focuses on the economic potential and how to enlarge this, this section will provide background information on policies that are known to influence the price-cost gap that was found in the results on economic potential in Chapter 5.

Electricity tariff regulations
As was seen in the stakeholder analysis, the MoEMR is mainly responsible for policies related to solar energy. This includes the regulation of tariffs paid to power producers by PLN. This pricing scheme is regulated under PERMEN ESDM no.50/2017 on Utilization of Renewable Energy Sources for Electricity Supply. This regulation states that PLN pays an upfront agreed on tariff to a utility-scale solar PV power producer in a PPA. The agreement must be approved by the MoEMR. As previously elaborated on in Part i of this thesis, the maximum allowed PPA tariff is also laid down in the regulation. In practice, this policy disincentivises PLN to agree on any tariff with a power producer lower than the maximum allowable tariff [ADB, 2020].

Issues with current tariff regulations
The ADB [2020] raises three concerns about the current maximum allowable tariff regulation for utility-scale solar PV and other renewable energy technologies: (1) the BPP and maximum tariffs based on the BPP are often below the costs of new renewable energy projects making the projects not financially viable. This can be confirmed for utility-scale solar PV based on the results on economic potential presented in Chapter 9. (2) The BPP is based on average historical costs of electricity generation and not on electricity costs that are more likely in the future. In addition, the BPP is based on values in the past that are now depreciated. And (3), the BPP does not reflect non-financial benefits of renewable energy technologies such as reduction in carbon dioxide emissions and population health. To use the BPP as a baseline for the maximum PPA tariffs thus undervalues the benefits of utility-scale solar PV compared to fossil fuel.

Furthermore, it could be argued that it is unfair that utility-scale solar PV tariffs are based on the BPP, since the BPP is mainly determined by the low costs of electricity produced by coal-fired power plants [ADB, 2020]. By not adjusting the maximum tariffs, manufacturers of utility-scale solar PV components such as solar PV modules do not get a chance to develop economies of scale and lower the costs to be able for solar PV to compete with coal and other fossil fuels. This can especially be deemed as unfair given that coal-fired power plants receive annual fiscal support, whereas renewable energy power plants are not known to have received any support. The total fiscal support for coal-fired power plants was 0,7 billion US$ on average in 2016 and 2017 through budgetary transfer and tax exemptions [IISD, 2019]. There are no know subsidies or other incentives to financially support utility-scale solar PV power plants. This means that the costs of solar PV generation have to compete with the subsidized generation costs of fossil fuel-based power plants. In some cases, solar PV costs even have to compete with a fraction of those costs, given that the maximum allowed PPA tariff is only 85% of the BPP in some regions.

Local content requirement (LCR)
Another policy that influences the price-cost gap of utility-scale solar PV in Indonesia, is the LCR policy, regulated under MoEMR regulation No. 12/2017 and under MoI regulation No.5/2017. The LCR policy is in place for both materials and services used for solar PV power plants. The LCR policy is designed to encourage the development of local industries and create jobs in Indonesia. For used materials for solar PV power plants, a minimum of 34,1% must be produced in Indonesia. For services, this must be 100%. The total combined local content value must be at least 43,85% as of 2021. For solar PV modules specifically, the LCR is 60%. In September 2021, the MoI has expressed the intention to increase the LCR even further to 90% by 2025 to increase domestic industry growth [MoI, 2021].

Issues with LCR regulation
The LCR policy for solar energy comes with issues for the economic potential and development of solar PV power plants in Indonesia. First of all, LCR is associated with inefficient resource allocation resulting in a cost increase for solar PV components. This is especially true for PV modules. PV modules that are produced in China, are made in large quantities and have economies of scale. PV modules that are produced in Indonesia, currently don't have this advantage and are more expensive [IESR, 2019b]. Since PV modules are calculated to account for about 36% of the total CAPEX of a utility-scale solar PV power plant, the LCR influences the costs of solar PV power plants in Indonesia. The IISD [2018] has even stated that there is a real risk that the LCR, combined with the PV module cost gap between local and international production, can prevent the development of the utility-scale solar PV industry in Indonesia and the development of competitive prices compared to fossil

fuel projects.

Secondly, and related to the first issue, the LCR policy has been said to lead to a vicious cycle in the solar industry. Investments and cost reductions for the domestic production of solar PV components are expected to come when the demand is large enough. However, due to the relatively expensive domestic products, among other things, the demand for solar PV components is not growing very fast. The IEEFA [2019] has surveyed several of the in total eleven Indonesian solar panel manufacturers and found that they are struggling because of limited demand for their products, which makes it hard for them to scale up and achieve economies of scale.

Thirdly, it seems that the current domestic solar industry does not have the capacity to supply enough materials to be able to meet the targets. In 2018, the total combined local content value for solar PV power plants achieved 35.3%, versus the 2018 target of 42,2% [Sulmaihati, 2019]. This poses the question if the domestic industry would be able to provide enough materials for an LCR of 90% in 2025. If not, this would limit the development of utility-scale solar PV power plants.

6.3 OPTIONAL POLICY INTERVENTIONS

To close the gap between the costs of utility-scale solar PV power plants expressed in LCOE and the maximum allowed PPA tariffs, a variation of policy interventions is possible. Globally, a wide range of policy interventions has been seen to support the development of renewable energy technologies. Based on desk research and conversations with industry experts, four policies stand out for the case of Indonesia: (1) a capacity-based subsidy, (2) a price-based subsidy, (3) a carbon tax and (4) to lift LCR regulation. Next, for each of these policy interventions, it is explained why this policy is considered to be an interesting policy intervention to increase the economic potential of utility-scale solar PV.

6.3.1 Capacity-based subsidy

Investments subsidies are capacity-based subsidies and refer to providing subsidies upfront based on the system size of a project. The CAPEX is partly subsidized and paid for by the government. The general idea behind an investment subsidy or any other subsidy for a renewable energy technology is that an electricity price often only reflects the financial costs and not the economic costs. Within economic costs, all costs and benefits for society are included, and not just the costs and benefits of the project owner. Fossil fuel power plants have negative side-effects that are not reflected in the electricity price, such as greenhouse gas externalities and public health effects. The positive side-effects of renewable energy technologies are in their turn, also not reflected in the electricity price. A subsidy helps to adjust the electricity price of solar PV power plants to a price that is more equal to the economic value of the project, instead of the financial value.

Investment subsidies for solar PV projects are not much seen anymore around the world. An example where investment subsidies for solar PV projects are still in place is India. India subsidizes up to 30% of the CAPEX of solar parks with a size of 500 MWp [Ministry of New and Renewable Energy, 2021]. China and Greece are examples of countries that used to have investment subsidies, but have shifted the focus towards price-based policy instruments [He, 2018] Greece used to subsidize between 20% and 60% of the CAPEX of a renewable energy project under the

National Development Law 3299/2004 from 2004 until the expiration of the law in 2010. One of the reasons that investments subsidies have become less popular than price-based policy instruments, is that it does not encourage cost reductions. Since investment subsidies are paid upfront as a percentage of the CAPEX, the actual electricity output over the years does not play a role in the size of the subsidies. The incentives to reduce costs and optimize the power plant are less present with an investment subsidy than with a price-based subsidy.

However, an investment subsidy could still be an interesting policy option. A research by Ozdemir et al. [2019] into the benefits and cost of both capacity-based and price-based subsidies for renewable energy technologies, showed that capacity-based subsidies can actually result in more renewable energy investments than price-based subsidies. They do conclude that price-based subsidies is often more cost-effective when it comes to electricity production of a power plant, but also mention that capacity-based subsidies result in more initial investments and more learning by doing effects within the industry. Since the development of solar PV power plants in Indonesia is one of the interests in this study, this is an interesting policy option. Another positive about this policy option is that the costs are paid for by the government budget, and not directly passed through to consumers in the electricity tariffs. This is a positive given the sensitivities around the electricity tariffs and the affordability of electricity for consumers in Indonesia, as has been observed by the ADB [2020].

6.3.2 Price-based subsidy

As was seen in Section 6.2, there is criticism on the current regulation of maximum tariffs paid to utility-scale solar PV power producers. In some provinces, the maximum allowed tariffs are lower than the average estimated LCOE of solar PV. To close this price-cost gap, a price-based subsidy is a possible policy intervention. A price-based subsidy refers to providing a government subsidy per unit of electricity that is produced. Similar to a capacity-based subsidy, a price-based subsidy helps to adjust the total costs to a level that is more equal to the economic value of a projected, instead of the financial value. Price-based subsidies are seen in many places around the world and have been found cost-effective compared to other types of subsidies and stimulating for the development of renewable energy power plants [Ozdemir et al., 2019]. If the solar PV sector grows in Indonesia due to the price-based subsidy, this could also lead to cost reductions for solar PV power plant components because of economies of scale and 'learning by doing' effects. This has been seen before for renewable energy projects and solar PV specifically [Huenteler et al., 2016]. It is therefore important to note that when implementing a price-based subsidy, frequent re-evaluation of the height of the subsidy should take place. If this is not done although investment costs have decreased, this dis-incentivizes power producers to produce power for the lowest price possible.

An alternative to a price-based subsidy is to adjust regulations on maximum tariffs paid to utility-scale solar PV power producers by PLN. However, an issue with this, is that it is likely that the higher tariffs are passed through to electricity tariffs, decreasing the affordability of electricity for consumers [ADB, 2020]. That creates an undesirable situation, especially when the share of utility-scale solar PV energy rises in the electricity mix. Therefore, a price-based subsidy is deemed more suitable for Indonesia.

6.3.3 Carbon pricing scheme

Another way to improve the economic potential of utility-scale solar PV without directly influencing the costs of utility-scale solar PV is to influence the costs of fossil fuel-based power. This can be done with a carbon pricing scheme. A carbon pricing scheme puts a price on carbon emissions. The envisioned effect of a carbon price scheme in the context of this research is that it increases the price of electricity produced with fossil fuels. An increase in this price will logically increase the BPP, which is based on average electricity costs. This is likely to happen since fossil fuels account for the largest share in the electricity mix, as was seen in Figure 1.2a. Consequently, utility-scale solar PV power generation costs can become more competitive compared to fossil fuel power generation costs.

Carbon pricing schemes are seen in many places around the world: The World Bank [2021b] estimates that currently about 40 countries use carbon pricing schemes, with more scheduled to implement over time. And not without results: Countries with a carbon pricing scheme are estimated to have a 2% lower annual growth rate in carbon dioxide emissions from electricity production than countries without such as scheme [Best et al., 2020]. Two main types of carbon pricing are distinguished by The World Bank [2021b]: (1) An emission trading system (ETS) and (2) carbon taxes. An ETS caps the total level of carbon dioxide emissions for industries, but allows for trading of emission permits between entities. This results in a market price for carbon dioxide based on the supply and demand of permits. Carbon taxes directly sets a price on carbon dioxide emissions. The carbon dioxide price is pre-defined, where is this is not the case in an ETS. As for Indonesia, the IISD [2021] recommends a carbon tax because it is a relatively easy policy intervention to administer.

6.3.4 Lift LCR regulation

As was seen in Section 6.2 there are some issues with the LCR regulation. One of those issues is that it influences the CAPEX of utility-scale solar PV power plants since it requires developers to use mostly domestically produced components, which are for solar PV modules known to be significantly more expensive than modules produced in other countries such as China [IESR, 2019b; PVinsights.com, 2021]. By lifting the local content requirement regulation, cheaper solar PV modules can be imported from other countries that benefit from economies of scale. This could result in a lower LCOE for utility-scale solar PV in Indonesia and subsequently a higher economic potential.

6.3.5 Other policy interventions

As previously stated, there are many policy interventions possible to directly or indirectly increase the economic potential of utility-scale solar PV or incentivize the development of power plants in different ways. The four policies discussed in more detail are the policies that stood out of the crowd when assessing literature on policy interventions in general and Indonesia specifically. Furthermore, they all focus on overcoming the price-cost gap barrier to utility-scale solar PV development in Indonesia. A selection of other possible policies that are not further discussed in this research but could be interesting are the removal of fiscal support for coal power plants, financial risk reduction for solar PV power plant developers, tax reductions or auction schemes.

Auction schemes are an example of policies that have gained popularity throughout the world over the past few decades to stimulate growth in the renewable energy sector and to bring LCOE's down. It refers to a government or electricity network actor to open an auction for a power plant with a certain capacity and given technology or a group of eligible technologies. Project developers can participate in the auction and submit a bid in price per unit of electricity. A PPA is then signed with the chosen project developer. This can be the project developer with the lowest bid price, or who has the highest score based on multiple criteria. Auction schemes are praised worldwide for their usefulness in establishing competitive prices and cost efficiency due to price competition. They can serve as a way to discover the real costs of utility-scale solar PV. The ADB [2020] therefore recommends competitive and transparent auctions for utility-scale solar PV projects in Indonesia on a large scale. It should be noted that Indonesia has already set out some auctions for renewable energy projects, such as a 168 MWp solar PV power plant in Sumatra in 2017 [Petrova, 2017].

7 METHOD - POLICY ANALYSIS

From the technical and economic potential analysis in Part I of this research, it became clear that in some provinces in Indonesia there is a gap between the LCOE and the assumed PPA tariff paid to a solar power producer, resulting in limited economic potential compared to the technical potential. In some provinces, including ones with relatively high electricity demand, no economic potential was found. As was discussed in the introduction chapter, this research also aims to perform a policy analysis and assess several policy interventions meant to increase the economic potential, which seems to be important given the current economic potential. The method that was chosen to perform this policy analysis is a multi-criteria analysis. This chapter elaborates further on the details of the method by first giving a general explanation of the multi-criteria analysis method, and then discussing the methods used to execute each step of the analysis in more detail.

7.1 MULTI-CRITERIA ANALYSIS

To be able to assess and to some extent compare policy interventions meant to enlarge the economic potential of utility-scale solar PV, a MCA was chosen as a method. It is a method that is widely used for decision-making on policies and can also be seen as a guided exploration of a problem and possible policy interventions [Dodgson et al., 2009]. A MCA compares a set of alternatives based on a set of criteria, sometimes using weighting techniques. The method was chosen because it makes impacts and trade-offs of policy interventions insightful due to the inclusion of multiple criteria. Furthermore, an advantage of the method is that the results can be reproduced, which leads to transparent results [Janssen, 2001].

There are different ways to conduct an MCA. Table 7.1 shows the steps of a general MCA as proposed by Dodgson et al. [2009] in their manual on multi-criteria analysis. Steps 1 - 4 are the steps that are followed in this research. Steps 5 - 8 are not included. These steps require the weighting of criteria and the scoring of policy interventions. It was chosen not to include these steps but to leave the task of interpretation of the results to policy-makers. Dodgson et al. [2009] call this a basic MCA. A basic MCA still assists in decision-making by providing insights into the effects of policy interventions and critically assessing them. Also, in a basic MCA, qualitative criteria can be included, which is desirable as can be seen in Section 7.4. Next, the execution methods for steps 1 to 4 are described in more detail.

Table 7.1: Steps in a multi-criteria analysis as presented in the multi-criteria analysis manual by Dodgson et al. [2009].

	Steps in a multi-criteria analysis
1	Establish the decision context. What are the aims of the MCA, and who are the decision-makers and other key players?
2	Identify the options.
3	Identify the objectives and criteria that reflect the value associated with the consequences of each option
4	Describe the expected performance of each option against the criteria (if the analysis is to include steps 5 and 6, also 'score' the options, i.e. assess the value associated with the consequences of each option.
5	'Weighting'. Assign weights for each of the criteria to reflect their relative importance to the decision.
6	Combine the weights and scores for each of the options to derive an overall value.
7	Examine the results.
8	Conduct a sensitivity analysis of the results to changes in scores or weights.

7.2 STEP 1: ESTABLISH THE DECISION CONTEXT

The decision context is previously laid out in Chapter 1 to 5, and complemented with the presentation of the policy context and actor analysis retrieved with desk research in Chapter 6. The aim of the basic MCA is to get insights into the effects of several policy interventions meant to increase the economic potential of utility-scale solar PV in Indonesia.

7.3 STEP 2: IDENTIFY THE OPTIONS

Section 6.3 identified four policy interventions and discussed that these could increase the economic potential of utility-scale solar PV in Indonesia. These policies are: (1) a capacity-based subsidy, (2) a price-based subsidy, (3) a carbon tax and (4) lift LCR. These are the policies that will be explored further. As a benchmark, 'business as usual', further referred to as the base case, is also included as an option. In the following sections, the more detailed design of the identified policies is explained and substantiated.

7.3.1 Capacity-based subsidy

This policy intervention entails the subsidization of 30% of the CAPEX of a new utility-scale solar PV power plant. A capacity-based subsidy as large as 30% of the CAPEX was chosen because it is within the range of other investments subsidies seen around the world as seen in Section 6.3. Furthermore, a capacity-based subsidy that is much higher than this is expected to have unwanted effects: it results in fewer incentives for the power producer to be cost-effective both when developing a power plant as during the lifetime of the power plant [Ozdemir et al., 2019]. Other subsidy sizes are not included in this policy analysis.

7.3.2 Price-based subsidy

This policy intervention entails a price-based subsidy. But what should the height of the price-based subsidies be? In this policy design, that is answered with as a basis the difference between the current maximum allowed PPA electricity tariffs that are in place for each province, and the electricity tariffs paid to power producers that are needed to be able for the economic potential to be equal to 31% of the estimated electricity demand in 2050. 31% of the 2050 demand was chosen because 31% is the target for renewable energy in the energy mix in 2050 as presented in the NEP. It was chosen to let the expected electricity demand in 2050 be a reference point, and not current demand because the demand is expected to rise significantly and this should be taken into account when designing and assessing policies.

The needed electricity tariffs to be able for the economic potential to be equal to or higher than 31% of the 2050 electricity demand are calculated using the results on economic potential per province and an estimation of the provincial electricity demand in 2050. The results of this calculation are presented in Figure C.1. The calculation method of the tariffs is elaborated on in Appendix C. The figure shows that for 18 out of the 33 provinces, the maximum allowed PPA tariff is not high enough to be able for the economic potential of utility-scale solar PV to be equal to or higher than 31% of the estimated electricity demand in 2050.

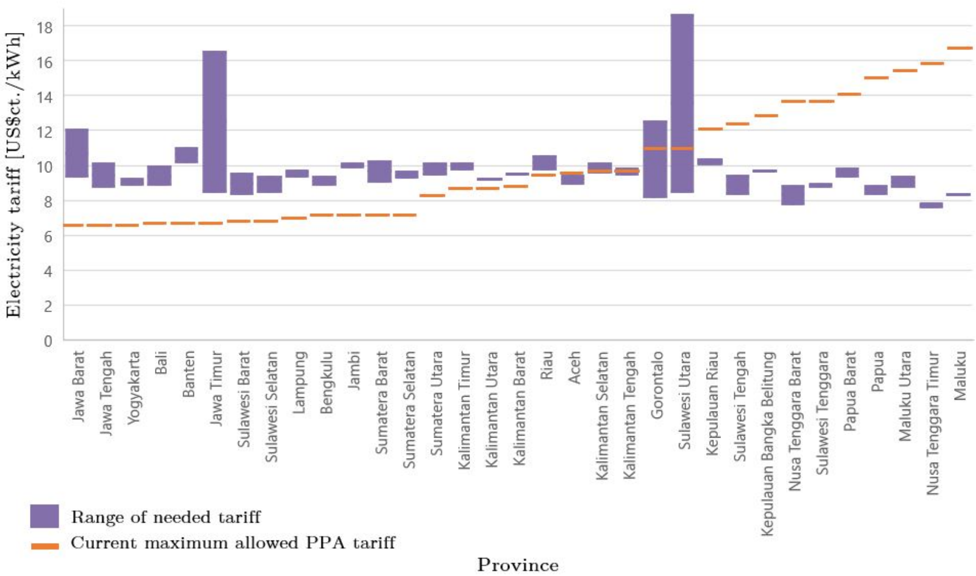


Figure 7.1: The range of electricity tariffs that is needed for the economic potential of utility-scale solar PV to be equal to 31% of the estimated 2050 electricity demand per province

The height of the price-based subsidies for each province is set equal to the difference between the current maximum allowed PPA tariffs, and the minimum of the range of the needed tariff. This means that the subsidy height varies per province. The subsidy is only in place in the 18 provinces in which the minimum needed tariff is higher than the current maximum PPA tariff. The heights of the price-based subsidies for these provinces are presented in Table 7.2 above the line. The table is sorted on the subsidy height from highest to lowest. As can be seen, the subsidy heights range between 0,3 and 3,5 US$ct./KWh. In the design of this policy, a subsidy will not be in place in the other 15 provinces because the current maximum tariffs in those provinces already suffice. It should be noted that in those provinces, a lowering of the maximum allowed PPA tariffs could be possible while sufficient economic potential still remains.

Table 7.2: Price-based subsidy heights per province (in the provinces under the line, no subsidies are in place)

Province	Current maximum PPA tariff [US$ct./KWh]	Minimum needed tariff to meet 31% of 2050 electricity demand [US$ct./KWh]	*Price-based subsidy height [US$ct./KWh]*
Banten	6,7	10,2	3,5
Jawa Barat	6,6	9,4	2,8
Jambi	7,2	9,9	2,7
Lampung	7,0	9,4	2,4
Daerah Istimewa Yogyakarta	6,6	8,9	2,3
Bali	6,7	8,9	2,2
Jawa Tengah	6,6	8,8	2,2
Sumatera Selatan	7,2	9,3	2,1
Sumatera Barat	7,2	9,1	1,9
Jawa Timur	6,7	8,5	1,8
Sulawesi Selatan	6,8	8,5	1,7
Bengkulu	7,2	8,9	1,7
Sulawesi Barat	6,8	8,4	1,6
Sumatera Utara	8,3	9,5	1,2
Kalimantan Timur	8,7	9,8	1,1
Kalimantan Barat	8,8	9,5	0,7
Kalimantan Utara	8,7	9,2	0.5
Riau	9,5	9,8	0,3
Kalimantan Selatan	*9,7*	*9,6*	*-0,1*
Kalimantan Tengah	*9,7*	*9,5*	*-0,2*
Aceh	*9,6*	*9,0*	*-0,6*
Kepulauan Riau	*12,1*	*10,1*	*-2,0*
Sulawesi Utara	*11,0*	*8,5*	*-2,5*
Gorontalo	*11,0*	*8,2*	*-2,8*
Kepulauan Bangka Belitung	*12,9*	*9,7*	*-3,2*
Sulawesi Tengah	*12,4*	*8,4*	*-4,0*
Papua Barat	*14,1*	*9,4*	*-4,7*
Sulawesi Tenggara	*13,7*	*8,8*	*-4,9*
Nusa Tenggara Barat	*13,7*	*7,8*	*-5,9*
Papua	*15,1*	*8,4*	*-6,7*
Maluku Utara	*15,5*	*8,8*	*-6,7*
Nusa Tenggara Timur	*15,9*	*7,7*	*-8,3*
Maluku	*16,8*	*8,3*	*-8,5*

7.3.3 Carbon tax

This policy intervention entails the implementation of a carbon tax in US$ per tonne of carbon dioxide. The height of the carbon tax is set at 35,9 US% per tonne of carbon dioxide. This figure was chosen because it is the equivalent of 30€ in 2021 per tonne of carbon dioxide, which is the minimum carbon tax rate that is considered by the OECD (2021) to be needed to trigger significant effects in the reduction of carbon dioxide emissions by fossil fuel power plants. It is also the low-end estimate of the damage that carbon emissions have on society expressed in monetary values as estimated by the OECD (2018).

The idea behind the carbon tax policy intervention is that it influences the average electricity production price, the BPP, in Indonesia, since the majority of the electricity mix consists of fossil fuels emitting carbon dioxide. The extra costs for electricity production due to a carbon tax can be calculated using the average carbon intensity of electricity in Indonesia. Carbon intensity refers to the amount of carbon dioxide that is emitted when producing one KWh of electricity. In Indonesia, the average carbon intensity of electricity was estimated to be 761 gram carbon dioxide per KWh in 2019 [IESR, 2019a]. If the average carbon intensity is multiplied by the carbon tax, the result is the average extra price that is to be paid by power producers. The effect on the BPP due to the carbon tax is assumed to be equal to this average extra price for electricity production.

Formula 7.1 shows the calculation of the new expected BPP due to a carbon tax. Performing this calculation for a carbon tax of 35,9 US$ per tonne of carbon dioxide results in an extra average price of electricity of 2,28 US$/KWh. Given the current national BPP of 7,56 US$ct./KWh, the new national BPP is assumed to be 9,84 US$ct./KWh due to the carbon tax in this policy option. That is a percentage change of about 30,2%. The regional BPP figures are adjusted in the same way in this policy intervention.

$$\mathrm{BPP}_{carbon\ tax}[\frac{US\$ct.}{\mathrm{KWh}}] = \mathrm{BPP}_{2018}[\frac{US\$ct.}{\mathrm{KWh}}] + \mathrm{CT}\ [\frac{US\$ct.}{t.CO2}]\ *\ \mathrm{CI}\ [\frac{t.CO2}{\mathrm{KWh}}] \tag{7.1}$$

Where:

$$\begin{aligned} \mathrm{BPP}_{\text{carbon tax}} &= \text{BPP figures taking into account the effect of a carbon tax} \\ \mathrm{BPP}_{2018} &= \text{current BPP figures} \\ \mathrm{CT} &= \text{carbon tax} \\ \mathrm{CI} &= \text{average carbon intensity of electricity in Indonesia} \end{aligned}$$

7.3.4 Lift LCR

This policy intervention entails lifting the local content requirement for solar PV modules. It was chosen to only assess the lifting of LCR for solar PV modules. This was chosen for two reasons: (1) solar PV modules make up a large part of the CAPEX of a power plant (about 36%, as was seen in Section 2.4), and (2) the difference between domestic costs and international cost for solar PV modules are publicly available and are known to be significant [IESR, 2019b; PVinsights.com, 2021]. This makes analysis of the effect of lifting the LCR of solar PV modules feasible. The effects of lifting the LCR for other components such as inverters or for services are not further explored and not included in the design of this policy intervention.

For this policy, it is assumed that PV module costs with the lift LCR policy intervention are lower than in the base case because PV modules produced outside of Indonesia can be used. The cost assumptions for the PV modules and the CAPEX in this policy intervention compared to the base case are presented in Table 7.3. The PV module costs with the LCR policy lifted is assumed to be 200 US$/**kWp!**, based on global average 2021 data from PVinsights 2021, leading to a change in CAPEX compared to the base case of 11,5%.

It should be noted that it is assumed that in the base case, only domestic solar PV modules are used. This has been done based on information retrieved through an interview with a former solar PV power plant development consultant [anonymous Indonesian industry expert, personal communication, June 25, 2021]. Although the current LCR regulation only requires about 60% of the solar PV modules to come from domestic manufacturers, the Indonesian solar power plants are currently using only domestic PV modules. This is because components of those PV modules have been imported from abroad, and already account for about the percentage of value that is allowed to come from outside of Indonesia. It is also assumed that when the LCR policy is lifted, only foreign solar PV modules will be used, given the cost benefits. Extra import costs are not taken into consideration.

Table 7.3: Comparison of cost assumptions of CAPEX and solar PV module costs in the base case and with policy intervention lift LCR

Cost factor	Base case	Lift LCR	*Difference between base case & lift LCR policy [%]*
CAPEX without PV module costs [US$/$KW_p$]	720,79	720,79	-
PV module cost assumption [US$/$KW_p$]	320	200	-37,5
CAPEX with PV module costs [US$/$KW_p$]	1040,79	920,79	-11,5

7.4 STEP 3: IDENTIFY THE OBJECTIVES AND CRITERIA THAT REFLECT THE VALUE ASSOCIATED WITH THE CONSEQUENCES OF EACH OPTION

Criteria are the measures of performance of the policy interventions and should reflect the relevant consequences for the MoEMR. In this research, they are based on the perspective and objectives of the MoEMR. Four criteria have been identified with that in mind, that make up the criteria-set: (1) economic potential, (2) ability to meet provincial demand (3) domestic industry growth and (4) social acceptance. Next, the choice for each criteria is explained in more detail including the operationalisation of the criteria.

7.4.1 Economic potential

It is logical to include the economic potential as a criterion since the increase of this criterion is the end goal of the policy interventions. The economic potential is operationalized as the total potential electricity generation in TWh/year. It was chosen not to include potential capacity as a criterion to avoid that criteria are too similar and represent the same objective. In this case, the potential electricity generation is a more interesting criterion than the potential capacity, because it takes solar PV system output depending on location into account.

Calculation methods for the policy interventions
For each policy intervention, the potential electricity generation is calculated in the same way as is done for the economic potential of the base case as discussed in Chapter 3.3. However, depending on the policy intervention, some of the values for the input parameters are changed. For the capacity-based subsidy, this is the case for the input parameter CAPEX, which is lowered by 30%. For the lift LCR policy, this is as well the case for the input parameter CAPEX, which is lowered by 11,5% because of the use of cheaper solar PV modules (see Section 7.3.4 for an explanation of this effect). For the price-based subsidy, the economic potential calculation changes compared to the base case by subtracting the provincial subsidy height of the LCOE. This models the effect of the price-based subsidy. For the carbon tax policy intervention, the input parameters national BPP and regional BPP's are changed according to the calculation method presented in the policy design in Section 7.3.3.

7.4.2 Ability to meet provincial demand

The national economic potential figure does not consider differences between provinces. From the results on economic potential in Section 5, it became clear that the economic potential can vary considerably between provinces, and that in some provinces with a relatively high electricity demand, there is currently little to no economic potential for utility-scale solar PV. Therefore, it is relevant to include a criterion that represents the ability of a policy intervention to create economic potential in all provinces. This criterion is operationalized as follows: The number of provinces where the economic potential is equal to or larger than 31% of the estimated electricity demand in 2050.

Calculation methods for the policy interventions
For each policy intervention, the number of provinces where the economic potential is equal to or larger than 31% of the estimated electricity demand in 2050 is calculated by following the economic potential calculation on a provincial level for the base case as discussed in Chapter 3.3. Similar to what is described in Section 7.4.1, per policy intervention some of the input parameters are varied. The result is a list of the economic potential expressed in potential electricity generation per province. That list is then compared to 31% of the estimated electricity demand in 2050, assuming an annual growth rate of 6,5%. The estimation method and assumed values of the demand can be found in Appendix D.

7.4.3 Domestic solar PV industry growth

One of the goals of the government is the growth of domestic industries, including utility-scale solar PV. This is made clear by the wide use of LCR regulations in Indonesia by the government, including for utility-scale solar PV Risnain [2018] and by the vision of growth and strength of domestic industries, as expressed by the MoI [2021]. Therefore, it can't be overlooked as a criterion and it is included in the criteria set. Because the operationalisation of domestic solar PV industry growth is difficult and requires an extensive analysis, this criterion is included as a qualitative criterion. The scores on this criteria are on an ordinal scale: low, medium or high. This refers to how much the policy intervention is expected to increase domestic solar PV industry growth.

7.4.4 Social acceptance

Social acceptance is of high importance for the successful implementation of renewable energy related policies by policymakers [OECD, 2019; Stigka et al., 2014; Segreto et al., 2020]. Furthermore, it is not always a given. For example, when a policy influences the electricity price for consumers, push-back can be expected [OECD, 2019]. Therefore, social acceptance is included as a criterion. The expected social acceptance of each policy intervention will be assessed qualitatively. The scores on this criteria are on an ordinal scale: low, medium or high. This refers to how likely social acceptance is. It will be discussed qualitatively how the policy interventions are likely to be received.

7.4.5 Overview of criteria

Table 7.4 presents an overview of the chosen criteria. It should be noted that this set of criteria does not fully represent all the effects of each policy intervention. This is acceptable because the goal of this MCA is not to choose between policy interventions, but to provide inside into the most important effects of policy interventions and to give direction to what policy interventions are interesting to explore in further detail.

Table 7.4: Overview of the criteria set on which the policy intervention are assessed

	Criteria	Type of criteria	Operationalisation of criteria
1	Economic potential	Quantitative	Potential electricity generation [TWh/year]
2	Ability to meet provincial demand	Quantitative	The number of provinces where the economic potential is equal to or larger than 31% of the estimated electricity demand in 2050.
3	Domestic solar PV industry growth	Qualitative	Low, medium or high
4	Social acceptance	Qualitative	Low, medium or high

7.5 STEP 4: DESCRIBE THE EXPECTED PERFORMANCE OF EACH OPTION AGAINST THE CRITERIA

In this step, the expected performance of each of the policy interventions on each of the criteria set are presented and discussed, following the methods described in the previous section on selected criteria. The results of this step are presented in Chapter 8. Given that a basic MCA is performed in this research, no scoring and weighting is added to the criteria and the expected performances will not be directly compared resulting in a preferred policy intervention based on weighted criteria scores.

8 POLICY ANALYSIS RESULTS

The results of the policy analysis by means of a basic MCA are presented in this chapter. The expected performance of each policy intervention on the selected criteria is discussed in separate sections for each criterion (Sections 8.1 to 8.4). A reflection on the possibility of the combination of multiple policy interventions can be found in Section 8.5. Finally, the conclusion of the policy analysis results is given in Section 8.6.

8.1 ECONOMIC POTENTIAL

Table 8.1 presents the effects of the policy intervention on the potential electricity generation in PWh/year. It is clear that each policy intervention results in a higher total economic potential on a national level. This makes sense given that the policy interventions were sought out to have this effect. The capacity-based subsidy results in the highest range in potential electricity generation. The price-based subsidy results in the lowest range.

It may seem surprising that the price-based subsidy comes out so low. However, the low values can be attributed to the way the policy is designed: in most provinces, there is no subsidy in place for utility-scale solar PV power plants because the current maximum allowed PPA tariffs there already suffice in creating economic potential. Therefore, the total economic potential on a national level does not increase as much as it does with the other policy interventions, which affect all provinces. The policy is focused specifically on a limited number of provinces in which an increase of the economic potential is arguably needed. This can be seen in the results on the criteria 'ability to meet provincial demand' in Section 8.2. A price-based subsidy has the most positive effect on this criteria. See Section 7.3.2 for further details on the policy design.

Table 8.1: Results on the economic potential expressed in potential electricity generation in the base case and for each of the policy interventions; values are rounded to the nearest integer.

		Economic potential: Potential electricity generation [PWh/year]	
	Policy intervention	*Low estimate*	*High estimate*
1	Base case	2	14
2	Capacity-based subsidy	7	37
3	Price-based subsidy	3	15
4	Carbon tax	5	29
5	Lift LCR	3	17

8.2 ABILITY TO MEET PROVINCIAL DEMAND

Table 8.1 presents the effects of the policy intervention on the number of provinces in which the economic potential is equal to or higher than 31% of the estimated 2050 electricity demand. It is clear that each policy intervention results in a higher range than in the base case. The policy intervention that stands out of the crowd for this criteria is the price-based subsidy. This makes sense, given that this policy consists of different subsidy heights in each province and was designed to be able to meet the provincial 2050 demand goal in every province. See Section 7.3.2 for further details on the policy design.

Table 8.2: Results on the number of provinces in which the economic potential is equal to or higher than 31% of the 2050 estimated electricity demand

		Ability to meet provincial demand: **Number of provinces in which the economic potential is equal to or higher than 31% of the 2050 electricity demand [-]**	
	Policy intervention	*Low estimate*	*High estimate*
1	Base case	11	15
2	Capacity-based subsidy	21	26
3	Price-based subsidy	26	33
4	Carbon tax	22	29
5	Lift LCR	17	23

8.3 DOMESTIC SOLAR PV INDUSTRY GROWTH

For the base case and each of the policy interventions, the effects on the domestic solar PV industry growth are discussed qualitatively. An overview of the results can be found at the end of this section in Table 8.3.

Base case
In the base case, there is no policy intervention present. This means, that the vicious cycle in the domestic solar PV industry, previously discussed in Section 6.2, remains. Why is that? The domestic solar PV industry is currently small in Indonesia. Therefore, it lacks economies of scale as are seen for solar PV modules in other parts of the world [IESR, 2019a; PVinsights.com, 2021]. Because of the LCR policy, however, solar PV power plant developers must buy these relatively expensive PV modules from the domestic industry. This makes a solar PV power plant more expensive and thus less financially attractive, resulting in less interest in the development of one. However, if the demand for solar PV components remains low, economies of scale will never be achieved in the domestic solar PV industry. This results in a vicious cycle, which is expected not to be broken in the base case by continuing with 'business as usual'. Therefore, the base case scores a *Low* on the criteria of domestic solar PV industry growth.

Capacity-based subsidy
By subsidizing the CAPEX of new solar PV power plants, the interest of investors in these type of plants are likely to grow. Especially given the increase of the economic potential as seen for that criteria compared to the base case in Section 8.1. This could result in the development of new power plants and therefore a growth of the domestic solar PV industry in terms of building and maintenance related jobs. Assuming that the LCR policy is still in place, this would also increase the demand

for solar PV modules and other components of the power plants, increasing the workload for domestic solar PV power plants component manufacturers. Overall, given the increase in economic potential and likely interest in the development of new power plants, this policy option could have a positive effect on the growth of the domestic solar PV industry. The score on this criteria is therefore *High* for the analyzed capacity-based subsidy.

Price-based subsidy
Similar to the capacity-based subsidy, the price-based subsidy is likely to increase interest in the development of utility-scale solar PV power plants. Possibly even more, because the policy is designed to increase the economic potential in provinces where the provincial demand is relatively high and the current economic potential is low. This is mainly the case for the most inhabited provinces, such as the provinces on the island of Java. These are also the provinces where most of the current solar PV component manufacturers are located, according to APAMSI (nd). Given that the LCR policy is still in place, this could result in domestic solar PV industry growth. Therefore, this policy intervention also scores a *High* on the criteria of domestic solar PV industry growth.

Carbon tax
Looking at the high impact on the economic potential of utility-scale solar PV compared to not introducing any policies of a carbon tax (see Section 8.1, it could be expected that a carbon tax of this level gives a large incentive for investors and power producers to look deeper into the development of utility-scale solar PV power plants. If indeed more solar power plants are built, this could result in a growth of the domestic solar PV industry, given that the LCR policy is assumed to still be in place in this policy intervention. Therefore, this policy intervention also scores a *High* on the criteria of domestic solar PV industry growth.

LCR lift
The LCR policy is meant to help the development of local industries and to create jobs. By lifting the LCR for solar PV modules, this might influence the existing local utility-scale solar PV industry, among which the eleven Indonesian solar PV module manufacturers [APAMSI, nd]. If this policy intervention results in only importing solar PV modules from abroad, which is assumed in the policy design, the local demand goes down and jobs may be lost. However, these solar manufacturing companies are mostly machine-based, so the impact would be limited. Furthermore, if the lifting of the policy results in the development of more solar PV parks, this would increase jobs in another side of the sector: the parks need to be built and maintained over the years. Overall, this policy intervention scores a *Low* on the criteria of domestic solar PV industry growth, since it would impact the existing industry, although small, significantly.

Table 8.3: Ordinal scores on domestic solar PV industry growth criteria of each policy intervention and the base case

	Policy intervention	Domestic solar PV industry growth ordinal score
1	Base case	Low
2	Capacity-based subsidy	High
3	Price-based subsidy	High
4	Carbon tax	High
5	Lift LCR	Low

8.4 SOCIAL ACCEPTANCE

For the base case and each of the policy interventions, the expected effects on social acceptance are discussed qualitatively. An overview of the results can be found at the end of this section in Table 8.4.

Base case

The base case does not involve any new policies. It is 'business as usual'. This sparks no discussion on whether a policy intervention is the right choice or not. However, given that fossil fuels receive large amounts of financial support and renewable technologies almost none, much criticism is seen on the current situation, as was discussed in Section 6.2. Especially given the renewable energy targets set in NEP. Therefore, the base case scores a *Medium* on the criteria of social acceptance.

Capacity-based subsidy

There is no direct indication that capacity-based subsidies would result in major negative social acceptance. However, it could be argued that only subsidizing utility-scale solar PV power plants, is unfair towards other upcoming renewable energy technologies. The majority of other renewable energy technologies are also not known to receive any fiscal support. Those sectors might start a discussion on this. Furthermore, subsidizing something means that the money needs to come from somewhere within the government budget, possibly by increasing certain taxes. This could result in push-back from taxpayers, who would prefer lower taxes or for their money to be spent on other purposes. This could be mitigated by setting a budget for the subsidies. If the budget is then empty, it is empty. Furthermore, the effects on taxpayers could be mitigated by moving some of the financial support for fossil fuels towards this subsidy budget. In conclusion, this policy option scores a *Medium* on the criteria social acceptance.

Price-based subsidy

The expected social acceptance of a price-based subsidy is similar to that of a capacity-based subsidy. It could be that the social acceptance is a little higher, because the policy is designed to incentivise cost reductions for a power producer, as discussed in Section 6.3. However, there is still the chance of push-back from other renewable energy technologies and taxpayers. Therefore, this policy option also scores a *Medium* on the criteria social acceptance.

Carbon tax

While a carbon tax is considered to be a relatively easy policy to administer, it would also result in an increase in electricity prices for consumers, because the higher BPP would likely be passed through to consumers paying the price. Policy instruments that have this effect have proved to be politically challenging to implement, according to the OECD [2019]. Often, there is a lack of social acceptance. A recent example of this is the rejection of a climate law in Switzerland through a nationwide referendum. The law proposed increased taxes on petrol and diesel and an extra fee for flying. About 51% of the Swiss voters voted against the implementation of the law [The Federal Council - Swiss government, 2021]. One of the arguments that were put forward by the opponents was that the law could result in a large financial burden for the Swiss citizens [Swissinfo.ch, 2021]. Therefore, this policy option scores a *Low* for social acceptance. It should be noted that the social acceptance for a carbon tax could be higher when the revenues from the taxes are used as cost compensation for vulnerable groups that face energy poverty, or as investments in the education or healthcare system. Furthermore, for some groups such as high-income households and both domestic and international organisations from the renewable energy sector are likely to be more accepting towards a carbon tax.

Lift LCR

The lifting of the LCR policy for solar PV modules could spark a discussion on LCR regulations in general. In many sectors in Indonesia, LCR policies are in place. Examples of such sectors are the modern retail, electronic and oil & gas sectors [Risnain, 2018]. Push-back can be expected from stakeholders within these sectors, who do not think it is fair that they still have to deal with LCR regulations when the solar PV sector does not. Furthermore, push-back from the domestic solar PV manufacturers can be expected, since the lifting of the LCR is likely to influence their current sales to power plant developers. This also touches upon a greater discussion: if LCR regulations are fair and effective national policy instruments in general. The OECD for example, considers LCR regulations to have a negative impact on international economic development and is critical of the use of such regulations [OECD, nd]. The organisation states that while LCR, also for renewable energy technologies specifically, can sometimes help countries to achieve short-term objectives, long-term competitiveness is undermined and economies of scale are often delayed [OECD, 2015]. In conclusion, push-back can be expected from multiple stakeholders, and the policy intervention is not likely to be implemented smoothly without sparking a larger discussion. Therefore, this policy option scores a *Low* for social acceptance.

Table 8.4: Ordinal scores on social acceptance of each policy intervention and the base case

	Policy intervention	Social acceptance ordinal score
1	Base case	Medium
2	Capacity-based subsidy	Medium
3	Price-based subsidy	Medium
4	Carbon tax	Low
5	Lift LCR	Low

8.5 COMBINING AND DESIGNING POLICY INTERVENTIONS

One policy intervention does not necessarily exclude another one. This section discusses some possibilities. First of all, to lift the LCR regulation in combination with a price-based subsidy, carbon tax or capacity-based subsidy, could increase the positive effects on the economic potential of utility-scale solar PV further. As was seen in Section 8.1, the lift LCR policy alone only results in limited effects on the criteria 'ability to meet provincial demand'.

Secondly, combining auction schemes with one of the discussed policy interventions is an interesting option. Although auction schemes are not included in the policy analysis, they are interesting to reveal real market prices of utility-scale solar PV power, control the total capacity of utility-scale solar PV and are known to have brought costs down due to its competitive nature, as discussed in Section 6.3.5. A combination of an auction scheme with a price-based subsidy or a capacity-based subsidy could result in extra incentives for the development of utility-scale solar PV power plants while also stimulating to reduce costs due to the competitive nature of an auction scheme [Peñasco et al., 2021]. IRENA [2015] considers a combination of a form of subsidy and an auction scheme to be more effective than a subsidy alone due to these advantages and the ability to control the installed capacity of utility-scale solar PV, which is useful in meeting renewable energy targets.

Finally, a combination of a carbon tax with some form of renewable energy subsidies is said to be able to help in the development of renewable energy projects without leading to high energy price increases, which is often considered to be a negative side effect of carbon pricing [Kalkuhl et al., 2013].

An interesting starting point to design further policy interventions or combinations of them would be the calculated gap between the current maximum allowed PPA tariffs and the range of needed tariffs for the economic potential to be equal to or higher than 31% of the estimated electricity demand in 2050, presented in Figure C.1. The figure shows that for 18 provinces, a financial barrier is present for the development of utility-scale solar PV. Policies can be further designed and optimized with as an end goal to fill the gaps for those provinces. For example, a carbon tax can partly increase the maximum PPA tariffs because of the dependency of this tariff on the BPP. Next to that, a price-based subsidy can decrease the needed tariffs by bringing down the costs. Combined they can fill the gap.

8.6 CONCLUSIONS ON POLICY ANALYSIS

From the policy analysis by means of an MCA on four interesting policy interventions, several conclusions can be drawn, which are discussed next.

The base case creates an undesirable situation for the economic potential and keeps the domestic industry in a vicious cycle
All four policy interventions are likely to increase the economic potential in terms of potential electricity generation and are able to achieve an economic potential equal to or higher than 31% of the expected electricity demand in 2050 in more provinces than in the base case. In the 'business as usual' case, there is little to no economic potential found in most of the provinces, including those with a relatively high electricity demand, as was also seen in the economic potential results in Chapter 5.3. The base case, therefore, creates an undesirable situation compared to the other policy interventions. Also, it keeps the domestic solar PV industry in the vicious cycle of no growth and no creation of economies of scale, because in the base case, fast development of utility-scale solar PV power plants is not likely to happen, keeping the demand for solar PV power plant components low. Furthermore, the social acceptance of 'doing nothing' has multiple perspectives: on one side, it keeps current electricity prices for consumers low, which are mostly determined by the current relatively low prices of fossil fuel-based electricity. However, there is also much criticism on doing nothing, especially given the high technical potential of utility-scale solar PV in Indonesia and the set targets for growth of renewable energy in the electricity mix in the NEP.

A carbon tax is an interesting option with positive economic potential effects, but wide social acceptance is not expected
A carbon tax would result in a significant increase in the economic potential, also spread throughout the provinces. It makes utility-scale solar PV power plants a financially more interesting option compared to fossil fuel power plants. If this economic potential is utilized, the domestic solar PV industry is expected to grow, assuming that the LCR regulation is still in place. This is also likely to result in economies of scale achievements in the industry. However, given that a carbon tax is likely to result in increased electricity prices for consumers, the general social acceptance of this policy intervention is expected to be low.

The price-based subsidy is a focused and effective option, but can be expensive in some provinces
Although the price-based subsidy does not result in the greatest increase in the total economic potential, it is a very effective policy in increasing the economic potential in provinces in which that is needed the most, compared to the economic poten-

tial in the base case. It creates economic potential and competitive LCOE prices in provinces where the electricity demand is the highest (the provinces on Java). This makes sense given that this policy is designed to be as successful as possible in achieving provincial economic potential equal to the expected electricity demand in 2050. Furthermore, if the relatively higher economic potential also is utilized, the domestic solar PV industry is expected to grow (given that the LCR regulation is still in place). This is also positive given that this is likely to result in economies of scale achievements in the industry, making the need for subsidies or other policy interventions smaller. It should be noted that due to this reason, it is advisable to re-evaluate subsidy heights frequently. If subsidies are not needed anymore to make utility-scale solar PV competitive with other energy technologies, it would be a waste of money. This is especially of importance for the provinces in which the subsidies are the highest in US$/kWh, such as Banten, Jawa Barat, Jambi, Lampung, Jawa Tengah, Bali, Sumtera Selatan and Sumatera Barat. In all these provinces, the price-based subsidy height is higher than 2 US$ct./kWh.

To lift the LCR results in the most limited economic potential growth, and social acceptance is not likely
This policy option has the smallest effect on the economic potential criteria compared to the other policy interventions. Also, the effect on the ability to meet the provincial demand target with the economic potential in each province is the most limited. This seems logical given that this policy only results in an assumed decrease of the CAPEX of 11,5%, compared to for example a decrease of 30% of the CAPEX in the capacity-based subsidy. Furthermore, the social acceptance for this policy intervention would be a complex issue, given that LCR regulations are used widely throughout Indonesia and the lifting of this regulation alone is not likely to go down quietly. Also, push-back from the domestic industry can be expected. This also touches upon the point that this policy is likely to result in the shrinkage of the domestic solar PV industry.

The capacity-based subsidy is effective in increasing economic potential but less effective than a price-based subsidy
The capacity-based subsidy policy option results in the largest relative increase in economic potential expressed in total potential electricity generation. This is an upside of this policy intervention. However, it is a less focused policy option than the price-based subsidy, which can be seen in the more limited effect on the ability to meet provincial demand with economic potential criteria. It should also be noted that this policy intervention entails that a capacity-based subsidy can be requested in any province in Indonesia. However, in some provinces, the LCOE of utility-scale solar PV is already lower than the maximum allowed PPA tariff. In those provinces, the subsidy could be seen as a waste of money and not an incentive for a solar power plant developer to be cost-effective and create as low electricity prices as possible.

Other (combinations of) policies can be designed with the needed versus the maximum allowed PPA tariffs as a starting point
The found gap between the current maximum allowed PPA tariffs and the needed tariffs for the economic potential to be equal to or higher than 31% of the estimated electricity demand in 2050 in 18 out of the 33 provinces, can be used as a starting point to design further policies. The gap could be closed with a combination of several policy interventions, such as a carbon tax and a price-based subsidy.

Part III

DISCUSSION AND CONCLUSIONS

9 DISCUSSION

In this chapter, the limitations of the methods used in Part i and Part ii of this thesis are discussed in Section 9.1, as well as recommendations for future research based on both the discussed limitations and the results of this research in Section 9.2.

9.1 LIMITATIONS IN METHOD

This research is imperfect and knows limitations for both the technical and economic analysis part and the policy analysis part. For both parts, the limitations of the method is discussed.

9.1.1 Limitations of the technical and economic potential analysis

For this part of the thesis, a GIS-based method was followed. To calculate the technical and economic potential on a national and provincial level, simplifications and assumptions were made. This results in limitations that should be made aware of. These are further discussed and some improvements are proposed.

Disregard of economies of scale and other system size related differences in costs and system output in the LCOE calculation
As discussed in Section 3.3.2, the calculated LCOE values refer to the LCOE of a utility-scale solar PV power plant in general, and not a solar PV system with a specified capacity. This was done because the found cost estimations in literature in most cases did not specify a system size, but referred to utility-scale solar PV in general. However, this disregards the difference in costs and output between different system sizes. It is likely that the system costs of a one MWp power plant differ from those of a 100 MWp power plant, given factors like economies of scale and differences in factors such as transmission losses and grid connection costs [Farell, 2019]. For the results of this thesis, this means that the LCOE results are not necessarily representative for all utility-scale solar PV power plants.

Exclusion of the potentials of floating and rooftop utility-scale solar PV
This research is focused on the potential of ground-mounted utility-scale solar PV and excludes water bodies and inland seas in the calculations of the potentials. However, floating utility-scale solar PV power plants, which are solar PV power plants located in lakes, water reservoirs or inland seas, are also interesting forms of solar PV power plants due to less interference with other purposes of land use. Furthermore, Indonesia seems to be particularly interesting for floating solar power plants because of the large number of reservoirs, natural lakes and inland seas with limited impact of strong winds and waves [Silalahi et al., 2021]. Also, the differences in technology and costs between ground-mounted and floating solar PV power plants, are not that big, according to the The World Bank [2018]. There are higher construction costs involved due to the complexity of the needed structures, but this is compensated by a higher system performance compared to ground-mounted systems and the likely less land acquisition costs. This can be somewhat validated given that recently, the construction of a floating solar PV power plant of 145 MWp in West-Java has started, with an agreed PPA tariff of 5,81 US$ct./KWh

[IESR, 2021b]. Furthermore, rooftop solar PV systems could also contribute to the total potential of solar PV, especially in the more inhabited provinces such as those located on Java. Overall it should be clear that this research only provides insights into the potentials of utility-scale solar PV, and does not paint a complete picture of the potential of solar PV in general. Additional research is needed for this.

Simplification of grid connection costs
In the CAPEX calculation method, the grid connections costs are simplified and expressed in US$/$KW_p$/km while taking a connection distance factor into account, as can be seen in Section 3.3.2 along with other economic parameter assumptions. This is a very rough simplification, given that grid connection costs are depended on the voltage of the needed cable, the true distance between a power plant and the connection point and the location of the actual point on the electricity grid to which the power plant can be connected, taking into account supply and demand in the electricity network. However, through desk research and conversations with industry experts, a more appropriate method to estimate grid connection costs of a general utility-scale solar PV power plant could not be found that was feasible for this thesis given limited time. Especially given that the economic potential is based on general utility-scale solar PV power plants and does not specify a system capacity, which makes the cable costs per km difficult to determine. This results in possibly higher or lower LCOE estimations that are the case in reality. It should also be noted that transmission losses over cables are not taken into account with regard to the length of the cable. This may result in higher LCOE estimations than would be the case in some of the more remote areas.

Disregard of several factors influencing costs and practicability of a site
First of all, extra costs related to power plants in sites that are not flat are not considered in this research in the calculation of the LCOE. From interviews with experts in utility-scale solar PV power plant development, it becomes clear that slope does influence the investments costs, but that the relationship between ground slope and extra investments costs is hard to define. The calculation method could be improved by further researching this relationship and including it in the calculation.

Second of all, a utility-scale solar PV power plant in a place that is not nearby an area where there is electricity demand and electricity infrastructure through which the electricity can be distributed to consumers, does not make much sense, especially given transmission losses over the cable and true grid connection costs. In this research, this was only taken into account by including a simplification of grid connection costs based on the distance to the nearest medium or high voltage substation or national, provincial or regional capital. However, this does not fully represent the effects, leading towards an estimation of the LCOE that's likely too low in these remote areas such as in the province of Papua, in which there is only a limited electricity infrastructure [The World Bank, 2021a]. Furthermore, remote areas also have the disadvantage of being further away from major shipping routes over water or land, which may lead to higher shipping costs of needed components and the difficulty of getting people with the knowledge to build and operate a power plant to these places. This is also not considered in the cost estimations.

Finally, this research does not consider extra costs of energy storage systems in the form of batteries which might be required by PLN to be able to supply non-intermittent solar energy to the electricity grid, especially in the case of power plants with a large capacity.

Disregard of extra grid extension and energy storage costs in case of a high penetration of utility-scale solar PV on the electricity grid
If the share of utility-scale solar PV in the electricity mix rises, this requires changes

in the electricity grid to be able to ensure the security and stability of the power system given the fluctuations in energy supply Al-Shetwi et al. [2020]. These changes include grid extensions and the inclusion of energy storage solutions, which are not free of charge. Therefore, a high penetration of utility-scale solar PV in the electricity mix may result in higher system costs. This is not taken into consideration when calculating the economic potential. The results are only valid when the penetration in the system is limited.

Overall
From this overview of limitations, the question arises whether the results on the technical and economic potential are still valid. The main value of this part of the research is to give an overall idea about in which areas utility-scale solar PV might be financially interesting, and to identify provinces in which policy interventions may be needed to increase the economic potential. Given that the limitations are mainly related to uncertainties and simplifications that may affect the potentials and LCOE on a local scale, the main insights are still valid. As was discussed previously in this section and also highlighted in interviews with experts in utility-scale solar PV power plant development, the actual LCOE of a specific site can only be accurately assessed when all local circumstances are analysed on a detailed level. Before the actual development of a utility-scale solar PV power plant, a detailed analysis should always be performed on the economic factors and land suitability.

9.1.2 Limitations of the policy analysis

For this part of the thesis, several policy interventions meant to increase the economic potential especially in provinces where that is considered to be needed the most, were assessed based on several criteria. The limitations of the method and results are further discussed in this section.

Limited number of explored policy interventions & only focused on overcoming a financial barrier
Four policy interventions were chosen to be analyzed. However, there are many more options possible that might also be interesting. Also within the analyzed policy interventions, there is room for variations. For example for the capacity-based subsidy, which was set at 30% for every solar PV power plant in Indonesia. Various input percentages could be explored and lead to a better substantiated percentage height. Furthermore, the policy interventions were chosen because they are expected to help in overcoming the financial barrier that utility-scale solar PV faces in Indonesia. And although the financial barrier is an important roadblock, as seen in the results on the technical and economic potential analysis in this research and in literature [IISD, 2018; IESR, 2019b], other barriers are also present. Maulidia et al. [2019] identified, among other things, problems with the unclear mandates and responsibilities, contradicting policies and rigid bureaucracy for renewable energy development in Indonesia. These institutional barriers are not addressed in this research. However, these roadblocks also deserve attention, not just for utility-scale solar PV development, but for all renewable energy technologies in Indonesia.

Limited number of criteria that excludes costs
The effects of policy interventions are not limited to the static criteria presented in this research. Each policy intervention might result in side effects that are not discussed in this research. Therefore, policy-makers are wrong to decide on a policy intervention without further exploration of the effects by means of a thorough analysis. An important criterion that is not included in the policy analysis but should be assessed further are the system costs, referring to the total costs that a policy intervention has. This criterion was not included because it would have required a more extensive policy design, a scenario analysis and a clear definition of the sys-

tem costs and for who the costs are. Furthermore, the system costs are difficult to assess and compare because of the different policy intervention types. An example follows: A carbon tax would result in revenue for the government, but costs for fossil fuel-based power plants and indirectly electricity consumers. The costs, however, are likely to change each year, assuming that the policy intervention will do its job of decreasing the share of fossil fuels and increasing the share of renewable energy in the electricity mix, reducing the revenue of the carbon tax. A scenario analysis would therefore be needed to assess annual costs. On the other hand, for the capacity-based subsidy, the costs are depended on how many utility-scale solar PV power plants will be developed and make use of this subsidy. Again, a different type of scenario analysis is needed. These differences in policy interventions and how the costs should be addressed make the complexity clear of assessing different types of policy interventions on system costs, especially if the costs are to be compared.

Lack of validation on the performance on the criteria
The results of the policy analysis were not validated by means of interviews with experts on the utility-scale solar PV industry and policy context in Indonesia. This would have been an improvement for this study, especially given that two of the four criteria (social acceptance and domestic solar PV industry growth) are qualitatively addressed based on desk research by looking at reports, literature and similar situations in other countries. Perspectives of stakeholders would provide valuable knowledge on the possible effects of the policy interventions within the Indonesian context.

Performance is based on static criteria and not dynamic
The selected quantitative criteria on which the performance of the policy interventions is analyzed are static criteria. They do not take into account changes over time, such as reduction in costs of utility-scale solar PV components or improvement of the capacity factor of solar PV systems due to technological innovations. Again, this asks for a more detailed analysis using scenarios.

Simplified estimation method of electricity demand in 2050
The estimation of the electricity demand in 2050 is calculated based on the 2018 electricity demand as published by BPS [2020b] and an annual growth rate of 6,5% for each year between 2018 and 2050. This is a simplified estimation method that does not take into account likely differences in growth per province. Furthermore, the annual growth rate is based on historical growth rates. However, the past does not necessarily predict the future. This results in uncertainty for the results on the criterion expressed in the number of provinces in which the economic potential can reach 31% of the electricity demand in 2050. An improvement for the analysis would be to look further into scenarios on the expectation of electricity demand in 2050 on a provincial level and to use an estimation method with less uncertainty.

Overall
Due to the limitations of the policy analysis, the results can be used in policy-making to a certain extent. The results provide insights into the effects of a limited number of policies on a limited number of criteria, excluding costs. Therefore, it can be seen as valuable knowledge that can be used in developing a policy road map for the further development of utility-scale solar PV in Indonesia. To further develop such a policy road map, more roadblocks next to the financial one should be researched further. Also, a more detailed policy analysis in which more policy interventions are compared on more (dynamic) criteria) can paint a broader picture of what is possible and what the effects are.

9.2 RECOMMENDATIONS FOR FURTHER RESEARCH

Three main recommendations for further research that were identified based on the results and discussed limitations of the methods are presented.

1. Assessment of the potentials of floating utility-scale solar PV and rooftop solar PV systems
As previously discussed in Section 9.1.1, floating utility-scale solar PV deserves an assessment of the technical and economic potentials in the opinion of the author. The low electricity tariffs seen in projects in Indonesia, the smaller issue of interference with other ground land use purposes, the large number of lakes and reservoirs and the relatively attractive circumstances in the calm inland seas of Indonesia are reasons for this. Such research can help in showing more completely to policy-makers, investors and other interested parties, the role that utility-scale solar PV can play in the energy transition and how economically viable it is. Furthermore, an in-depth analysis of the potentials of rooftop solar PV systems is also recommended. Especially in provinces that are highly urbanized, such as DKI Jakarta, rooftop solar PV could be interesting. The IESR [2021c] has previously studied the technical potential of residential rooftop solar PV in Indonesia, which resulted in an estimation in the range of 194 to 655 GW_p. An addition would be to study the economic potential taking into account regional electricity tariffs, similar to what has been done in this study for utility-scale solar PV. Given the higher average costs of a rooftop solar PV system versus a utility-scale solar PV system, as was discussed in Section 1.2, insights into the economic potential are useful.

2. Analysis of other non-financial roadblocks to utility-scale solar PV development
Next to the cost-price gap issue that is addressed in this thesis, utility-scale solar PV development is not going so smooth in Indonesia for various other reasons. Maulidia et al. [2019] has identified some of the other roadblocks for renewable energy technologies in general, such as an unclear regulatory framework, rigid bureaucracy and a monopolised power sector. Further research on these roadblocks and how to overcome them would provide valuable insights for policy-makers to further help the development of utility-scale solar PV and other renewable energy technologies.

3. In detail assessment of (combinations of) policy interventions including costs
The policy interventions are only roughly analyzed on a few criteria. However, before implementing policy interventions to tackle the financial barrier that utility-scale solar PV faces in some provinces, more detailed assessments are needed. What other side effects are there that fall outside of the criteria included in this research? What costs can be expected for each policy intervention and how do these compare?

In addition to this, it is recommended to further explore combinations of policy interventions and to design cost-effective policies. A starting point for a cost-effective policy strategy can be the gap between the current maximum allowed PPA tariffs and the range of needed tariffs for the economic potential to be equal to or higher than 31% of the estimated electricity demand in 2050. This gap, which is present in 18 provinces, can be filled in numerous ways. For example by means of a combination of an auction scheme, carbon tax and a price-based subsidy. Combining policy interventions and designing them together to address the financial barrier could be a policy strategy that is cost-effective and has the positive effects of multiple policy interventions. Further research on this can help to give policy-makers insights in cost-effective manners to increase the development of utility-scale solar PV in Indonesia.

10 CONCLUSION

In the final chapter of this thesis, the sub-questions and main research question posed at the start of this thesis are revisited and answered.

Sub-question 1. What is the technical potential of utility-scale solar PV in Indonesia?
The technical potential of utility-scale solar PV in Indonesia is depended on what types of land cover are considered suitable and what ground slope limit is found acceptable for the development of solar power plants. In literature, inconsistency is found in what are considered to be appropriate site selection criteria. Therefore, fifteen scenarios were set up that vary in site selection criteria. More specifically, they vary in ground slope limit and land cover types on which there are different opinions on how suitable or desirable the land cover types for solar PV power plant development is. This is for example the case for land that is currently used for agricultural purposes. The results of the technical potential depend on the scenario and range on a national level between 9 and 53 TW_p expressed in potential capacity. The range in technical potential expressed in potential electricity generation is 12 and 73 PWh/year. This can completely cover the 2018 total electricity demand of 175 TWh/year and the estimated total electricity demand of 1793 TWh/year given an annual growth rate of 6,5%. The capacity factor, which shows the ratio between the potential electricity generation and potential capacity, is estimated to range between 15 and 16 % in Indonesia.

Sub-question 2. What is the economic potential of utility-scale solar PV in Indonesia?
The economic potential is addressed by assessment of the LCOE for utility-scale solar PV and by the comparison of the LCOE with the regional maximum allowed electricity tariffs. This comparison results in the economic potential expressed in both potential capacity and potential electricity generation. First, on a resolution of five km^2, the LCOE was calculated using cost assumptions found in literature and by interviews with industry experts. The location depended factors were the grid connection costs based on the distance to the nearest connection point and the average electricity output in KWh/KW_p. The results are a range in LCOE between 7,6 and 25,7 US$ct./KWh.

Then, the potential capacity and potential electricity generation were calculated. Since the economic potential builds upon the technical potential, the economic potential was also explored for fifteen scenarios. The results are a range in potential capacity between 2 and 9 TW_p and a range in potential electricity generation between 2 and 12 PWh/year. Although the maximum of this range lies outside of the higher technical potential estimation, the economic potential can still cover the 2018 total electricity demand of 0,2 PWh/year and the estimated total electricity demand of 2 PWh/year given an annual growth rate of 6,5%. This emphasizes that utility-scale solar PV can be a competitive form of renewable energy against fossil fuels.

However, an analysis of the economic potential on a provincial level shows that the economic potential varies significantly per province. In 12 out of the 33 provinces, no economic potential was found at all, given the definition used in this research. The provinces of Jawa Barat, Jawa Tengah and Banten, which together account for about 49% of the national electricity demand in 2018, are part of these 12 provinces. This emphasizes that the economic potential is not distributed equally over the provinces and not located in the provinces where it could be argued that renewable electricity is nominally needed the most. What also strikes from the results is that the average LCOE in these provinces is not significantly lower than the average in other provinces. This means that the various regional maximum allowed PPA tariffs are the driver behind the differences in economic potential per province.

Based on the results on economic potential on a provincial level, it can be argued that policy interventions are needed to increase the economic viability of utility-scale solar PV, especially in the provinces where no economic potential was found given the definition of economic potential used in this research and the cost assumptions.

Sub-question 3. What are possible policy interventions to increase the economic potential of utility-scale solar PV in Indonesia?
Out of the large number of policy interventions that are possible to increase the economic viability of utility-scale solar PV in Indonesia, four policies were identified as interesting policy options to further explore: (1) a capacity-based subsidy of 30% of the CAPEX, (2) a price-based subsidy varying in height per province, (3) a carbon tax of 35,9 US$ per tonne of carbon dioxide and (4) the lifting of the LCR regulation currently in place. These policy interventions are expected to directly or indirectly affect the economic viability of utility-scale solar PV power plants.

Sub-question 4. How do the policy interventions affect the economic potential and other relevant system factors?
The performance of the four identified policy interventions and the base case ('business as usual') are explored with four criteria at the basis. The five criteria are: (1) economic potential expressed in potential electricity generation, (2) ability to meet provincial demand expressed in a number of provinces in which the number of provinces where the economic potential is equal to or larger than 31% of the estimated electricity demand in 2050, (3) domestic industry growth and (4) social acceptance. The final two criteria are assessed qualitatively. For each policy intervention and the base case, a conclusion is drawn based on its performance:

The base case
The base case, ´business as usual´, creates an undesirable situation for the economic potential on a provincial level, limiting the economic viability of utility-scale solar PV power plants in some of the provinces with the highest electricity demand. Furthermore, it keeps the domestic industry in a vicious cycle: without more demand for solar PV components, the industry is not likely to grow.

Capacity-based subsidy
A capacity-based subsidy of 30% of the CAPEX of a utility-scale solar PV power plant is effective in increasing the economic potential on a national level, but it is less focused than the price-based subsidy. This can be seen in the more limited effect on the ability to meet 31% of the estimated demand in 2050 per province. It can also be seen as a waste of money in the provinces where the maximum allowed PPA tariff is already higher than the average estimated LCOE values in that province. In those provinces, a subsidy is not always necessary for utility-scale solar PV power plants to be competitive with fossil fuel-based power plants.

Price-based subsidy
The price-based subsidy is found to be a focused and effective option but can be expensive in some of the provinces. The policy was designed to close the gap between the maximum allowed PPA tariff in a province and the LCOE in that province,

enough to be able to meet 31% of the estimated electricity demand in 2050 in the high estimate. Therefore, its success on that criteria is naturally high compared to the base case and the other policy interventions. It is an effective and focused policy option.

Lift LCR
By lifting the LCR regulation, there is only a limited effect on the two criteria related to national and provincial economic potentials. The cheaper solar PV modules with global prices that can be used due to the lifting of the LCR only have a limited impact on the total price of the PV system. Furthermore, this policy option is likely to have little social and political acceptance, given that the LCR regulations are seen in a wide range of sectors in Indonesia. Its lifting for one sector is likely to result in discussions and push-back from other sectors.

Carbon tax
A carbon tax is an interesting option with positive economic potential effects, on both the national and provincial levels. However, wide social acceptance is not expected since a carbon tax is likely to result in increased electricity prices for consumers. These types of policies are known for their issues with social acceptance.

Main Research Question

What is the technical and economic potential of utility-scale solar PV in Indonesia and what can be recommended in the policy context to increase the economic viability of utility-scale solar PV?

The first part of the main research question is addressed in the answers to sub-questions 1 and 2. In conclusion, there seems to be enough economic potential on a national level to be able to meet the current national electricity demand in 2018 and the expected demand in 2050. This emphasizes that utility-scale solar PV could play an important role in the energy transition in Indonesia. However, the economic potential on a provincial level creates a less optimistic picture. In some of the provinces with the highest electricity demand, no economic potential could be found given used cost estimations. It can therefore be argued that policy interventions are needed to increase the economic viability of utility-scale solar PV power plants, especially in the areas where there is high electricity demand and limited economic potential.

This brings us to the second part of the main research question. The basis for the answer lies in the answers to sub-questions 3 and 4. First of all, 'business as usual', is not likely to get very far in overcoming the financial barrier that utility-scale solar PV faces in some provinces. Furthermore, it disregards the potential that utility-scale solar PV has in the Indonesian energy transition given the declining costs of solar PV systems and large technical potential. Therefore, it is recommended to implement some kind of policy strategy that addresses the economic viability, especially in the provinces where that is needed the most. The analyzed policy options are all somewhat effective in this, compared to doing nothing. In addition to these policy interventions, a transparent auction scheme could also bring added value in revealing real solar PV system costs and may result in lower costs due to the competitive nature of auctions.

It is also recommended for policy-makers to do a more in-depth analysis of the effects of combinations of policy interventions. One policy intervention does not necessarily exclude another one, and combinations of policies might be more effective in stimulating the development of utility-scale solar PV in Indonesia. A good starting point for that are the calculated gaps between the current maximum allowed PPA tariffs and the range of needed tariffs for the economic potential to be equal to or higher than 31% of the estimated electricity demand in 2050. For 18 provinces, a gap was found. Policies can be further designed and optimized with as an end goal to fill the gaps for those provinces. An example could be a combination of a carbon tax, price-based subsidy and an auction scheme, which can together be effective in closing the gap between the maximum allowed tariffs and needed tariffs. Given the differences in the need for more economic potential in the provinces, it is also recommended to consider a policy strategy that differentiates between provinces. That way, support is provided in the places where support is needed the most.

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A CAPEX CALCULATION METHOD

The CAPEX of utility-scale solar PV is an economic parameter used to calculate the LCOE of utility-scale solar PV systems. The assumption for the total CAPEX in this research is 1041 US$/$\mathrm{KW_p}$. The values used to calculate the CAPEX are presented in Table A.1. Except for the module costs, all values come from the 2020 renewable energy cost database of IRENA [2021]. These values have been converted from 2020 US$ up to September 2021 US$ taking cumulative inflation into account, using the latest US government data as published by the Board of Governors of the Federal Reserve System [2021]. The most recent value for module prices in Indonesia was found through an interview with a solar PV consultant in Indonesia with knowledge on the PV module market, taking local content requirement into consideration [anonymous Indonesian industry expert, personal communication, June 25, 2021]. Finally, the CAPEX input value is rounded to the nearest integer to 1041 US$/$\mathrm{KW_p}$.

Table A.1: Values used to calculate the CAPEX

Category	Cost component	2020 price [US$/$\mathrm{KW_p}$]	2021 price [US$/$\mathrm{KW_p}$]	Reference
Module and inverter hardware	Modules	-	320	Anonymous Indonesian industry expert, personal communication, June 25, 2021
	Inverters	64,12	67,63	IRENA [2021]
Balance of system costs	Racking and mounting	77,18	81,41	
	Grid connection	71,35	75,26	
	Cabling/wiring	91,60	96,62	
	Safety and security	88,62	93,48	
	Monitoring and control	27,53	29,04	
Installation	Mechanical installation	9,67	10,20	
	Electrical installation	8,42	8,88	
	Inspection	12,86	13,57	
Soft costs	Margin	218,22	230,19	
	Financing costs	7,16	7,55	
	System design	3,66	3,86	
	Permitting	9,02	9,51	
	Costumer acquisition	3,92	4,13	
Total			*1040,79*	

B BPP FIGURES IN INDONESIA

Table B.1 shows the regional and national BPP figures throughout Indonesia expressed in US$ct./KWh. The names of the provinces and regions are in Indonesian. The figures were published by the MoEMR in 2017 and have been converted to 2021 US$ct./KWh using the latest inflation rates up to September 2021 as published by the Board of Governors of the Federal Reserve System [2021]. The figures have not been updated since 2017, to the authors' best knowledge.

Table B.1: BPP figures in provinces and regions of Indonesia and the national BPP figure [MoEMR, 2017a]

Province or region	**BPP [US$ct./KWh]**	**Province or region**	**BPP [US$ct./KWh]**
Jawa Barat	6,65	Selayar	16,52
Jawa Tengah	6,65	Fak Fak	16,78
Daerah Istimewa Yogyakarta	6,65	Sanana	16,8
Banten	6,66	Flores Bagian Barat	16,92
DKI Jakarta	6,66	Timor	17,49
Bali	6,66	Merauke	17,52
Jawa Timur	6,68	Pulau Simeuleu	17,91
Lampung	7,02	Bacan	18,07
Sumatera Barat	7,15	Bangka	18,11
Sumatera Selatan	7,17	Tambora	18,47
Sumatera Jambi	7,17	Timika	18,49
Sumatera Bengkulu	7,17	Tiga Nusa	18,66
Kepulauan Seribu	7,86	Terminabuan	18,8
Palu Poso	7,91	Serui	19,47
Sulawesi Bagian Selatan	7,94	Toli_Toli	19,55
Sumatera Utara	9,8	Tahuna	19,79
Sorong	9,9	Halmahera	20,02
Kalimantan Timur & Utara	10,18	Sumba	20,03
Kalimantan Barat	10,3	Seram	20,07
Riau	11,18	Saparua	20,22
Aceh	11,3	Ambon	20,34
Kalimantan Selatan & Tengah	11,36	Buru	20,4
Bintan	12,07	Nias	20,48
Belitung	12,16	Flores Bagian Timur	20,48
Bintuni	12,24	Karimun Jawa	20,55
Sulawesi Bagian Utara	12,96	Tanah Merah	20,55
Manokwari	13,64	Kaimana	20,55
Lombok	13,81	Kepulauan Mentawai	20,55
Tanjung Balai Karimun	14,26	Daruba	20,55
Jayapura	14,61	Madura	20,55
Nabire	14,8	Bawean	20,55
Natuna	15,13	Sarmi	20,55
Anambas	15,32	Gili Ketapang	20,55
Ternate Tidore	15,53	Saumlaki	20,55
Pulau Weh	15,56	Dobo	20,55
Kendari	15,68	Tual	20,55
Bau Bau	16,01	Pulau Panjang	20,55
Biak	16,14	Wamena	20,55
Luwuk	16,24	Raja Ampat	20,55
National	*7,56*		

C TARIFF CALCULATION

This appendix contains the calculation method of the electricity tariffs that are needed for the economic potential of utility-scale solar PV to be equal to 31% of the expected electricity demand per province, and the results of this calculation. The used data on estimated electricity demand in 2050 can be found in Appendix D.

C.1 CALCULATION METHOD OF TARIFFS

The new tariffs are calculated by taking the data-set of each province in each scenario, which contains information for each grid cell on the estimated LCOE and potential electricity generation in that area. For each data-set, this method is followed:

In the python environment, a loop function runs through the data-set and picks the grid cell with the lowest LCOE value. For that grid cell, the LCOE value is saved in an empty list. The potential electricity generation in the grid cell is saved in a separate variable 'potential electricity generation'. The grid cell is removed from the data-set, and the loop function runs again through the smaller data-set, finding the grid cell with the lowest LCOE value. The then lowest LCOE value is added to the list with the previous LCOE values. The potential electricity generation in the grid cell is added to the 'potential electricity generation' variable. This loop continues, until the stop condition is met. The stop condition is when the value of the 'potential electricity generation' variable is equal to or larger than 31% of the expected electricity demand in 2050 in the province. The tariff that is assumed to be needed for the economic potential to be equal to 31% of the expected electricity demand in 2050, is the highest LCOE value found in the LCOE value list.

C.2 RESULTS

Table C.1 present the results of what the electricity tariffs should be to result in an estimated economic potential equal to 31% of the estimated 2050 electricity demand per province. There is a range per province because of the multiple scenario approach: the actual needed tariff is expected to lay somewhere in between, depending on what types of land will be considered for utility-scale solar PV development. For some provinces, the range is significantly larger than for other provinces. This can be attributed to the fact that in some provinces, the technical potential is so limited compared to the electricity demand in 2050 that to be able to get the economic potential to this level, all suitable land areas should be used for utility-scale solar PV development, including areas that have a relatively high LCOE. What becomes clear from the results is that for 15 out of the 33 provinces, the current maximum allowed PPA tariffs are high enough for the economic potential of utility-scale solar PV to be equal to 31% of the 2050 electricity demand. This is not the case for the other 18 provinces, for which the current maximum allowed PPA tariff does not suffice.

It should be noted that for some provinces, the current maximum allowed PPA tariff as presented in Table C.1 is based on an average of the present maximum allowed PPA tariffs in the various BPP regions that fall into that provinces. This is the case for the following 10 provinces: Kepualuan Riau, Maluku, Maluku Utara, Nusa Tenggara Barat, Nusa Tenggara Timur, Papua, Papua Barat, Sulawesi Tengah, Sulawesi Tenggara and Kepualuan Bangka Belitung.

Table C.1: The range of electricity tariffs that is needed for the economic potential of utility-scale solar PV to be equal to 31% of the estimated 2050 electricity demand per province

Province	**Current maximum PPA tariff [US$ct./KWh]**	**Needed tariff to meet 31% of 2050 electricity demand**		**Difference between current maximum tariff and lowest needed tariff [US$ct./KWh]**
		Low estimate [US$ct./KWh]	*High estimate [US$ct./KWh]*	
Jawa Tengah	6,6	8,8	10,1	2,2
Daerah Istimewa Yogyakarta	6,6	8,9	9,2	2,3
Jawa Barat	6,6	9,4	12,0	2,8
Bali	6,7	8,9	9,9	2,2
Banten	6,7	10,2	11,0	3,5
Jawa Timur	6,7	8,5	16,5	1,8
Sulawesi Barat	6,8	8,4	9,5	1,6
Sulawesi Selatan	6,8	8,5	9,3	1,7
Lampung	7,0	9,4	9,7	2,4
Jambi	7,2	9,9	10,1	2,7
Bengkulu	7,2	8,9	9,3	1,7
Sumatera Barat	7,2	9,1	10,2	1,9
Sumatera Selatan	7,2	9,3	9,6	2,1
Sumatera Utara	8,3	9,5	10,1	1,2
Kalimantan Timur	8,7	9,8	10,1	1,1
Kalimantan Utara	8,7	9,2	9,2	0.5
Kalimantan Barat	8,8	9,5	9,5	0,7
Riau	9,5	9,8	10,5	0,3
Aceh	9,6	9,0	9,4	-0,6
Kalimantan Tengah	9,7	9,5	9,8	-0,2
Kalimantan Selatan	9,7	9,6	10,1	-0,1
Sulawesi Utara	11,0	8,5	18,6	-2,5
Gorontalo	11,0	8,2	12,5	-2,8
Kepulauan Riau	12,1	10,1	10,3	-2,0
Sulawesi Tengah	12,4	8,4	9,4	-4,0
Kepulauan Bangka Belitung	12,9	9,7	9,7	-3,2
Nusa Tenggara Barat	13,7	7,8	8,8	-5,9
Sulawesi Tenggara	13,7	8,8	8,9	-4,9
Papua Barat	14,1	9,4	9,8	-4,7
Papua	15,1	8,4	8,8	-6,7
Maluku Utara	15,5	8,8	9,3	-6,7
Nusa Tenggara Timur	15,9	7,7	7,8	-8,3
Maluku	16,8	8,3	8,3	-8,5

D ELECTRICITY DEMAND IN 2018 AND 2050

This appendix presents an overview of the electricity demand in 2018 and the estimated electricity demand for 2050. The electricity demand for 2018 was retrieved from the statistical yearbook of BPS [2020b], which provided data on the distributed electricity per province in 2018. The electricity demand is assumed to be equal to this for each province. It should be noted that the demand in the area of Jakarta, which is treated separately by BPS, is added to the demand for the province of Banten.

The electricity demand for 2050 was estimated using an annual growth rate of 6,5%. This is based on the average over the period between 2015 and 2019 [Lolla and Yang, 2021]. To keep a growth rate into consideration makes sense given the economic and population growth and rising electrification ratio [Maulidia et al., 2019]. It should be noted that the actual annual growth rate is likely to not be equal for each province, given differences in economic and population growth in the provinces. The used estimation method is a simplified model of the reality.

Table D.1: Electricity demand in 2018 and the estimated electricity demand in 2050 using an annual growth rate of 6,5%

Province	Electricity demand in 2018 [TWh/year] [BPS, 2020b]	Estimated electricity demand in 2050 [TWh/year]
Aceh	2,6	19,4
Bali	5,3	39,4
Banten	23,7	424,0
Bengkulu	0,9	6,8
Daerah Istimewa Yogyakarta	2,86	21,5
Gorontalo	0,5	3,8
Jambi	1,2	9,2
Jawa Barat	52,9	396,7
Jawa Tengah	23,56	176,8
Jawa Timur	35,8	268,7
Kalimantan Barat	2,4	17,8
Kalimantan Selatan	2,6	19,5
Kalimantan Tengah	1,2	9,2
Kalimantan Timur	3,6	27,3
Kalimantan Utara	0,2	1,4
Kepulauan Bangka Belitung	1,0	8,0
Kepulauan Riau	3,0	22,4
Lampung	4,2	31,9
Maluku	0,6	4,5
Maluku Utara	0,4	3,0
Nusa Tenggara Barat	1,8	13,3
Nusa Tenggara Timur	0,9	7,0
Papua	0,9	6,9
Papua Barat	0,6	4,3
Riau	4,4	32,8
Sulawesi Barat	0,4	2,6
Sulawesi Selatan	5,5	41,1
Sulawesi Tengah	1,1	8,8
Sulawesi Tenggara	0,9	6,8
Sulawesi Utara	1,7	12,6
Sumatera Barat	3,5	26,2
Sumatera Selatan	5,5	41,3
Sumatera Utara	10,5	78,4

E LCOE RESULTS - PROVINCIAL AVERAGES

Table E.1 shows the average found LCOE values for utility-scale solar PV in Indonesia per province for scenario 1A, 2C and 3E. The table is sorted from highest to lowest value in scenario 3E.

Table E.1: Average estimated LCOE value per province in scenario 1A, 2C and 3E

Province	Average LCOE [US$ct./KWh]		
	Scenario 1A	*Scenario 2C*	*Scenario 3E*
Papua	13,8	13,8	14,2
Maluku	13,2	13,2	13,1
Kalimantan Utara	12,9	13,2	13,0
Kalimantan Timur	12,9	12,9	12,9
Papua Barat	12,6	12,6	12,8
Kalimantan Barat	12,5	12,5	12,5
Kalimantan Tengah	12,3	12,4	12,4
Maluku Utara	11,9	11,8	12,1
Riau	12,0	12,0	12,1
Jambi	11,8	11,9	12,0
Kalimantan Selatan	11,5	11,6	12,0
Sumatera Selatan	11,6	11,5	11,9
Sulawesi Tengah	11,7	11,7	11,7
Kepulauan Riau	11,7	11,7	11,7
Sumatera Barat	11,5	11,5	11,5
Kepulauan Bangka Belitung	11,4	11,4	11,4
Sulawesi Barat	10,9	11,0	11,2
Sumatera Utara	11,0	11,0	11,2
Sulawesi Tenggara	11,0	11,1	11,1
Aceh	10,9	11,0	11,1
Bengkulu	10,8	10,8	10,9
Lampung	10,8	10,7	10,9
Sulawesi Selatan	10,3	10,4	10,9
Banten	10,6	10,6	10,4
Jawa Barat	10,3	10,5	10,4
Jawa Timur	9,7	9,9	10,2
Sulawesi Utara	10,0	10,0	10,1
Gorontalo	9,9	9,8	10,0
Jawa Tengah	9,9	10,0	9,8
Bali	9,8	9,9	9,7
Daerah Istimewa Yogyakarta	9,4	9,4	9,6
Nusa Tenggara Barat	9,4	9,4	9,4
Nusa Tenggara Timur	9,3	9,4	9,3

F MOEF LAND COVER CATEGORIZATION

Table F.1 shows the land cover categorization in the data-set as published by the Indonesian Ministry of Environment and Forestry [2017]. The description of each category was retrieved from the Indonesian National Standard on land cover categorization as published by the BSN [2010].

Table F.1: Land cover categorization and description by the Ministry of Environment and Forestry [2017]

Nr.	Land cover class	Category in this research	Description
1	Primary dryland forest	Natural forests	Natural dryland forests that have not shown signs of logging or disruption.
2	Secondary dryland forest	Natural forests	Natural dryland forests that have shown signs of logging or disruption.
3	Primary swamp forest	Natural forests	Natural swamp forests that have not shown signs of logging or disruption.
4	Secondary swamp forest	Natural forests	Natural swamp forests that have shown signs of logging or disruption.
5	Primary mangrove forest	Natural forests	Natural mangrove forests that have not shown signs of logging or disruption.
6	Secondary mangrove forest	Natural forests	Natural mangrove forests that have shown signs of logging or disruption.
7	Plantation forest (man-made)	Plantation forests	Forests that have been grown in dry habitats by human intervention.
8	Bush/Shrub	Bush/Shrub	Dry land overgrown with various types of heterogeneous natural vegetation with rare to dense density levels and dominated by low vegetation.
9	Swamp shrub	Wetland	Swamp areas with fresh water puddles or permanent brackisch water on land with some grass vegetation.
10	Swamp	Wetland	Swamp areas with fresh water puddles or permanent brackish water on land.
11	Savannah	Savannah	Open areas dominated by various types of grass and trees that grow spread out and sparsely.
12	Dry agricultural land	Dry & Shrub-mixed dry agricultural land	Areas used for cultivation of single-type crops. Between planting period, this area is usually not covered with vegetation.
13	Shrub-mixed dry agricultural land	Dry & Shrub-mixed dry agricultural land	Areas used for cultivation of more than one type of crop. Between planting period, this area is usually not covered with vegetation.
14	Estate crop plantation	Agricultural land	Land that is used for farming activities without changing crops for at least two years.
15	Rice field	Agricultural land	Agricultural areas where food crops (mostly rice) are planted. Water is received through rainfall, tidal water of irrigation technology.
16	Transmigration area	Settlement area	Transmigration areas including government-sponsored, spontaneaous and local transmigration areas.
17	Fish pond	Agricultural land	Man-made fish ponds for aquaculture purposes.
18	Bare land	Bare land	Land without cover. Either natural, semi-natural or artificial.
19	Mining area	Mining area	Open land as a results of mining activities.
20	Settlement area	Settlement area	Residential environment or places for activities that support people's lives.
21	Airports/harbours	Airports/harbours	Airports that are used for domestic and/or internationalflights. Harbours that are used to dock ships for both passengers & cargo related activities.
22	Bodies of water	Bodies of water	Bodies of water and large rivers.

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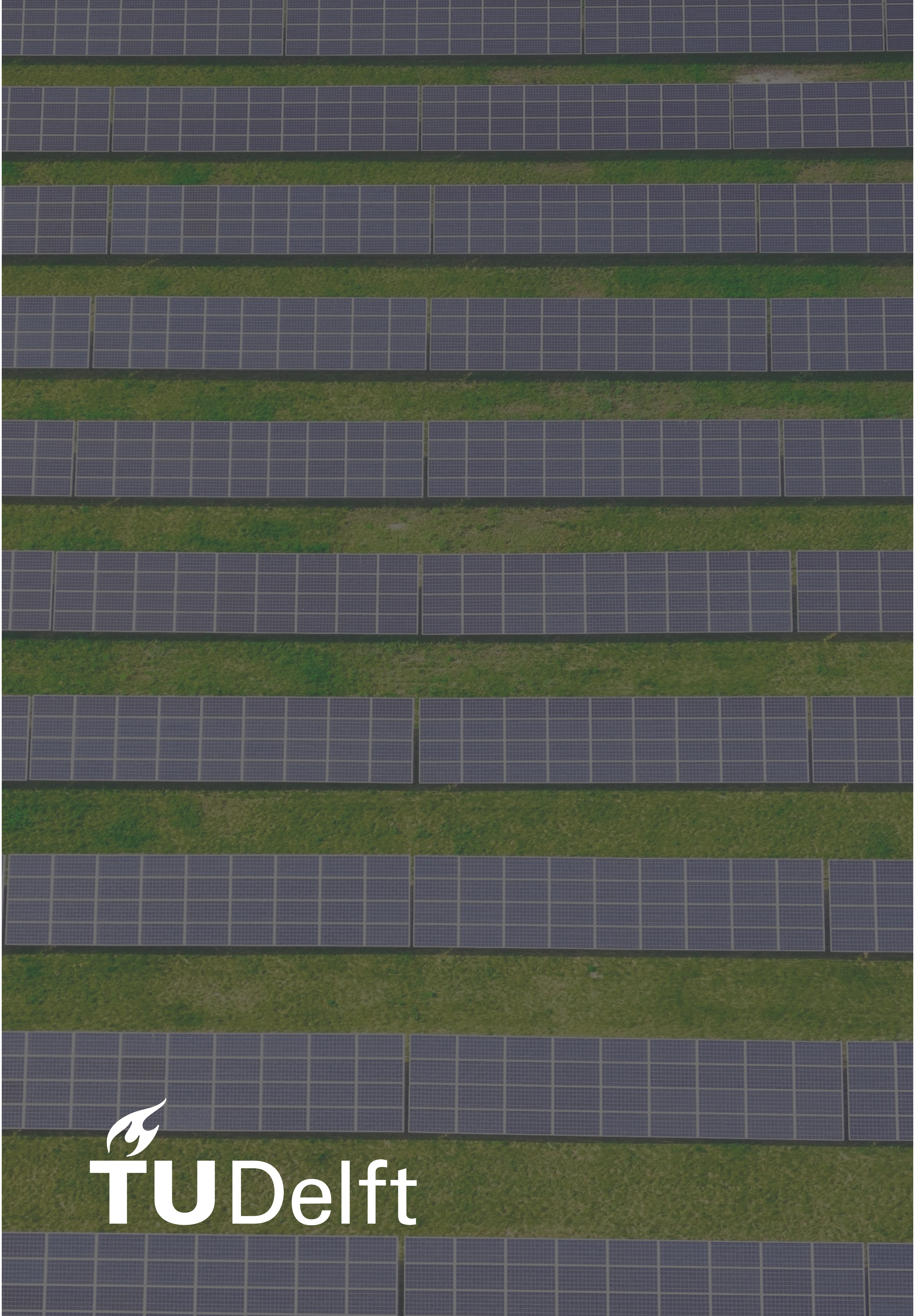
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