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A System Dynamics Model for Rooftop Solar PV System Development in Indonesia

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ABSTRACT: Despite of Indonesia's vast solar energy potential according to the Indonesian Ministry of Energy and Mineral Resources, Indonesia's total installed capacity of rooftop solar photovoltaic (PV) is very far from Indonesia's target of 3.6 GW in 2025. Indonesia once applied net metering scheme for rooftop solar PV policy and was expected to be able to boost rooftop solar PV growth. A system dynamics approach is used in the research to develop an assessment model to evaluate the policies' impact on residential rooftop solar PV system growth. A Causal Loop Diagram was established then transformed into Stock and Flow Diagram (SFD) using software Vensim PLE 10.1.3, which was used to simulate several policies' scenarios related to residential rooftop solar PV adoption and CO_2 emissions reduction. Ten scenarios were simulated in this study involving three groups of intervention: initial net metering tariff, reduction on initial solar PV cost, upper limit of ROI, and combination of initial net metering tariff and initial solar PV cost reduction. The simulations revealed that combination of increasing net metering tariff to 80% & initial cost reduction 30% has the highest potential solar PV installations, the highest CO2 emissions reduction, and the lowest accumulation cost of net metering in 2030. This study can be used as reference by the policy makers in Indonesia to formulate the optimum policy to boost rooftop solar PV growth as the simulations shows that residential rooftop solar PV with the right intervention can meet the government's target of rooftop solar PV in 2030.

KEYWORDS: Emission Reduction, Net Metering, System Dynamics, Solar PV.

I. INTRODUCTION

The Indonesia economic development combined with the population growth exceeding 275 million people [1] has strived to growing domestic energy demand. Indonesia annual population growth rate relatively steady at 1.25% between year of 2010-2020 but show a slight decline to 1.17% between year of 2020-2022 most possible cause by Covid-19 pandemic. In the energy supply perspective, population growth shapes the world's energy system and act as basic drivers of energy demand [2]. A study by (Dat et al., 2020) [3] revealed that using the history of energy consumption can predict Indonesia economic growth. Based on data from International Energy Agency (IEA), Indonesia energy mix in year of 2021 is predominantly fossil fuels (coal, oil, and natural gas). Coal is predominantly used in power plant for electricity generation while oil is predominantly used in transportation sector.

Electricity is taking into account 16% of share in Indonesia final energy consumption. As of 2021, Indonesia electricity consumption has increased 169% become 1.04 MWh/ Capita compare to year of 2000. Indonesia electrical consumption is dominated by Industrial sector (36.2%), Residential (41%) and commercial and public services (21.9%), meanwhile transportation sector is accounted for only 0.1%. Household electricity is mainly used for heating, cooling, lighting, cooking, and home appliances. There are several options to fulfill the electricity consumption, but mostly still fossil fuel based which make our dependency to the fossil fuel is still high. As energy demand for electricity generation has increased, coal has stepped in to fill the gap. Coal supplied 62% of Indonesia's on-grid power generation equal 181 TWh per year [4]. In share of Indonesia's total emission, power sector today contributes around 40% emission. Per unit of energy consumed, the country's energy sector now emits one-third more CO2 than it did in 2000. Total emissions from the energy sector have grown faster than energy demand, which has increased more than doubled in the past two decades. In 2021, emissions from the energy sector will be around 600 million tons of carbon dioxide (Mt CO_2), making Indonesia the ninth largest emitter in the world. However, per capita energy CO_2 emissions are only 2 tons, half the global average [5] although the trend in year of 20021 increased 71% compared to year of 2000.

The objective of this study is to identify all variables and parameters related to residential rooftop Photovoltaic (PV) system Indonesia to develop an assessment model to evaluate the policies' impact on promoting residential rooftop solar PV system. The variables and parameters specified will be modelled into a system dynamics model. The model will be a baseline for the proposed best scenario to address the business issue related to residential PV system development in Indonesia. The scope of this research is

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limited to rooftop solar PV system in residential area (households) in Indonesia, specifically PLN on-grid customers. History of residential PV system installation from year of 2018 to 2021 and future projection for the year of 2022 to 2030 will be the concerned time frame of the research. Specific policies related to renewable energy development particularly in solar PV system which is MEMR regulation no. 49/ 2018. Some limitations may occur due to data availability and quality, assumptions made in the modelling may result uncertainties in the findings, and last but not least that resource constraint like budget, time and data limitations may impact the depth and breadth of this research.

A. Paris Agreement

The Paris Agreement is an international agreement on climate change. It was adopted by 196 Parties at the United Nations Climate Change Conference (COP21) in Paris, France, on December 12, 2015. It is to maintain "global average temperature rise to well below 2°C above pre-industrial levels" and continue efforts to "limit temperature rise to 1.5°C above pre-industrial levels". To meet Paris agreement target, greenhouse gas emissions must peak by 2025 at the latest and fall by 43% by 2030 to limit global warming to 1.5°C. In COP21, all parties submitted their National Determined Contribution (NDC) to outline their target and actions to achieve global net zero emission by 2060. Each country submitted their plan to phase-out fossil fuel and shift to renewable energy. Indonesia announced its ambitious objective to reach net zero emissions by 2060 during the UN Climate Change conference (COP26) in Glasgow, 2021.

Indonesia has committed to reduce greenhouse gas emissions 29% by 2030, but then enhanced to 31.89% independently and up to 43.2% with international cooperation and support under the 2015 Paris Agreement. In addition, in 2014, the government has revived the National Energy Policy, aiming to not only achieve nearly 100% electrification by 2020 from the current 96% rate, but also achieve a renewable energy share in the energy mix, national volume at 23% by 2025 is made in RUPTL 2021-2030 [6]. The National General Energy Plan (Rencana Umum Energi Nasional [RUEN]) was established in 2017, prepared by the Ministry of Energy and Mineral Resources (MEMR) to achieve the objective of the *National Energy Policy* (Kebijakan Energi Nasional [KEN]). RUEN projected 6.5 GW of solar power generated electricity in 2025 and 45 GW in 2050 or 22% of the solar power potential of 207.9 GW [7]. Ministry of Energy and Mineral Resources (MEMR) encourages domestic households to adopt solar PV power system, where the target is 3.6 GW by 2025 [4]. Residential rooftop solar PV system is predicted to have a significant share in Indonesia renewable energy supply; however, the current installed capacity is still far from the target due to complexities of its development. Many stakeholders involved that have different interest, not to mention uncertainty of regulation & technology advancement. By Using system dynamics approach, several scenarios to be simulated to find the best option to develop residential rooftop solar PV system in Indonesia. This study will enrich the literature and knowledge related to residential rooftop solar PV system in Indonesia.

B. Indonesia Solar Energy Potential

Located in equatorial line, Indonesia is blessed with abundance of solar energy potential throughout the year. The country's geographical position along the equator guarantee consistent irradiance level thus solar level is uniformly distributed. With daily average solar irradiance of 4.8 kWh/m2/day [8], make it ideal for the development of solar photovoltaic (PV) system installation. (RUEN, 2017) [7] suggested Indonesia solar potential of 207.9 GW whilst (Veldhuis & Reinders, 2013) [9] suggested the total potential of grid-connected PV was around 1492 TWh. (Silalahi et al., 2021) [8] Identified that Indonesia's solar energy potential far exceeds the country's current and future energy demand and even larger than all other type of renewable energy sources combined altogether.

C. Solar Industry Profile

The rooftop photovoltaic system industry is a dynamic and rapidly growing sector in the renewable energy landscape. This involves installing solar panels on the roofs of residential, commercial, and industrial buildings to harness sunlight and convert it into electricity. According to Indonesia Solar Energy Outlook 2023 [10], China has been dominating 75% of 460 GW/year of global solar module manufacturing in recent years and more than 80% of each key manufacturing phases. This condition poses a supply chain disruption risk potential in the future. Any trade restriction to china makes the supply chain is vulnerable.

In local context, Indonesia's solar PV supply chain is only doing module assembly using imported cells, with total annual production capacity only 1.644 MWp from 21 manufacturers registered in the Association of Indonesia Solar Panel Manufacturer (APAMSI). 50% of the total production capacity is contributed by three manufacturers located in Batam Island with export orientation. Technical and economic obstacles make investments on the higher value chain is not currently feasible.

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II. LITERATURE REVIEW

Solar PV system development in Indonesia has the potential to play a significant role in the country's energy transition and reduction of carbon emissions. Indonesia, as an equatorial country, benefits from high solar energy availability throughout the year, with low seasonal variation in both energy demand and solar energy availability [8]. This eliminates the need for large-scale seasonal storage of energy, making solar PV systems a viable option for meeting the country's energy requirements. The vast solar energy potential in Indonesia has been recognized by major countries such as China, Japan, South Korea, the USA, and the European Union, which have expressed their intention to decarbonize their energy systems through renewable electrification [8]. It is estimated that Indonesia could meet a realistic upper bound on its entire energy requirements in 2050 from domestic solar energy, considering the projected increase in electricity consumption [8]. The study also highlights the availability of space for solar PV deployment, including rooftops, inland reservoirs, and mining wasteland [8]. However, despite the potential, the renewable energy sector in Indonesia, including solar PV, is still in the early stages of development. Indonesia aims to increase the share of renewable energy in its national energy mix to 23% by 2025.

System Dynamics (SD) has been widely used in research in the PV industry, but with different focuses [11]. (Salim et al., 2021) [12] presents the development of a System Dynamics (SD) model for management end-of-life (EoL) rooftop PV modules based on the circular economy concepts. Four socio-technical transition pathways examined in the study include *market-driven growth*, *conservative development*, *shared responsibility*, and *disruptive change*. However, this paper does not study related development of solar PV power but more of how to manage rooftop PV panel upon its EoL. (Sani et al., 2018) [13] introduce System Dynamics (SD) in solving the problematic Indonesia energy management. This paper shows that government policies regulating fossil energy investment, PLN tariff barriers, and various incentives that favor oil import cartels have led to robust fossil energy development and other ways in which new and renewable energy (NRE). However, this paper does not specifically study the solar PV power system as part of NRE power system.

A. *Existing Studies*

(Hsu, 2012) [14] uses system dynamics approach to develop simulation for assessing policies on feed-in tariffs (FITs) and capital subsidies to attract public society and private companies in Taiwan to invest in adoption of solar photovoltaic (PV) systems. The study revealed that when only adopting policy on FITs or capital subsidies with fixed upper limit of return on investment (ROI), the rise of FIT prices or subsidy was a good approach. In overall, the study concluded that the policy with higher subsidy and lower FIT price has a lower cost average cost of CO2 emission reduction. However, this study does not exercise other possible policy such as net metering scheme.

(Al-Refaie & Lepkova, 2022) [15] developed system dynamics models to evaluate the effects of policies on social acceptability to adopt solar PV systems, energy security, and CO2 emission reduction in the small-scale sector in Jordan. This study assessed feed-in-tariffs (FiTs), subsidy policies and annual net-metering tariff policy on the increment of solar PV adoption. The developed models are found a useful tool to measure the impacts of energy policies. However, a quantitative assessment is still needed to measure the extent to which these policies can meet the clean energy goals and support the policy’s decision making. Jordan is expected to achieve a high level of clean energy security by 2050 to contribute to mitigating global warming.

(Hidayatno et al., 2020) [16] investigating policies on improving household rooftop photovoltaics adoption in Indonesia. Government could not provide a significant amount of investment to stimulate solar PV adoption in Indonesia, therefore, one solution is through household rooftop PV where the investment is by the homeowner. This study was aimed to assess the effectiveness of net metering and net billing policies by analyzing and understanding the dynamic complexity of the residential rooftop solar PV adoption in Indonesia. The study emphasizes the importance of taking a system perspective to understand the dynamic complexity of solar energy development. Unfortunately, no options of effective policies on improving the residential solar PV adoption were simulated.

B. *Indonesian Regulation for Rooftop Solar PV*

The Indonesian government has issued series of regulations to encourage development of rooftop photovoltaic (PV) system, from presidential regulation to ministry regulations. Following is the list of applied regulation in Indonesia:

Ministry of Energy and Mineral Resources (MEMR) Regulation no. 17/ 2013: this regulation focuses on regulations related to electricity procurement auction and pricing in Indonesia. MEMR set the feed-in tariff (FiT) of US$ 0.25/kW (using solar modules with less than 40% of local content) and US$ 0.30/kWh (using solar modules more than 40% of local content).

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Ministry of Energy and Mineral Resources (MEMR) Regulation no. 19/ 2016: this regulation replaced MEMR no. 17/ 2013 and focuses on regulations related to renewable energy development. FiT decreased between US$ 0.145/ kWh – 0.25/ kWh depend on the region. Total solar industry quota under this regulation is 250 MWp.

Ministry of Energy and Mineral Resources (MEMR) Regulation no. 12/ 2017: this regulation focuses on regulations related to electricity procurement and pricing in Indonesia. FiT range decreased further between US$ 0.48/ kWh – US$ 0.144/ kWh. Under this regulation, electricity tariff should be lower than national electricity production cost (National BPP) or no more than 85% of local electricity production cost (regional BPP).

Ministry of Industry (MOI) Regulation no. 5/ 2017: this regulation focuses on industrial development and operations. This regulation specifically regulates the minimum 40% local content requirement for solar industry, continued increase to 50 in January 2018 and 60% in January 2019. This condition has put barriers for solar PV development in Indonesia.

Ministry of Energy and Mineral Resources (MEMR) Regulation no. 49/ 2018: this regulation focuses on regulations related to the utilization of rooftop solar power generation by PLN consumers. Under this regulation, rooftop solar PV installation require verification and approval from PLN and net metering scheme is applied. Rooftop solar PV installation is limited to maximum of 100% of the PLN customer's installed electricity capacity. Excess electricity production from rooftop solar PV system is then exported into the grid and valued at 65% of PLN tariff as compensation. Electricity bill will be calculated monthly based on kWh import minus kWh export to the grid through net metering scheme.

Ministry of Energy and Mineral Resources (MEMR) Regulation no. 26/ 2021: this regulation is revision of MEMR regulation no. 49/ 2018 and focuses on regulations related to the utilization of rooftop solar power generation connected to licensees of power generator for public use. Electricity exported into the grid is valued at 100% compensation under this regulation.

III. RESEARCH METHODOLOGY

System thinking is known as principles of organization or theory of self-organization and the way of using it involves systematic or holistic thinking [17]. This research uses a system thinking approach since it deals with complex situations in development of residential rooftop solar PV in Indonesia. The study begins with literature review and data gathering to identify stakeholders and variables affecting residential solar PV growth and CO2 reduction impact. The system dynamics model is constructed by defining the model's boundary, identifying variables and parameters, designing causal loop diagram (CLD) and construct stock-flow diagram. Subsequently running the model for several scenarios and the final step is to analyze the result. Final step is to make recommendations dan propose solutions to the issues under the study.

The closed-system boundary is frequently used in system dynamic modelling to simplify the analysis and focus on the interactions within the system being studied. Closed-system boundary modelling assumes the system is isolated from external influences to provide a starting point for understanding the internal dynamics of the system. Several key variables have been identified which have essential role in residential rooftop solar PV system development and emission reduction in Indonesia: 1. Residential Rooftop Solar PV System Adoption, 2. CO2 Emission Reduction, 3. Public Awareness and Attitudes, 4. Government Policies (Net Metering Scheme), 5. Electricity Demand, 6. Cost of Solar PV Systems, 7. Technology Advancements, 8. Grid Electricity Prices, 9. Revenue from Excess Electricity Generation, 10. Installation Cost, 11. Operation & Maintenance Cost, 12. Total Cost of Solar PV Systems, 13. Return on Investment (ROI), 14. CO2 Emission Reduction Cost, 15. Population, 16. GDP (Economic Growth).

A. Causal Loop Diagram (CLD)

The causal loop diagram developed in this study is adapted from existing study by (Hsu, 2012) [14] with some modifications based on literature study and interview with some stakeholders.

Reinforcing Loop 1: Reinforcing loop 1 is highlighting CO2 emission reduction and adoption acceleration. Residential rooftop solar PV adoption increment reduces dependency on fossil fuels, resulting higher CO2 emissions reduction. Declining in CO2 emissions shows that rooftop solar PV adoption's effectiveness in mitigating climate change, bolstering broader public awareness and positive attitudes on solar power potential. High public demand for sustainable energy sources resulting government policies like the net metering scheme. Supportive government policies acting as incentive to rooftop solar PV adoption, causing increment

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in revenue from excess electricity generation. Higher revenue enhances solar PV return on investment (ROI) for homeowners, making rooftop solar PV adoption is more attractive. As CO2 emissions decrease, it bolsters the public perception that rooftop solar PV adoption is an effective way of climate change mitigation.

Reinforcing Loop 2: Reinforcing loop 2 is highlighting economic growth, technology advancements, and emission reduction. Economic growth subsequently increasing electricity demand. Increased electricity demand encourages solar PV system adoption. Higher solar PV adoption means more electricity is generated from rooftop solar PV. Increased rooftop solar PV adoption by households consequently more CO2 emissions reduction. As more CO2 emissions are reduced encourages investments in technological advancements on solar PV systems. Technological advancements reduce the cost of solar PV system installation and increase efficiency, making rooftop solar PV systems more attractive to homeowners that lead to adoption rate increment. Higher rooftop solar PV adoption rate subsequently increase CO2 emissions reduction. Declined CO2 emissions contribute to sustainable environment and economic growth.

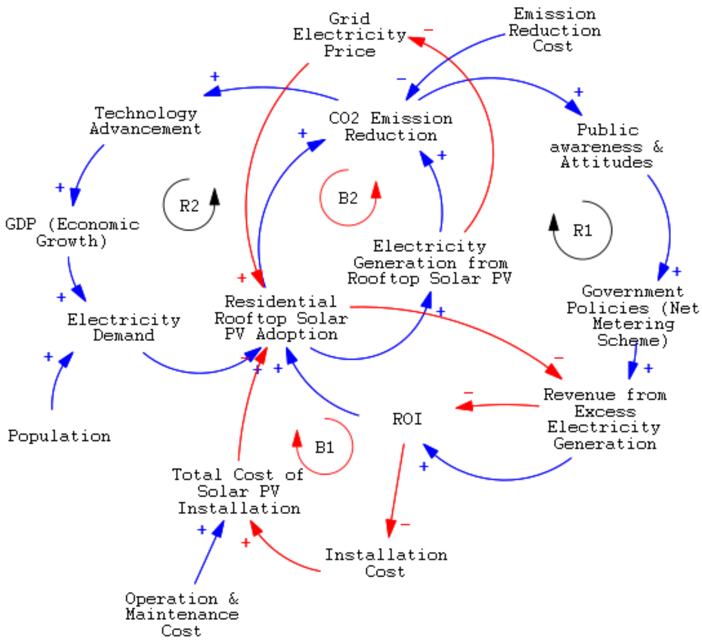

Figure 1. Causal Loop Diagram for Solar PV Development

Balancing Loop 1: Balancing loop 1 is highlighting Installation cost and Adoption Stabilization. In general, high installation costs have been an obstacle to rooftop solar PV adoption. Increment in the total installation costs has reduced the attractiveness of rooftop solar PV systems, leading to a decrease in adoption rates for households use. Lower adoption rates mean less revenue from excess electricity generation, consequently lower return on investment (ROI) for homeowners which reduces the rooftop solar PV adoption attractiveness. This condition is stabilizing the adoption rate and balancing the system.

Balancing Loop 2: Balancing loop 2 is highlighting Grid Electricity Price and Solar PV Adoption. Increase in grid electricity prices causing rooftop solar PV system adoption is becoming more financially attractive. As increased rooftop solar PV system adoption reduces demand for grid electricity, finally have potential in lowering grid electricity prices. Decreased grid electricity prices reduce the revenue from excess electricity generation and subsequently lowering the attractiveness of rooftop solar PV adoption, leading to a stabilized adoption rates and balancing the system.

B. Stock and Flow Diagram (SFD)

In modelling residential rooftop solar panel development and CO2 reduction in Indonesia, there are five stocks of the identified variables in the CLD as follows: 1. Residential Rooftop Solar PV System Installed, 2. CO_2 Emission Reduction, 3. Solar PV System Cost Reduction, 4. Net Metering Tariff, 5. Net Metering Cost. This study use “Vensim PLE 10.1.3” software to develop the model.

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CLD and SFD above to build a model for system dynamic is run using Vensim software. The equation for each variable is developed to ensure that the built model can simulate our intended scenarios. Initial values to be given for all the stock and all the flows will have a flow rate as basis for calculation. All parameters in SFD are defined as numerical values and parameter's relationships are calculated with function as shown in Table 1.

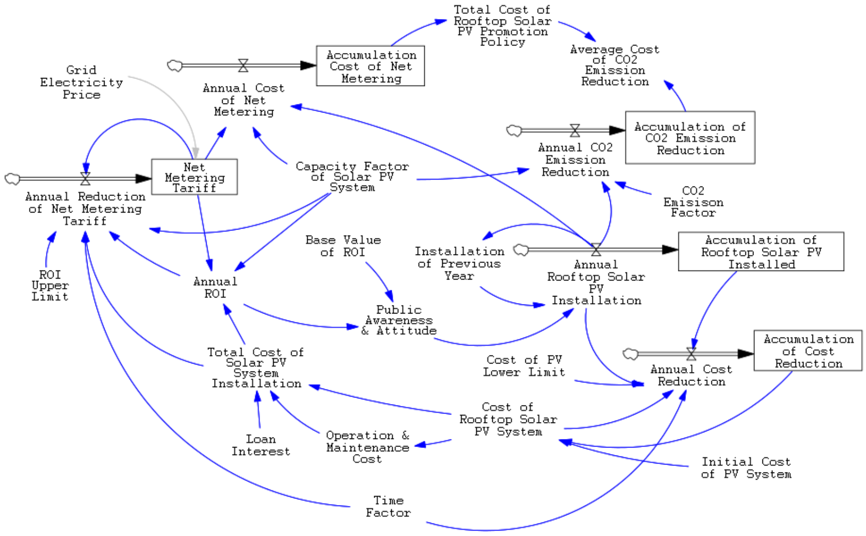

Figure 2. Stock and Flow Diagram for solar PV Installation and CO_2 Emission Reduction

Table 1. Parameter's Unit and Formulas of System Dynamics Modelling

No.	Parameter	Unit	Function
1	Net Metering Tariff (NMT)	Rp/kWh	(0.65*Grid Electricity Price) – INTEG (annual reduction of Net Metering Tariff)
2	Annual Reduction of Net Metering Tariff	Rp/kWh/Year	0 [if annual ROI < ROI upper limit] Net Metering Tariff – (base value of ROI * Total Cost of PV Installation)/ (365 * capacity factor of PV System) [if annual ROI > ROI upper limit] [b]
3	Accumulation of Solar PV Installed	kW	Initial accumulation of rooftop solar PV system + INTEG (Annual Rooftop Solar PV Installation) [c]
4	Annual Rooftop Solar PV Installation	kW/Year	Public Awareness * Installation of Previous Year
5	Installation of Previous Year	kW/Year	DELAY Fixed (Annual Rooftop Solar PV Installation, 1, initial solar PV system)
6	Public Awareness	-	Annual ROI/ Base Value of ROI
7	Annual ROI	-	(Capacity Factor of Solar PV * Net Metering Credit) * 365 (day)/ Total Cost of Solar PV Installations [d]
8	Total Cost of Solar PV Installation	Rp/kW	Cost of Rooftop Solar PV + Loan Interest + Maintenance Cost[e]
9	Maintenance Cost	Rp/kW	Cost of Solar PV System * 0.05[f]
10	Cost of Rooftop Solar PV	Rp/kW	Initial Cost of Rooftop Solar PV – Accumulation of Cost Reduction
11	Accumulation of Cost Reduction	Rp/kWh	INTEG (Annual Cost Reduction)
12	Annual Cost Reduction	Rp/kWh/Year	IF THEN ELSE (Cost of Rooftop Solar PV > Cost of

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No.	Parameter	Unit	Function
			PV Lower Limit, Cost of Rooftop Solar PV * ((Accumulation of Solar PV Installed + Annual Rooftop Solar PV Installation/ 1000/ Accumulation of Solar PV Installed) ^ (-3.32193), 0)
13	Accumulation of CO_2 Emission Reduction	$KgCO_2$/Year	INTEG (Annual CO_2 Emission Reduction)
14	Annual CO_2 Emission Reduction	$KgCO_2$/Year	Annual Rooftop Solar PV Installation * Capacity Factor of Solar PV * CO_2 Emission Factor * 365 (day) * 20 (Year)[g]
15	Total Cost of Rooftop Solar PV Promotion Policy	Rp	Accumulation Cost of Net Metering
16	Accumulation Cost of Net Metering	Rp	INTEG (Annual Cost of Net Metering)
17	Annual Cost of Net Metering	Rp/Year	Annual Rooftop Solar PV Installation * Capacity Factor of Solar PV * Net Metering Credit *365 (day) x 20 (Year)[h]
18	Average Cost of CO_2 Emission Reduction	Rp/$KgCO_2$	Total Cost of Rooftop Solar PV Promotion Policy/ Accumulation CO_2 Emission Reduction
19	Grid Electricity Price	Rp/kWh	Electricity price table

[a] NMT is the NMT in the first year of the simulation (USD/kWh). INTEG is an operation in Vensim software used to integrate the parameters inside the parentheses of each time step.
[b] When annual ROI is above the upper limit of ROI, NMT will be adjusted automatically so that annual ROI is approximately equal to the base value of ROI.
[c] the initial accumulation of Solar PV installed represents the sum of PV systems already installed in Indonesia prior to the simulation.
[d] the capacity factor of solar PV systems represents the daily average time for a solar PV system with 1kW of capacity to reach full loading in 1 year.
[e] Loan interest is calculated based on the sum of loan, annual interest rate (10%), and loan period (10 years).
[f] This study assumes each solar PV system has operational lifetime of 20 years and the maintenance cost is 5% of the cost of Rooftop Solar PV system.
[g] CO_2 emission factor is the average weight of CO_2 produced per kWh of electricity generated in Indonesia ($KgCO_2$/kWh). Indonesia CO2 emission factor in 2018 is 0,703 $KgCO_2$/kWh [18].
[h] the annual cost of NMC is the total cost for NMC for solar PV system from the period of installation to the next 20 years.

C. Data Collection Method

Data Source: The data used in this research are primary data and secondary data which are collected from several sources. Primary data are collected from interview with selected stakeholders and secondary data are collected from government reports related to renewable energy policy, energy consumption data form Handbook of Energy & Economic Statistics of Indonesia 2022, solar potential data, world and Indonesia GDP growth report, and some reports related to Indonesia energy transition outlook. All data then will be sorted out based on its relevance to be used to build the system dynamics model.

Data Collection Procedure: Some data required for this research are collected through published government report, published report from related International Organization, some stake holders' interview when necessary. Data from government reports are

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collected from official government websites. Data from International Organization (IRENA, IEA, IESR, etc.) are collected from the published report on their official website. Semi-structured Interview is required with using a list of guides to find out further in-depth information about the research topic from the stake holders' point of view.

D. Model Validation

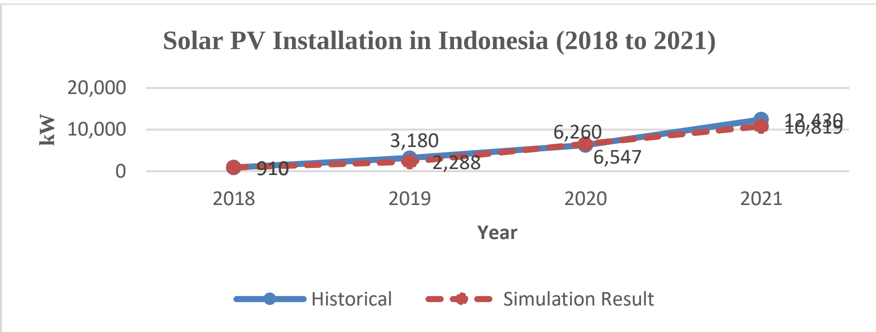
Historical data on residential rooftop solar PV installations between 2018 and 2021 in Indonesia [19] were used to validate the result of the system dynamics model developed in this study. In this study, initial parameter values shown in Table 2 were adopted to simulate the system. Net Metering Tariff adopted is 65% of the grid electricity price as per MEMR Regulation no. 49/ 2018. The exact base value of the ROI is unknown, in this simulation, ROI base value 2.95% from (Hsu, 2012) [14] is adopted.

Table 2. Initial Value for Parameters (2018 to 2021)

Parameter	Value
Initial number of solar PV systems	910 kW (0,91 MW)[a]
Loan interest	10%[b]
Initial cost of solar PV systems	USD 1200/kW[c]
Capacity of solar PV systems	4,5 kWh/day/kWp[d]
Net Metering Tariff	Rp953,73/kWh (65% of Rp 1.467,28/kWh)[e]

[a] According to (EBTKE-MEMR, 2024) [19] installation accumulated in 2018.
[b] According to report of (World Bank, 2022) [20], Lending interest rate Indonesia floated between 10,53% and 8,92% between 2018 and 2021. We adopted mean value of 9,84% for this study but for simplification is rounded up to 10%.
[c] According to (Pujantoro, 2019) [21] capital cost for solar PV system in Indonesia ranges from 700 to 1200 USD/ kWh. Average Bank Indonesia Foreign Exchange rate [22] in 2018, USD 1 = Rp14,250.
[d] According to [8]
[e] According to [23] most residential PLN customers use power 2200 VA (Watt) and the most possible household solar PV users are with PLN installed capacity ≥2200VA according to [24]. Refer to [25] PLN tariff for electric capacity ≥2200VA is Rp 1467.28/kWh. Net Metering Tariff as per MEMR Regulation no.49/ 2018 is 65% of electricity price.

Accumulation of rooftop solar PV installation is modelled as a function of public awareness and installation of the previous year. Based on comparison between the model simulation and historical data of residential rooftop solar PV installation between 2018 to 2021 (Figure 3), the model showed the similar increasing trend with the actual historical data, means that the developed model is valid.



	2018	2019	2020	2021
Historical	910	3.180	6.260	12.430
Simulation Results	910	2.288	6.547	10.819

Figure 3: Simulation results of Solar PV installations in Indonesia from 2018 to 2021

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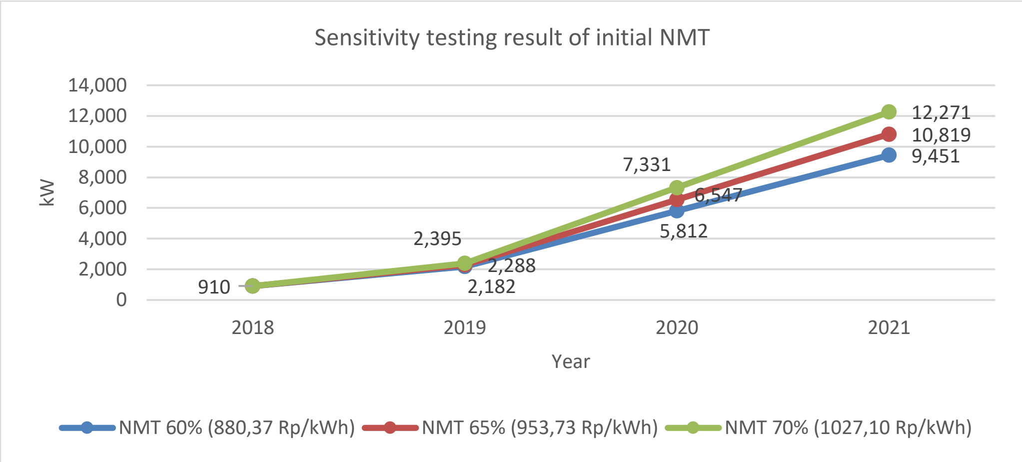
E. Sensitivity Analysis

Sensitivity analysis was conducted with using three different values of Net Metering Tariff (60%, 65%, and 70%) or equal (880,37 Rp/kWh, 953,73 Rp/kWh, and 1.027,10 Rp/kWh). Based on simulation with the initial NMT 880,37 Rp/kWh, the predicted number of solar PV system installations is 9.450,9 kW in 2021. When the initial NMT increases to 953,73 Rp/kWh, the predicted number of solar PV system installations in 2021 changes to 10.818,7 kW. For every 5% increment in the initial NMT, the number of solar PV systems in 2021 increases by 1.368 kW. When the initial NMT increases to 1.027,10 Rp/kWh, the predicted number of solar PV system installations in 2021 changes to 12.271,4 kW. For every 5% increment in the initial NMT, the number of solar PV systems in 2021 increases by 1.453 kW (Figure 4). We can conclude that the model is sensitive to NMT value changes.



	2018	2019	2020	2021
NMT 60% (880,37 Rp/kWh)	910	2.182	5.812	9.451
NMT 65% (953,73 Rp/kWh)	910	2.288	6.547	10.819
NMT 70% (1027,10 Rp/kWh)	910	2.395	7.331	12.271

Figure 4: Sensitivity test result of initial Net Metering Tariff

IV. RESULT AND DISCUSSION

Having successfully established, verified, and validated the system dynamics model, the developed model is then used to simulate residential rooftop solar PV development from year 2022 to 2030. Once the simulation results of accumulation of residential rooftop solar PV adoption in 2030, accumulation of CO_2 emission reduction, and the average cost of CO_2 emission reduction in 2030 are obtained. Next step is to set some scenarios of intervention on some variables in the model to see the impact on residential solar PV adoption, CO_2 emission reduction, accumulation cost of net metering, and the average cost of CO2 emission reduction.

By end of 2021, total number of rooftop solar PV installations in Indonesia reached 48,41 MW and for household or residential alone is about 12,43 MW (12.430 kW). In the following simulation from 2022 to 2030, initial solar PV adoption was set as 12,43 MW (12.430 kW). Electricity price for period of January to June 2022 is 1.444,70 Rp/kWh for all capacity (≥1.300 VA) and for period of July to December 2022 is 1.444,70 Rp/kWh for capacity ≤ 2.200 VA and 1.699,53 Rp/kWh for capacity ≥ 3.500 VA. The average price is 1.572,12 Rp/kWh, which will be used in the simulation.

Table 3. Initial Values for Parameters (2022 to 2030)

Parameter	Value
Accumulation Cost of Net Metering (2021)	Rp 220.066.000.000,-
Accumulation of CO2 Emission Reduction (2021)	228.827.000 $KgCO_2$ (0,23 million-ton CO_2)
Initial number of solar PV systems	16.810 kW (16,81 MW)
Loan interest	10%

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Parameter	Value
Initial cost of solar PV systems	1.200 USD/kW (17.100.000 Rp/kW)
Capacity of solar PV systems	4.5 kWh/day/kWp
Electricity Price	1.572,12 Rp/kWh
Net Metering Tariff (BAU)	1.021,88 Rp/kWh (65% of electricity price)

There are ten (10) scenario simulations in this study. The simulations were conducted using software Vensim PLE 10.1.3. Simulation results over time from 2022 to 2030 for accumulation of solar PV installations, accumulation of CO_2 emission reduction, average cost of CO_2 emission reduction, and accumulation cost of net-metering to be observed and analyzed.

Table 4. Scenario Summary

No.	Initial Net Metering Tarif (NMT)	Initial Solar PV Cost Reduction	Return on Investment (ROI)	Combination
1	A1 (NMT 80%)			
2	A2 (NMT 90%)			
3	A3 (NMT 100%)			
4		B1 (10% reduction)		
5		B2 (20% reduction)		
6		B3 (30% reduction)		
7			C1 (10%)	
8				D1 (A1+B3)
9				D2 (A2+B2)
10				D3 (A3+B1)

The simulation results of all ten scenarios show the effect of initial net-metering tariff (NMT), initial cost of solar PV system, upper limit of ROI, and combinations of NMT and initial cost of solar PV system are different. Summary of simulation results in 2030 are shown in Table IV.

Table 5. Comparison of the simulation results for all scenarios in 2030

Scenario	Accumulation of Solar PV System (MW)	Accumulation of CO_2 Emission Reduction (Mt)	Total Cost of Policy (billion Rp)	Average Cost of CO_2 Emission Reduction (Rp/KgCO_2)
A1	3.288,64	75,89	10.448	138,20
A2	3.888,09	89,73	12.312,30	137,21
A3	4169,96	96,24	13.720,80	142,57
B1	2.992,13	69,04	8.441,74	122,27
B2	3.359,79	77,53	8.606,65	111,01
B3	3.830,97	88,41	8.820,23	99,76
C1	7.719,07	178,20	45.260,40	253,98
D1	4.638,68	107,07	11.203,90	104,65
D2	4.393,91	101,41	12.313,90	121,42
D3	4.614,95	106,52	13.993,80	131,38

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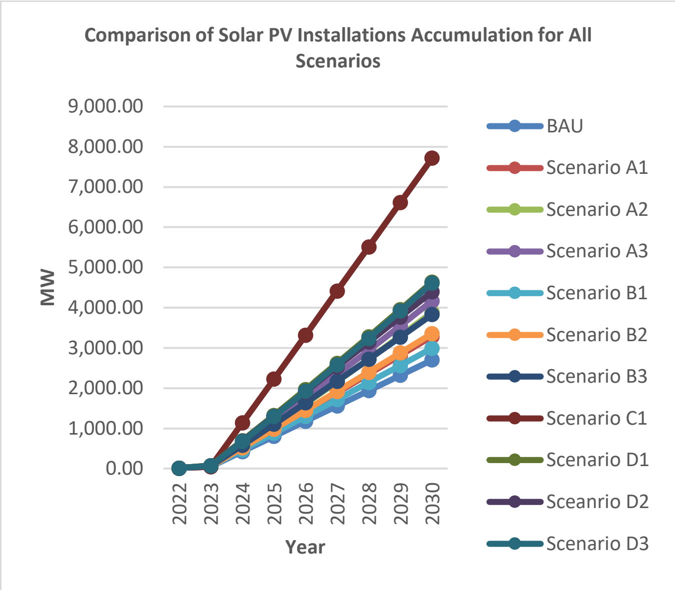

Figure 5: Solar PV Installation accumulation.

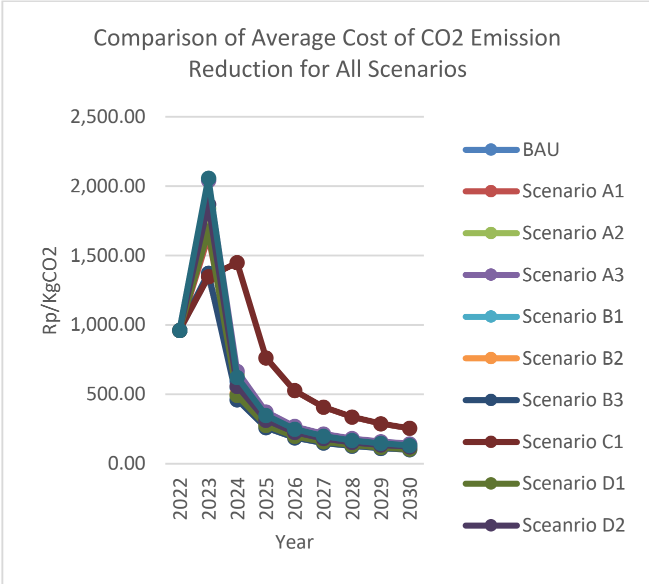

Figure 6: Average Cost of CO2 Emission Reduction

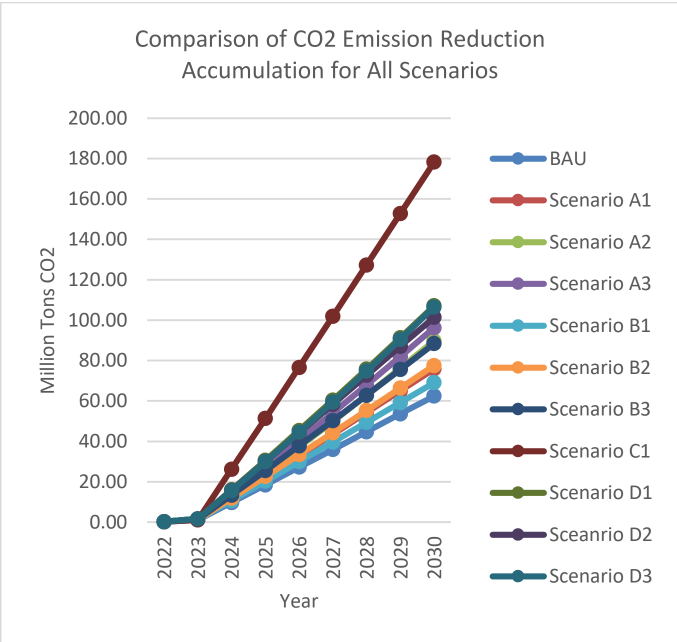

Figure 7: CO2 Emission Reduction Accumulation

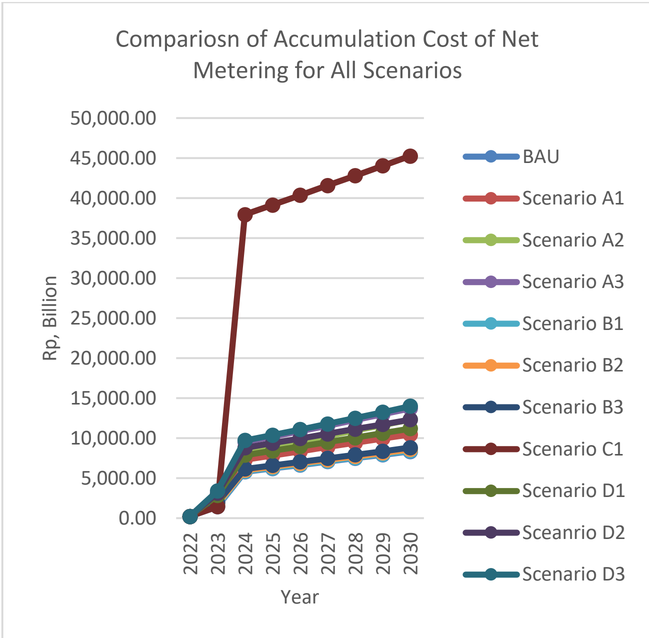

Figure 8: Average Cost of CO2 Emission Reduction

The highest number of accumulations of solar PV installations and accumulation of CO_2 emission reduction in 2030 is Scenario C1 with value 7.719,07 MW (7,72 GW) and 178,2 million tons, followed by scenario D1 with value 4.638,68 MW (4,64 GW) and 107,07 million tons. There is a huge gap between the highest and the second highest value as seen on Figure 5 and Figure 6, accumulation of solar PV installation gap is 3.080,39 MW and CO2 emission reduction gap is 71,14 million tons. However, between the second highest and other scenarios' difference range is between 23,73 MW to 471,18 MW for solar PV installations and 0,55 to 10,88 million tons for CO2 emission reduction. The lowest average cost of CO_2 emission reduction is scenario B3 with value 99,76 Rp/KgCO_2, followed by scenario D1 as the second lowest with value 104,65 Rp/KgCO_2. In term of accumulation cost of net-metering, scenario C1 is the highest cost with Rp 45.260,60 billion (Rp 45,26 trillion) and followed by scenario D3 in the second place with Rp 13.993,8 billion (Rp 13,99 trillion).

When the upper limit of ROI constant in scenario A1 to A3 and B1 to B3, higher initial net-metering tariff (NMT) means more solar PV system installations. Higher NMT means more income/ benefit to the solar PV system owners which improve the ROI that eventually increase public awareness and willingness to adopt solar PV system for households. However, higher number of solar PV adoption is also mean higher government spending and increases in spending consequently will also increases the average cost of CO_2 emission reduction.

Increasing the upper limit of ROI from 7,5% to 10%, significantly affect the accumulation of solar PV installations and accumulation of CO_2 emission reduction. However, the increment is showing an extreme value compared to another scenario in the second highest value. A careful analysis may be required to uncover the reason of such extreme result. Other than the upper limit of ROI (scenario C1), intervention combinations between increasing NMT and lowering initial cost of solar PV system in scenario D1 is showing the highest accumulation of solar PV systems and accumulation of CO2 emission reduction. Meanwhile for accumulation cost of net-metering (total policy cost), other than increasing the ROI, intervention combination between NMT 100% and lower reduction of initial cost of solar PV system (10%) has the highest cost due to higher NMT means higher government spending on compensation. A very careful analysis should be done by the policy makers for selection policy combinations to achieve residential rooftop solar PV installations target as well as reducing CO2 emission, but also to maintain government spending minimum.

V. CONCLUSION AND RECOMMENDATION

A. Conclusion

Despite of accumulation of rooftop solar PV system installations at the end of 2021 was only 12,43 MW, simulation results of all scenarios show that predicted installation in 2030 are ranged from 2.740 to 7.719 MW (2,74 – 7,72 GW). These numbers mean that from residential rooftop solar PV alone has a potential to fulfill solar PV target in RUPTL 2021-2030, which is 4,68 GW. This study used system dynamics to develop a simulation model for assessing residential rooftop solar PV system adoption in Indonesia. Net-Metering Tariff and initial cost of solar PV system highly affected public's willingness to adopt solar PV system for household since higher NMT and lower initial cost will increase customer's ROI. Higher NMT and lower initial cost of solar PV system affects the number of solar PV system installations. Higher solar PV system installations is directly proportional with CO_2 emission reduction. However, more installations mean more government's spending on compensation for excess electricity exported into PLN grid. The growth of solar PV system installations prediction in 2030 also means that there is a high potential in solar PV system business opportunity.

B. Recommendation

This study show that a careful policy combination can be used by the policy makers to improve residential solar PV system installations. A balance between government spending and improving number of solar PV adoption can be further assessed by simulating more scenarios. As simulations in this study show that Net-Metering Tariff and Initial cost of solar PV systems highly affected solar PV adoption, some measures like tax reduction can be implemented by the government to support reduction on solar PV system initial cost. This study only considers Net-Metering Tariff and other parameters' value are remained unchanged during simulation for simplification (ceteris paribus). Further study should be performed to include variance of policies like applying feed-in tariff (FIT) or initial cost subsidy or combination and comparing with other countries' policy.

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