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CAMA Working Paper 2/2019
January 2019

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This study estimates the impacts of four solar energy policy interventions on the photovoltaic (PV) market potential, government expenditure, economic growth, and the environment. An agent-based model is developed to capture the specific economic and institutional features of developing economies, citing Indonesia as a specific case study. We undertake a novel approach to energy modelling by combining energy system analysis, input-output analysis, life-cycle analysis, and socio-economic analysis to obtain a comprehensive and integrated impact assessment. Our results, after sensitivity analysis, call for abolishing the existing PV grant policy in the Indonesian rural electrification programs. The government, instead, should encourage the PV industry to improve production efficiency and to provide after-sales service. A 100-watt peak (Wp) PV under this policy is affordable for 33.2 percent of rural households without electricity access in 2010. Rural PV market size potentially increases to 82.4 percent with rural financing institutions lending 70 percent of capital cost for five years at 12 percent annual interest rate. Additional 30 percent capital subsidy and 5 percent interest subsidy slightly increase the rural PV market potential to 89.6 percent of PV adopters. However, the subsidies are crucial for creating PV demands by urban households but the most effective policy for promoting PV to urban households is the net metering scheme. Several policy proposals are discussed in response to these findings.

Keywords

hybrid energy model, developing country, renewables policy, impact assessments, agent-based modelling, photovoltaic system

JEL Classification

C60, Q21, Q43, Q48

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ISSN 2206-0332

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This study estimates the impacts of four solar energy policy interventions on the photovoltaic (PV) market potential, government expenditure, economic growth, and the environment. An agent-based model is developed to capture the specific economic and institutional features of developing economies, citing Indonesia as a specific case study. We undertake a novel approach to energy modelling by combining energy system analysis, input-output analysis, life-cycle analysis, and socio-economic analysis to obtain a comprehensive and integrated impact assessment. Our results, after sensitivity analysis, call for abolishing the existing PV grant policy in the Indonesian rural electrification programs. The government, instead, should encourage the PV industry to improve production efficiency and to provide after-sales service. A 100-watt peak (Wp) PV under this policy is affordable for 33.2 percent of rural households without electricity access in 2010. Rural PV market size potentially increases to 82.4 percent with rural financing institutions lending 70 percent of capital cost for five years at 12 percent annual interest rate. Additional 30 percent capital subsidy and 5 percent interest subsidy slightly increase the rural PV market potential to 89.6 percent of PV adopters. However, the subsidies are crucial for creating PV demands by urban households but the most effective policy for promoting PV to urban households is the net metering scheme. Several policy proposals are discussed in response to these findings.

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1. Introduction

The link between energy access and economic development is widely acknowledged. A secure access to affordable, reliable, sustainable and modern energy *for all by 2030* remains one of the Sustainable Development Goals (SDGs). However, lack of universal electricity access is a common problem encountered by developing economies like Indonesia. Low-density loads scattered across many small islands challenge providing electricity access in Indonesia. Hence, decentralised technologies such as oil-based power plants become the priority to accelerate energy access since the Dutch colonisation era (McCawley, 1971) given that the technology is available in small scales and at low investment costs. The massive development of oil-based power plants increased the electrification levels from less than 10% in 1975 to 89.1% in 2016. Meanwhile, electricity consumption per capita significantly increased from 14 kWh in 1971 to 835 kWh in 2016 (McCawley, 1978; PLN, 2017; WB, 2017).

The importance of off-grid renewable energy is also commonly emphasised to accelerate rural electricity access in developing economies. The renewables-based mini-grid or off-grid systems provide the most viable means of access to electricity for the rural population that is distant from power grids (Sovacool, 2013). Furthermore, advancements in smart grid and storage technologies, falling average costs and the associated environmental benefits have placed off-grid renewables high on the global rural electrification agenda. However, the deployment of renewable energy technologies encounters various barriers, including technical reliability, economic feasibility, environmental impacts, and social acceptance (Blum et al., 2013; Byrnes et al., 2013; Jacobson and Delucchi, 2011; Nepal, 2012). Overcoming these barriers requires relevant intervention policies which engender varying levels of policy-specific costs and benefits that need to be assessed (Sovacool, 2013).

The energy economic and modelling literature offers various analytical tools to assess the costs and benefits of proposed energy policies (Connolly et al., 2010; Siddaiah and Saini, 2016). However, most of the tools have been prescribed for developed economies with specific characteristics, such as high shares of commercial energy use and industrial energy demand, reliable energy supply, lower income inequality, and liberal energy markets (Bhatia, 1987; Bhattacharyya and Timilsina, 2010a; Pandey, 2002; Shukla, 1995; Urban et al., 2007; Van Ruijven et al., 2008). Using such analytical tools for analysis in developing countries requires significant adjustments and alterations (Al

Irsyad et al., 2017b). We, therefore, avoid the weaknesses of implementing borrowed tools that do not consider the local context and may lead to inappropriate energy policy conclusions. This is achieved by constructing a novel hybrid energy analytical tool based on Agent-based modelling (ABM) for application in the Indonesian solar energy policy context. We aim to answer the following research questions. Have the solar energy intervention policies been effective in Indonesia? What are their associated costs and benefits in terms of the economic and environmental impacts?

Indonesia provides an interesting case study because of her fame as the largest archipelagic nation consisting of more than 17,000 small islands. Island topography implies that distribution of energy by providing grid access is challenging and uneconomical (Timilsina and Shah, 2016). Island economies have smaller electricity markets that prohibit them to benefit from significant scale economies of power plants. Meanwhile, the remote location and isolation constrain market expansion through electricity exports. Most island economies are heavily dependent on oil-based power plants despite being vulnerable to the impacts of peak oil and climate change. However, the topography constraint is also an inherent opportunity to serve the electricity need through distributed renewable energy technologies, as small islands may not require a large-scale intensive infrastructure (Khodayar, 2017; Kuang et al., 2016).

The contributions of our study are three folds. First of all, to the best of our knowledge; our energy model is the pioneering model in integrating the micro socio-economic, macroeconomic, environment and energy system perspectives. The integrated model allows policymakers to understand the response of an individual household to a proposed policy and simultaneously to measure the associated costs and benefits of the policy in national perspectives. Second, we aim to fill the gap of energy studies, which have inadequately considered social , energy access and technology adoption behaviour leading to energy policies uncertainty and errors (Al Irsyad et al., 2017a; Sovacool et al., 2015). Last, our energy model features the characteristics of developing countries by considering the purchasing power of rural households without electricity access. The model holds global relevance since other developing countries could simply adopt the model by changing the data.

The remainder of the article is structured as follows. Section 2 discusses energy model in general and provides a case for integrating social and economic perspectives. Section

3 describes the methodology and data, while Section 4 and 5 present the results and policy implication respectively. Section 6 concludes the paper.

2. A Review of the Energy Modelling Studies

Energy models, in general, can be based on engineering and economic approaches (Al Irsyad et al., 2017b; Bhattacharyya and Timilsina, 2010b; Connolly et al., 2010; Nakata et al., 2011; Suganthi and Samuel, 2012). The engineering approach, also called the bottom-up approach, has the characteristics of a comprehensive database of technologies, energy potential, and costs. However, the bottom-up approach has weaknesses; one of them is ignoring the macroeconomic impacts (Li et al., 2015). On the other hand, the economic approach, also known as the top-down approach, emphasises the interaction of economic sectors in the market. This feature allows assessing the impacts of the proposed policy to macroeconomic indicators, such as economic growth, employment, and energy prices. The shortfall is that the top-down approach has fewer specifications of the energy sector (de Koning et al., 2015). Therefore, integrating both approaches is common to solve the weaknesses of each approach. Nevertheless, integrated energy models still lack the features of human and social elements, the most important factors in renewable energy development (Jacobson and Delucchi, 2011; Sovacool et al., 2015).

The application of agent-based modelling (ABM) for energy system is an emerging area of literature since ABM can surpass the limitations of conventional energy models. ABM could integrate engineering and economic approaches to social analysis in renewable energy systems as in Table 1 (Al Irsyad et al., 2017b; Alfaro et al., 2017; Rai and Robinson, 2015; Tang, 2013). An earlier study by Rai and Robinson (2015) differentiates social characteristics of households in Texas to evaluate the effectiveness of PV rebate policy. Tang (2013) assesses the behaviours of wind turbine developers in Brazil, China and India in response to financing support from the Clean Development Mechanism (CDM) scheme. Recently, Alfaro et al. (2017) develop BABSTER (Bottom-up Agent-Based Strategy Test-kit for Electricity with Renewables) model to compare the impacts of five strategies of renewable energy development in Liberia.

Table 1. ABM studies for renewable energy analysis

Studies	Included issues					
	Analysis scope	Engineering	Microeconomic	Macroeconomic	Social	Environment
Tang (2013)	Wind energy investment decisions by IPP (Independent Power Producer)	Power plant capacity and related costs; capacity factor	The impacts of clean development mechanism (CDM) credits and FIT to project feasibility	N/A	IPP’s experiences	Certified emission reduction (CER)
Alfaro et al. (2017)	Selecting the most favourable technology (PV, biomass, or micro-hydro power) for rural electrification	Power plant capacity and related costs, lifetime, efficiency; heat rate; transmission grid; peak and base electricity demand derived from number of population and their patterns in using appliances	Levelised cost of electricity	Employment and economic inflows	N/A	N/A
Rai and Robinson (2015)	The determinants of PV adoptions in urban area	PV technical data and related costs; solar radiation;	Rebate values; investment tax credit; payback period	N/A	Various data (e.g. home location, values, and environments) of 173,466 households; the distances between houses; households’ interactions	N/A

However, none of the previous ABM studies on renewable energy has analysed the integrated perspectives of engineering, macroeconomic, social, and environmental aspects simultaneously. Alfaro et al. (2017) discuss engineering and macroeconomic perspectives but exclude environmental and social issues, while Tang (2013) does not discuss the macroeconomic relationships. Therefore, our ABM, called ARISE (Agent-based Renewables for Indonesian Sustainable Energy) includes these four following issues for analysing potential impacts on PV policy in Indonesia.

The macroeconomic analysis relies on top-down approaches, such as econometric, input-output (IO) analysis, and computable general equilibrium (CGE). IO analysis may have a weakness as a static and naïve model, but it is still a useful analytical tool especially in data limitation situation (West, 1995). In fact, its simplicity lays it as the basis for more complex models and, thus its application is still growing in recent literature. For example, Markaki et al. (2013) use IO analysis to measure the impacts of renewable energy and energy conservation targets to economic outputs and employment in Greece. Tourkolias and Mirasgedis (2011) and Simas and Pacca (2014) assess employment growth by viewing renewable energy development in Greece and wind energy projects in Brazil respectively. Chun et al. (2014) estimate economic impacts of hydrogen energy development in South Korea.

Social science inclusion in energy system analysis is indispensable to achieve low-carbon future (Sovacool et al., 2015). Jacobson and Delucchi (2011) even suggest social and political factors as the main barriers to renewable energy deployment. Other literature also found significant influences of non-monetary factors to the decisions of renewable energy investments. Tang (2013) notices the importance of investors' experiences for the investment decisions. Graziano and Gillingham (2015) examine the significances of neighbour distance, rented house share, household income, race, age, political views, and the unemployment rate to 3,833 PV adopters in Connecticut State during 2005 - 2013. Rai and Robinson (2015) confirm the significant influences of location, home value and tree cover to 2,738 PV investing households in Austin City.

Environmental awareness is one of the motives of renewable energy adoptions by households; however, renewable energy has higher upfront environmental impacts due to their low power density (Hertwich et al., 2015; Rai and Robinson, 2015). Constructing a Mega Watt (MW) capacity of renewable energy requires more materials, energy and land compared to the fossil fuel-powered plants. In countering this dilemma, life-cycle analysis (LCA) becomes a powerful analytical tool to assess the entire environmental impacts of power plant technologies during their lifetime. Thus, the application of LCA is typically combined with other methods in advancing the system modelling framework (Earles and Halog, 2011; Halog and Manik, 2011).

3. Methodology and Data

The main feature of ARISE is the ability to simultaneously assess the technical, economic, environmental and social impacts of a proposed policy. Figure 1 shows the interaction and the integration of the four perspectives. The initial step involves calculating the investment cost and monthly costs of PV 100 Wp (for off-grid) and 1,500 Wp (for on-grid) based on technical data (e.g. capital cost, operational and maintenance cost) and policy intervention. A household then assesses their social attributes, PV costs and benefits for deciding on PV investment. ARISE then uses the physical capacity and the monetary values of PV investments to estimate the environmental and macroeconomic impacts correspondingly. The detailed descriptions of each analysis perspective are in the following subsections.

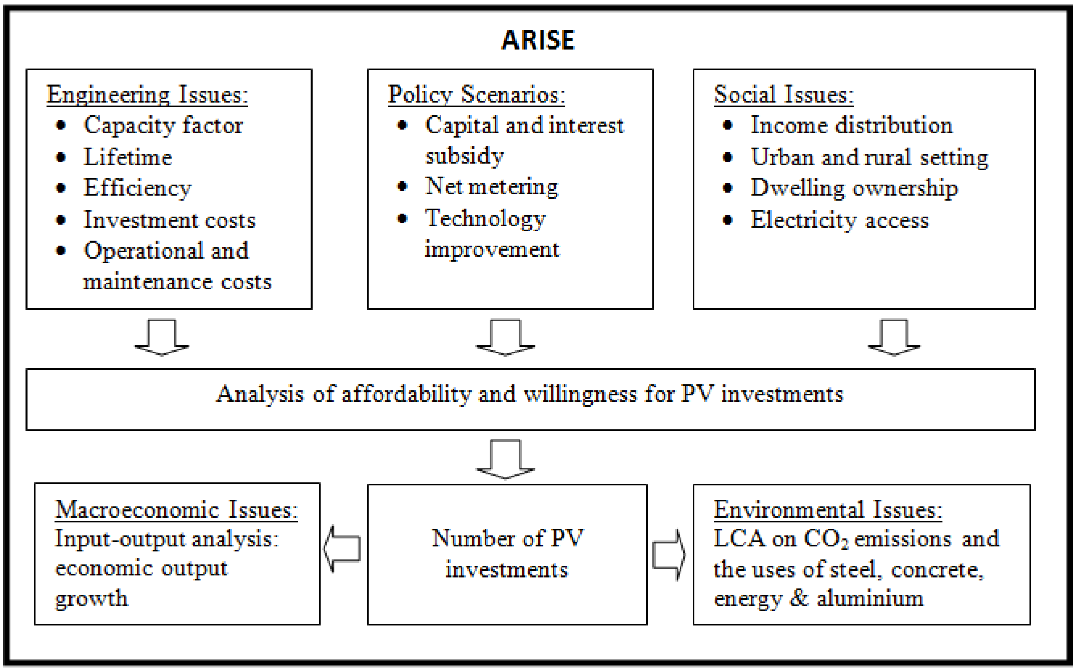

Figure 1. The linkage of four perspectives in ARISE

3.1. Engineering Perspective: Electricity System in Indonesia and Policy Scenarios

The paradigm of renewable energy policy in Indonesia has been altered recently. Previously, Ministry of Energy and Mineral Resources (MEMR) endeavoured the growth of renewables-based electricity production from the feed-in-tariffs (FIT) policy, providing high tariffs as incentives (MEMR, 2015a, b, 2016a, b). However, the policy was rejected by the State-owned Electricity Company (PLN) and other ministries because it escalated the electricity generation costs and electricity subsidy. In early 2017, FIT is replaced by the "reference tariff" policy which stipulates PLN's regional electricity generation costs as the maximum tariff to buy renewable energy-based electricity produced by IPP. In regions where the generation cost is higher than the average national costs, PLN could buy the electricity at maximum 85% of the regional costs. Meanwhile, the maximum tariff for other case is the generation cost in the region. The government also exerts a quota system for solar energy in every regional electricity grid to maintain the grid stability. Our study assumes no quota applied to measure the potential of PV market in urban households.

Renewable energy for rural electrification is undertaken through the donor gift scheme and the integrated IPP scheme. The first scheme for the PV technology has started since 1995 and received overwhelming criticisms mainly due to lack of knowledge transfer to villagers in preserving the PV performance (Sovacool, 2013). The second scheme may award a subsidy to IPP who sells the generated electricity to households without PLN grid connection (MEMR, 2016c). The subsidy worth constitutes the discrepancy between the IPP generation cost and the lowest PLN electricity tariff. Nevertheless, the subsidy volume is restricted to 84 kWh per household each month.

Our study juxtaposes the effectiveness and the efficiency of four PV policy scenarios. Table 2 encapsulates the assumptions used in each scenario with descriptions in the following paragraphs:

a. Scenario 1: Previous renewable energy policy

   The effectiveness and the efficiency of FIT policy (MEMR, 2015a, b, 2016a, b) and the donor gift scheme are inquired. The premise is that the donor scheme does not encourage villagers to invest in PV, resulting in undeveloped PV market, no maintenance service (i.e. zero maintenance cost), and shorter PV lifetime. Another supposition used is the interminable budget that enables the government to distribute free PV each year.

b. Scenario 2: Existing renewable energy policy

This scenario explores the effectiveness and the efficiency of the current reference tariff (MEMR, 2017), which is at the outset designed to compel the advancements of PV industry. On this basis, the central assumption used is that PV industries successfully reduce their production costs and institute their product retailers in the rural area. The last assumption is that the reference tariff (MEMR, 2017) increases 9.25%/ year, which was the growth rate of the average retail electricity price in 2010 -2015. The government then discontinues the donor gift scheme but fails to set up the microfinance service for PV investments in the rural area.

Table 2. Assumptions used in the analysis

Parameters	Scenario 1	Scenario 2	Scenario 3	Scenario 4
PV capacity unit (Wp)	100 (rural) 1,500 (urban)	100 (rural) 1,500 (urban)	100 (rural) 1,500 (urban)	100 (rural) 1,500 (urban)
PV lifetime (years)	2 (rural) 20 (urban)	20	20	20
Inverter life time (years)	10	10	10	10
Capacity factor (%/year)	16	16	16	16
PV price (USD/ Wp)	1.91	1.15	1.15	1.15
Inverter price (USD)	1,000	615.38	615.38	615.38
Annual OM costs (¢USD/ Wp)	0 (rural) 2.96 (urban)	0.12 (rural) 2.96 (urban)	0.12 (rural) 2.96 (urban)	0.12 (rural) 2.96 (urban)
Cost of equity (%/ year)	15	15	15	15
Value added tax (%)	10	10	10	10
Inflation (%/year)	5.1	5.1	5.1	5.1
Escalation (%/year)	1.0	1.0	1.0	1.0
Loan period (years)	0 (rural) 5 (urban)	0 (rural) 5 (urban)	5	5
Equity ratio (%)	0 (rural) 30 (urban)	30	30	30
Loan interest (%/year)	12	12	12	12
Debt reserves (% of yearly loan instalment)	100	100	100	100
Interest rate on debt reserves (%)	1.3	1.3	1.3	1.3
Incentives	Feed-in tariff	New tariff	New tariff	Net metering
Capital subsidy (%)	100 (rural) 0 (urban)	0	30	0
Interest subsidy (%)	0	0	5	0

* Exchange rate is assumed at IDR 13,000 / USD.

c. Scenario 3: Obligation for banks to finance renewable energy projects

Scenario 2 is revamped by subsuming the microfinance service in the rural area. The financing scheme is accessible for five-year loan period, 12% annual interest rate, and the maximum loan of 70% PV price. As accompaniments, 30% capital subsidy and 5% interest subsidy are bestowed.

d. Scenario 4: Net metering scheme

   The net metering scheme applies instead of the reference tariff and subsidy schemes. The new scheme allows a household to export PV-generated electricity to PLN's grid at the highest retail electricity price, which is for households with 6,600 volt ampere (VA) installed power capacity, and the price is also assumed to grow 9.25%/ year.

3.2. Social Perspective: Heterogeneity of Willingness for PV Investments

Heterogeneity in ARISE includes the disparity of households' expenditures, which portray the ability for PV investment. Moreover, ARISE dissociates households in 33 provinces to urban-rural segregation, three types of electricity access (i.e. PLN's electricity access, non-PLN's electricity access, and no electricity access), and two types of dwelling ownership status (i.e. owner and non-owner). The status is crucial since a family living in a rented house will be unlikely to invest in PV technology (Graziano and Gillingham, 2015).

The decision to invest in PV relies on economic feasibility (Rai and Robinson, 2015) and social position of the households. Therefore, we assume that PLN urban customers act as a profit seeker from the investment, while rural households without electricity access more concern the affordability of the PV price. Concretely, prerequisites for the on-grid investments are affordable PV prices and higher renewables tariff than revenue requirement. In contrast, a PV 100 Wp unit is intriguing in the off-grid area if the price is lower than monthly expenditure or if it is financed; the monthly expense is lower than average monthly electricity expenditure on the region. The last assumption is that households will invest in PV if its capacity factor (CF) and lifetime exceed reliability thresholds, which are 3% and five years respectively. CF 3% is the minimum CF for charging the battery in light emitting diode (LED) lamps. Meanwhile, five-year lifetime should be adopted as the minimum lifetime standard, so that PV without five-year warranty cannot enter the market.

The National Socioeconomic Survey (Susenas) 2010 (BPS, 2010) is the primary data source used for characterising the households agent. The dataset entails data for 293,715 household samples out of 61,387,200 total actual number of households in

2010. The household number and their expenditures in ARISE are rising at rates based on the divergence of sampling sizes and the average expenditures in Susenas 2010 and 2011 (BPS, 2010, 2011). In details, ARISE Geographic Information System (GIS) database contains the estimated number of households, household's expenditures (i.e. minimum, maximum, average, and standard deviation), and growth rate of the number of households.

3.3. Macroeconomic Perspective: Input-Output (IO) Analysis

I-O analysis, developed by Wassily Leontief (1936), manipulates the Input-Output (IO) table which shows the flow of output produced by industry *i* to industry *j* as a production input, and to final demand. The latest Indonesia's IO table records economic transactions in 2010 for 185 sectors, including electricity (sector 145) sectors (BPS, 2015). ARISE disaggregates the electricity sector into specific following power plant types (and its abbreviation):

- Coal-based power plant (PLTU)
- Combined cycled gas turbine power plant (PLTGU)
- Open cycled gas turbine power plant (PLTG)
- Geothermal power plant (PLTP)
- Hydropower plant (PLTA)
- Small and Micro-hydro power plant (PLTM/H)
- Wind turbine power plant (PLTB)
- City waste to energy power plant (PLTSa)
- Biomass-based power plant (PLTBio)
- Solar power plant (PLTS)
- Oil-based power plant (PLTD)

The disaggregation principle refers to McDougall (2002) who uses a reference IO table to disaggregate another I-O table. The reference IO table used in our study is the modified IO table 2008, developed by Ministry of Energy and Mineral Resources (MEMR), Agency of Fiscal Policy (BKF) and Central Bureau of Statistics (BPS) (Wargadalam, 2014). As a drawback, we assume that the structure of electricity sector remains unchanged throughout 2008 – 2050. After the disaggregation process, other sectors than electricity are aggregated into three economic groups, namely bank, services and industry sectors, for simplicity. Finally, ARISE assesses economic output changes by multiplying the transaction values of PV sector (i.e. costs, interest payment, and electricity sales values) with the Leontief inverse matrix derived from the simplified IO table.

3.4. Environmental Perspective: Life Cycle Analysis (LCA)

LCA is an analytical approach to estimate entire environmental impacts from the spare part manufacturing process until electricity generating process (Noori et al., 2015). However, the shortcomings of LCA features in ARISE is only accounting direct environmental impacts materialised in construction and operation stages of power plants. ARISE multiplies the environmental factors in Table 3 by electricity production and new power plant capacity to estimate the total environmental impacts.

Table 3. Environmental impact factors of PV

Construction (per MW capacity)					Emission in operating (kg CO_{2e}/ MWh)
CO_{2eq} (kg)	Steel (ton)	Aluminium (ton)	Concrete (ton)	Energy (GJ)	
4,039,116.9	103.5	4.0	50.0	491.6	148.0

Source: Tahara et al. (1997). Abbreviations: MW for megawatt, kg for kilogram, GJ for gigajoule, CO_{2eq} for carbon dioxide equivalent, and MWh for megawatt hour.

3.5. Structures of ARISE

ARISE, developed in NetLogo 5.3.1, has an interface in Figure 2 to serve users in performing data load, policy scenario setting, and the simulation. The foremost step is to open the datasets of initial values for variables and parameters, Leontief inverse matrix, regional socioeconomic and energy system data in GIS files. Household agents are created heterogeneously by using socio-economic data stored in the GIS files. Second, users should assign the values for policy scenarios by using sliders or default button. The third step is the simulation process which in sequence computes PV investments costs, PV adoptions by households, policy impacts, and growth of households' number and expenditure. The simulation outputs are displayed in a thematic map, two graphs showing the environmental impact and subsidy expenditures, and several output boxes showing economic output changes and other computation results. ARISE archives the numerical results of several prominent indicators to three spreadsheet files.

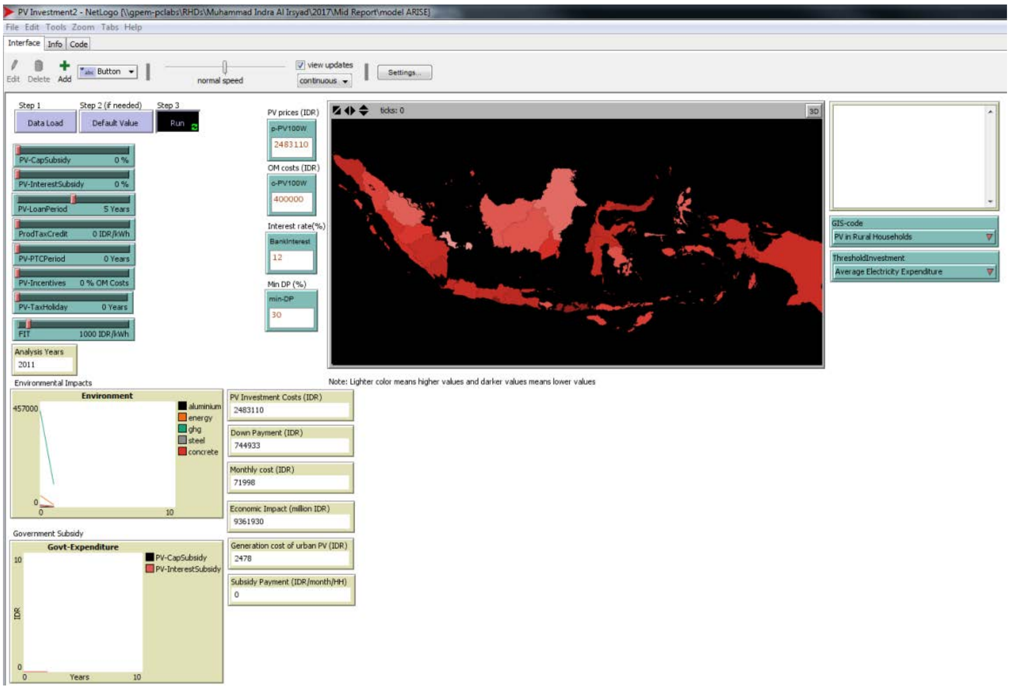

Figure 2. Interface of ARISE

The ARISE syntax is validated by equating ARISE outputs with manual computation in spreadsheet software. To this end, several input combinations are simulated to generate the number of households, PV investment costs, total PV capacity, electricity production, economic output, and environmental impact. For further information, ARISE and the manual, containing the Overview, Design concepts, and Details (ODD) protocol, more detailed information, and validation results, are accessible at the website of UQ's Industrial Ecology and Circular Economy Research Group[2] and the OpenABM website. Last, sensitivity analysis on ARISE main outputs (i.e. PV investments by urban and rural households) is performed to various values of main parameters (i.e. capital cost, capacity factor (CF), PV lifetime, OM costs by rural and urban households, equity cost, inverter cost, and tariff).

4. Results

[2] https://industrialece.wixsite.com/main/single-post/2017/12/31/Agent-based-Renewables-model-for-Indonesia-Sustainable-Energy-ARISE

4.1 Simulation Results

Simulation of Scenario 1 concludes that giving PV 100 Wp for all rural households without electricity access in 2010 will cost USD 559.5 million. Moreover, keeping the 3.3 million rural households to have the PV systems until 2050 potentially elevates the cost by 22 times. The lack of PV maintenance service needs PV re-giving in every two years, inflicting the cost surge. The policy drives new economic output for USD 34.8 billion but leads to severe environmental impacts, equivalent to 80 gr aluminium, 9.8 MJ energy, 2.1 kg steel and 0.1 kg concrete per Wp operating PV capacity in 2050. Moreover, the previous FIT is insufficient for enthralling PV investments by urban households, exposed by high levels of PV system costs and loan interest rate.

Moreover, 40% PV price reduction under the reference tariff regime in Scenario 2 still deficiently encourages PV investments by urban households. Meanwhile, PV market in the rural area in 2010 is approximated to be 33.2%, but it will grow to 71.5% of rural PV users in Scenario 1, or equivalent to 231 MWp, in 2050. The significant markets are West Kalimantan, East Nusa Tenggara and Papua provinces, whose total market potentially exceeds one million households in 2050.

Table 4: The effectiveness and efficiency of PV policy scenarios in 2050

Policy Scenario	Effectiveness (MWp)		Efficiency (per Wp)					
	Rural	Urban	Subsidy (USD)	CO_{2eq} (kg)	Aluminium (gr)	Energy (kJ)	Steel (gr)	Concrete (gr)
1	327	0.00	38.15	89	80	9,815	2,067	998
2	234	0.00	0.00	17	9	1,145	241	116
3	227	1,394	0.94	15	8	1,023	215	104
4	228	32,040	0.00	11	7	821	173	83

*Effectiveness and efficiency are measured based on operating PV capacity. Subsidy only covers capital and interest subsidies.

The policy of capital and interest subsidies in Scenario 3 is well accepted that in 2010, rural PV adopters in Scenario 3 is 10.4% lower but costs for the government is 79.9% lower compared to the donor gift scheme in Scenario 1. Another advantage is the emergence of urban PV market, reaching 1,394 MWp in 2050. The highest markets are East Nusa Tenggara, and West Nusa Tenggara provinces for rural and urban area successively.

The effect of the financing scheme alone without any subsidy in Scenario 4 is the increase of rural PV market potential in 2010 to 2.5 times of the market potential without financing scheme in Scenario 2. The rural market potential in Scenario 4 is also equivalent to 82.4% of rural PV adopters in Scenario 1. The most substantial markets are East Nusa Tenggara and Papua provinces with 433 and 330 thousand rural households respectively in 2050. Meanwhile, the net metering scheme is more enticing in fostering PV diffusions in the urban area. The scheme will withdraw massive PV investments starting in 2021 once the highest electricity retail price exceeds the revenue requirement, i.e. IDR 2,065 /kWh.

4.2 Sensitivity Analysis Results

Figure 3 and Figure 4 show the results of sensitivity analysis of PV investments by rural and urban households respectively. The horizontal axis shows the parameter changes, termed by "*parameter name – scenario number*", while the vertical axis represents the operating PV capacity in 2050. The PV investment in the rural area in all scenarios is less sensitive to changes in the parameters as shown in Figure 3. Some exceptions are changes to -80% or smaller on the lifetime value and -100% of CF value due to the reliability thresholds. Small fluctuations of all scenarios on Figure 3 are the effect of random income distribution assigned to each household agent. At zero capital cost (-100% change), Scenario 2 has higher rural PV adopters compared to Scenario 3 and Scenario 4 due to no OM cost in Scenario 2. On the other hand, at 100% higher capital cost, rural PV adopters in Scenario 2 is relatively lower than adopters in Scenario 3 and Scenario 4 due to the absence of rural financing sector.

In contrast, as shown in Figure 4, PV investment by urban households is more sensitive to the parameter changes except Scenario 4. The parameter changes in Scenario 4 only delay the investments, and once the rapidly growing electricity price exceeds the revenue requirement, all wealthy people would invest in PV. Therefore, the number of investments is relatively similar in 2050 for all parameters changes, except the lowest values of CF, lifetime and tariff. The reference tariff in Scenario 2 causes less sensitiveness of PV investments by urban households, while the presence of capital and interest subsidies in Scenario 3 has caused higher sensitiveness. Overall, the directions of investment changes meet the expectations. The investments by urban households increase as CF, lifetime and tariff improve, or costs and prices reduce. PV investments emerge in Scenario 1 and Scenario 2 when CF or tariff improves 20%. Similarly, 20% reduction of PV price, equity cost, or inverter price also creates PV demands by urban households.

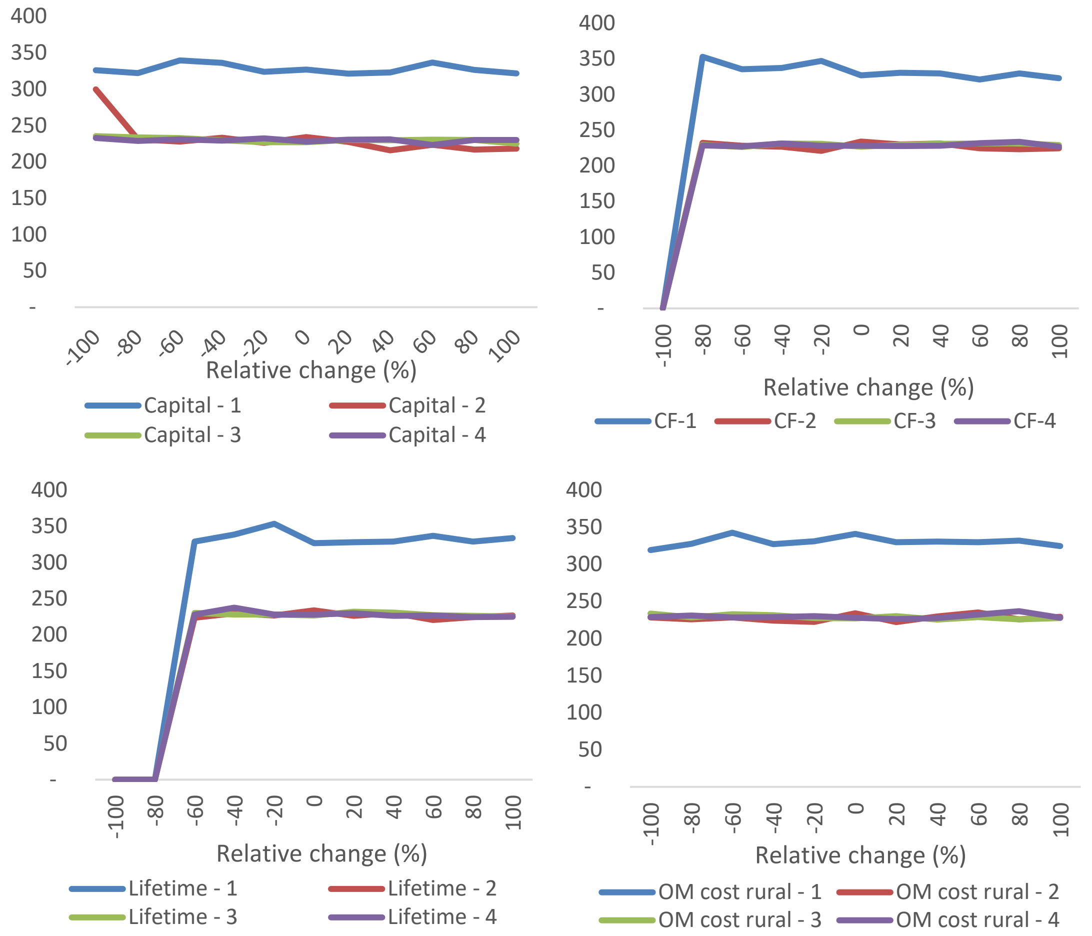

Figure 3 Sensitivity analysis: Operating PV capacity in rural area in 2050 (in MWp)

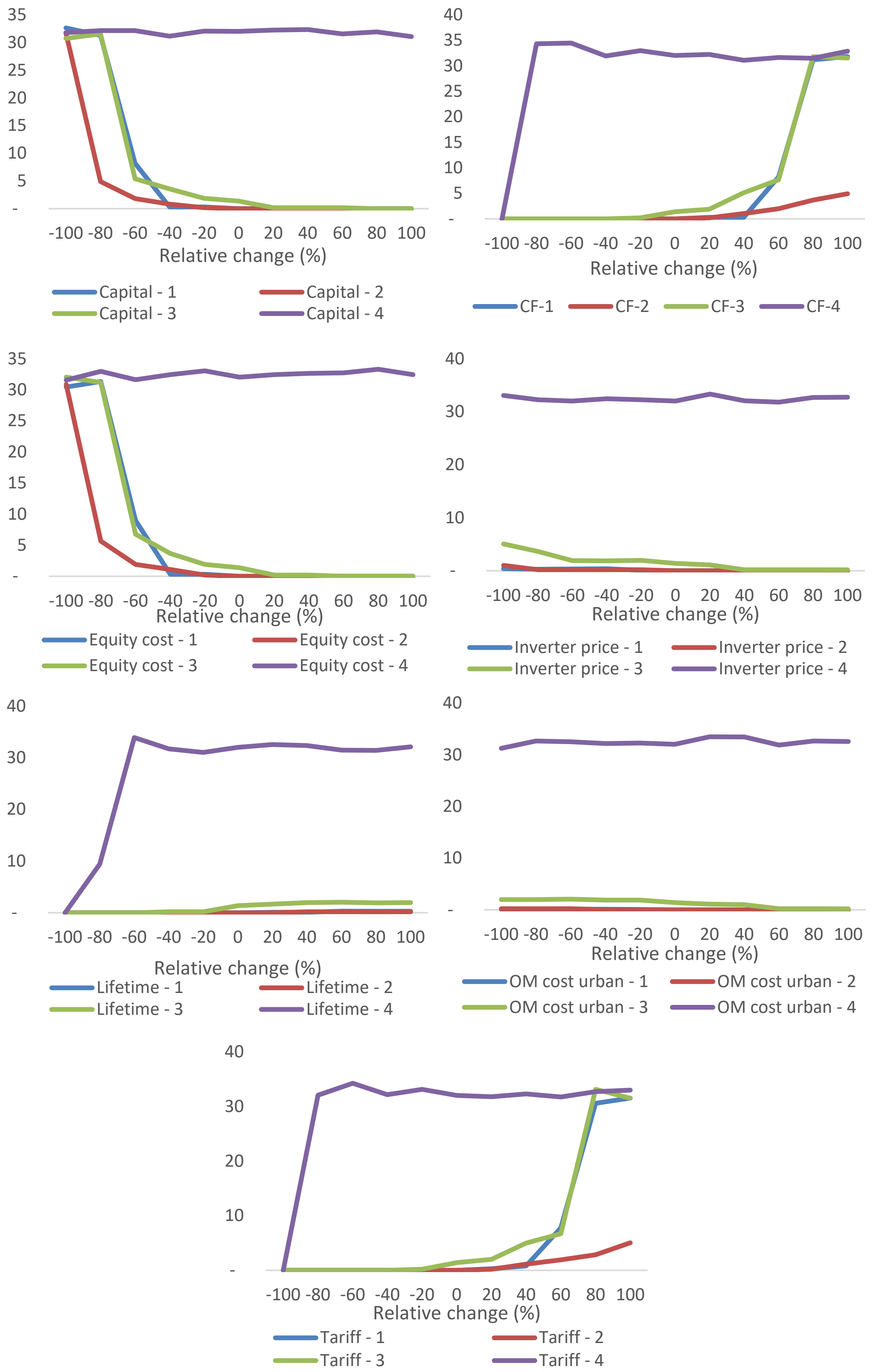

Figure 4 Sensitivity analysis: Operating PV capacity in urban area in 2050 (in GWp)

5. Policy Implications

In this section, we advise several critical policy proposals. First of all, the government should transform the donor gift scheme into the establishment of rural PV market. The donor gift policy in Scenario 1 is the most effective policy for deploying PV in the rural area but, at the same time, the most inefficient policy in terms of budget and resource uses. Eliminating the donor gift policy will enforce PV industries to shift their market target from governments’ projects to individual households, who should be convinced by the presence of after-sales services for maintaining PV reliability. The customer shifting also entails PV price reduction, which could be acquired from declining global PV prices. However, the regulation of minimum local content (MI, 2012) averts the import of the low-price PV and thus, the government should embrace cost-cutting policies. For instance, state-owned research institutions undertake high-cost technology and facility developments. The outcomes later are jointly utilised among domestic PV industries. The government could also temporarily lessen the import tariffs for intermediate parts while industrialising the required upstream sectors.

The government already encourages the market shifting by giving a subsidy for IPP directly selling the electricity to rural households (MEMR, 2016c). The government can further improve the policy by changing the subsidy scheme. Existing scheme, based on household’s electricity consumption, requires a power meter and consequently incurs labour costs for reading the meters. Moreover, typically electricity system with a power meter is a centralised system which needs investments in grid infrastructure. In contrast, a solar lighting kit, a PV system with several battery-powered light emitting diode (LED) lamps, does not lead to such costs but, as a consequence, the electricity generated cannot practically be measured. In light of this fact, the government should instead provide capital and interest subsidies to a PV-based IPP selected using an auction mechanism. The number of served customers becomes the basis for the amount of the subsidies, given at the commercial operation date (COD) of the project. As an obligation, IPP should provide the electricity for at least 20 years. In the operation stage, the IPP levies a fixed monthly electricity fee from the customers. This proposed scheme will provide a fix revenue stream, reducing IPP's business risks.

ARISE simulation results for urban area analysis in Table 4 show that attracting urban households to invest in PV cannot depend on previous FIT and the reference tariff alone. Other prerequisites are PV price reduction, capital and interest subsidies;

otherwise, urban households will wait for higher renewables tariff. Both the reference tariff and the net metering scheme have an automatic adjustment to fossil fuel cost so that once the PLN's electricity generation cost is higher than PV revenue requirement, PV demands by urban households will emerge. This finding should be the foundation for considering a policy to allow the residential-based PV IPP scheme offering two benefits. First, distributed PV systems technically provide better electricity supply stability to the electricity grid than a large-centralised PV system (Brouwer et al., 2014). Second, rooftop PV systems do not need financial and environmental costs for acquiring land as take place in centralised PV systems. The government may trial the net metering policy first in a region with significant electricity supply from oil- and gas-based power plants.

6. Conclusions

We assessed the effectiveness and efficiency of several alternative solar energy policies in Indonesia by exercising the Agent-based Renewables model for Indonesia Sustainable Energy (ARISE) in this study. ARISE simulation outputs suggest the necessity to reform PV donor gift scheme to PV financing scheme for efficiently deploying PV to rural households without electricity access. The financing scheme should be aided by capital and interest subsidies to encourage PV investments by urban households. However, the combination of declining PV price and net metering scheme is the most imperative factor for creating PV demands by urban households.

Our modelling describes how to integrate engineering, socio-microeconomic, macroeconomic and environmental perspectives in the agent-based model framework. ARISE has been devised by taking Indonesia's specific datasets but it could be adopted by other developing countries. ARISE uses free software and could be freely downloaded. The significant adjustment to adopt ARISE is changing the socioeconomic data.

However, current ARISE model still has several shortcomings like any other energy models. First, ARISE uses international cost data, selected from extensive reviews of costs in developed and developing countries. Moreover, the costs and price are still uniform for all provinces, neglecting differences in shipping and installing cost. Second, ARISE does not use the actual number of household types, which are available in Census data. Instead, it uses estimated numbers by considering household sample size in National Socioeconomic Survey (Susenas) 2010 and total actual household number. Third, ARISE cannot differentiate between types of dwelling, for example, house or apartment. This issue is notable since apartment owner is unlikely to invest in PV due to the space unavailability. Fourth, the urban household should be further categorised into a certain PLN's customer type by the installed power capacity. Customers with higher capacity has higher retail electricity tariff. Therefore, the consequence of using tariff for 6,600 VA consumers is an overestimation of PV investments by urban households with lower installed capacity. Fifth, the overestimation also occurs by using average electricity expenditure as a threshold for PV investment decision by rural households. The average expenditure represents the willingness to pay by households with electricity access while households without electricity access may have lower willingness to pay. Sixth, ARISE assumes static values for income growth, prices, technology efficiency, and Leontief inverse matrix for all analysis years. Seventh, the LCA only accounts environmental impact in construction and operating stage (direct impact) of PV systems while the actual impact is also influenced by output changes of other sectors economically benefited and suffered from the PV investments (indirect impacts). Lastly, ARISE scope narrows to analyse solar energy policy, so that the interactions of overall electricity system are not modelled yet. Thus, continually improving the existing ARISE model by considering its current limitations remains an area of future research for which this study provides an overarching foundation.

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Funding

The authors acknowledge the funding support from the Indonesia Endowment Fund for Education (LPDP), Ministry of Finance – the Republic of Indonesia (Grant no: 20141122092191).

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