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Over a century of small hydropower projects in Indonesia: a historical review

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Abstract

Background Hydropower is a mature energy technology and one that could play a more important role in providing clean and reliable energy. In small-scale contexts, hydropower is useful for providing electricity access, balancing intermittent resources, and as a potential source of energy storage. This paper provides a comprehensive exploration of the development of the small hydropower (SHP) sector in Indonesia, the world's fourth most populous country.

Methods Two research methods were employed: secondary data analysis through a desk review of relevant literature and primary data collection through site visits and expert and stakeholder interviews. Two case studies of micro-hydro applications in community-based rural electrification were analyzed. The paper explores how SHP projects were initiated, lessons learned, and policy recommendations of relevance to further development of distributed small-scale renewable energy in Indonesia.

Results The sector commenced during the Dutch Era and now centers on both community-based rural electrification projects and commercial schemes under the independent power producer (IPP) approach. Since the late 1980s, initiatives to implement SHP for rural electrification have flourished through various programs. Key regulatory, economic, and technical barriers include inconsistent and unclear supporting regulations, especially regarding electricity prices; artificially low retail electricity prices; capital and borrowing constraints; advantages provided to fossil fuels; limited technical experience and capabilities of project developers and project sponsors; risks from floods, earthquakes, and landslides; constraints on supporting infrastructure; and limited grid links. The most successful and sustainable SHP projects are ones that provide local economic benefits and for which local communities are empowered with ownership and have responsibility for maintenance.

Conclusions SHP will remain small from a macro perspective but could still play a key role in further improving energy access and equity in remote areas. Key initiatives to facilitate this development could include local-level capacity building and project participation and the adequate pricing of negative externalities from fossil fuel projects. Indonesia's long experience with SHP carries lessons for other developing countries.

Keywords Small hydropower, Micro-hydro, Historical review, Renewable energy, Indonesia

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Background

Hydropower is the most mature renewable energy (RE) technology for electricity generation. However, the development of large-scale hydropower, particularly large dams, is often associated with serious environmental and social issues, including land inundation, settlement relocations [1], the possibility of disasters due to dam leaks, and public resistance. Small-scale hydropower (SHP)—typically run-of-river systems—are smaller in nature and often do not have as many downsides.

SHP works by converting the potential and kinetic energy of flowing water into usable energy. The water is directed to a small weir and then flowed, piped, and dropped to a lower elevation to turn a turbine, generating mechanical energy and spinning a generator to produce electricity [2]. SHP offers a flexible energy source for rural electrification, self-use power generation, or feeding into the main grid [2–4]. While not a new technology, it has the potential to be used more broadly as part of efforts to reach the target of universal access to clean energy.

Based on its power generation capacity, SHP can be categorized into mini, micro, and pico hydropower [5–7]. The *World Small Hydropower Development Report* (WSHDR) 2019 by UNIDO [8] recommended that projects be categorized as per local definition. In the Indonesian context, large-scale hydropower generally refers to a hydropower plant with over 10 MW of capacity and a dam.[1] Mini hydropower (MHP) typically refers to a run-of-river plant of 1–10 MW—often an independent power producer (IPP) project supplying electricity to the grid. Micro hydropower typically includes projects of 10 kW to less than 1 MW, which are usually for off-grid rural electrification purposes. Pico hydropower includes projects smaller than 10 kW. These definitions are general and there is some variation in usage.

Previous research has identified various advantages of SHP. SHP can have a low environmental impact [2], high efficiency (70–90%), is reliable, and typically operates with a high capacity factor (>50%). This can make SHP economically attractive [9]. SHP can also have a high energy payback ratio, can allow communities to reduce or avoid the use of fossil fuels [10], and performs well in terms of public acceptability [11, 12].

According to the WSHDR 2019, out of 229 GW of global SHP potential, only about 78 GW have been harnessed—mostly in Asia [8]. Endowed with mountainous and hilly geography and relatively high rainfall and humidity, Indonesia has abundant SHP potential. The National Energy Plan (issued under Presidential Regulation No. 22/2017) estimated that Indonesia's total hydropower potential is up to 75 GW. Of this, the WSHDR 2019 indicated that SHP potential in Indonesia is about 12.8 GW [8]. Not all of this will be economically feasible to develop, however. Grid availability and limited local electricity demand are among the constraining factors [13]. In-depth site-specific feasibility studies are required for any individual hydropower investment decision [14, 15].

Prior research on SHP projects in Indonesia has predominantly emphasized its potential [16, 17] and carried out techno-economic analysis [18]. This paper instead provides a comprehensive historical exploration into SHP development in the Indonesian context: how SHP was initiated, its current status, and lessons learned. To our knowledge, it is the first to provide a comprehensive review of SHP development in Indonesia, incorporating both case study and broader evidence.

The paper is structured as follows. The methods will next be introduced. This is followed by a results section describing SHP development from the East Indies era (Dutch Occupation) until the golden period of commercial MHPs. A review of micro-hydro as a rural electrification solution and its adoption for government programs and policies since the 1970s is then presented. The key barriers to SHP development will then be discussed, followed by the key issues and reform options for boosting the development of SHP in Indonesia. The study finishes with a conclusion.

Methods

Two research methods were employed in this study. The first was secondary data analysis through a desk review and analysis of relevant literature. The second was primary data collection through site visits and expert and stakeholder interviews, including with investors, project developers, non-governmental organizations (NGOs), central government officials (e.g. from the Ministry of Energy and Mineral Resources/MEMR), local government officials, the State Electricity Enterprise (PLN),[2] and banks and financing institutions. The paper also draws on the experience of international organizations in supporting RE development in Indonesia, particularly the German Agency for International Cooperation *(Deutsche Gesellschaft für Internationale Zusammenarbeit*/GIZ).

[1] That this is the typical definition used in Indonesia was confirmed in discussion with our panel of experts including from the GIZ Energy Programme, Bandung Hydro Association, Ministry of Energy and Mineral Resources, and project developers. The categorization is also used for the project financing portfolios of PT Sarana Multi Infrastruktur.

[2] PLN (in Bahasa Indonesia: *Perusahaan Listrik Negara*).

Results

The use of SHP in the East Indies tea factories (1800s–1920s)

The first generation of SHP projects in Indonesia was designed using European Francis and Pelton turbines during the Dutch Occupation Era in the late 1800s. The projects were to supply electricity for the tea gardens and factories of the East Indies (the name of Indonesia under the Dutch Occupation Era), mainly in the mountainous ranges in the western part of Java Island. The tea factories were constructed and operated to support the demand for high-quality tea in European countries. Dutch private-sector operators leased the land from the East Indies Government. More than 400 SHP plants were reportedly erected by the Dutch during the late 1800s to the 1920s [19].

One of the visited sites in the field study was Malabar MHP, an early-generation plant in operation since 1913. The site is in the Malabar Tea Plantation, Banjarsari village, Pangalengan sub-district, Bandung regency—about 30 km to the south of the city of Bandung, West Java province. The plant remains in operation, although its performance has declined. Several other mini and micro-hydro plants were also erected in the surrounding area for the electrification of tea factories, including Cinangling (1.3 MW), Cijambe (837 kW), Indragiri (108 kW), and Gunung Tua (1.3 MW) [20].

During the Japanese occupation in World War II (1942–1945), some tea plantations were substituted with other food and crop commodities, leaving tea factories and their power plants abandoned [19]. Following Indonesian independence in 1945, all former East Indies assets, including the tea factories and the SHP plants, were nationalized under the *Pusat Perkebunan Negara* (PPN—National Estate Center). When these entities were transformed into limited liability companies in the 1950s, most assets switched to being managed by the plantation state-owned enterprise, PT Perkebunan Nusantara (PTPN).[3] Some plants have still been operating in recent years but have become inefficient and eroded by age. Others have been abandoned given the decline in Indonesia's tea industry. PTPN had planned to invite private investors to revitalize and operate the plants under long-term rent-operate-transfer (ROT) arrangements, with electricity sold at commercial rates to PLN. However, this scheme has yet to materialize [20].

The role of SHP for early electrification in the East Indies (1900s–1945)

Bandung, the capital of West Java province, was one of the Dutch East Indies Government centers, home to several utility-scale SHP plants built for regional electrification purposes. In 1906, the first reported utility-purpose MHP project was built in the northern part of the city. It was named *Waterkracht werk Pakar aan de Tjikapoendoeng nabij Dago* or simply the Pakar MHP, a 2 MW run-of-river system using water from the Cikapundung River. It was operated by the *Bandoengsche Elektriciteitsmaatschappij* (Bandung Electric Company). However, in the early 1920s the plant was abandoned and replaced by two units of cascade MHP and micro-hydro: Centrale Bengkok (3 × 1.05 MW) and Dago (700 kW). Both remain in operation.[4]

In the late 1920s, three cascade hydropower plants were built in the southern part of Bandung: Plengan (6.87 MW), Lamajan (19.56 MW), and Cikalong (19.20 MW). The water came from the Cisangkuy River, Cisarua, and the Situ Cileunca artificial reservoir. These plants are still in operation, managed under PT Indonesia Power, a subsidiary of PLN [21]. Figure 1 presents examples of Dutch heritage hydropower, designed for tea factory electrification plus supply to the main grid.

The early generation of SHP projects faced stagnancy and later hiatus [19]. Our discussions with experts identified that limited human resource capacity and access to spare parts led to high operational and maintenance costs for the old Dutch-used SHP projects.[5] The oil boom in the 1970s created an opportunity for Indonesia (an oil-producing country) to experience a bonanza [22]. Energy export revenue jumped from about 20% of the Indonesian central government revenue in 1970 to about 60% in the early 1980s [23, 24]. Oil euphoria pushed renewable energy development down the list of priorities [19].

The use of SHP as a rural electrification solution (1970s–present)

Rural electrification issues became increasingly important to the government of Indonesia from the mid-1970s, creating heightened interest in micro hydropower schemes. A key motivator was the low level of electrification; the residential electrification rate was only about 15% of households in the mid-1970s and about 10% in rural areas [25].

[3] PTPN (*PT Perkebunan Nusantara).*

[4] Site visit to PT Indonesia Power, Bengkok MHP and discussion with our panel of experts including Bengkok MHP plant supervisor, PT PLN, and the Bandung Hydro Association.

[5] Discussion with our panel of experts including GIZ Energy Programme, Bandung Hydro Association, and the Mandiri Foundation *(Yayasan Mandiri).*

Fig. 1 Examples of Dutch small hydropower plants for tea factory electrification and main grid supply during the East Indies Era [20, 21]

A fillip to the use of micro-hydro for rural electrification occurred in the late 1970s when a group of engineering students from Bandung Institute of Technology (ITB) established a non-governmental organization (NGO) named the Mandiri Foundation (*Yayasan Mandiri*). This NGO engaged in community empowerment and technology-based infrastructure development, including micro-hydro installations and community waterwheel repairs. It was also active in disseminating knowledge on micro-hydro technologies to rural communities and in carrying out technical studies and training.

In the late 1980s, some international donors started to cooperate with and sponsor non-profit activities. *Swisscontact*, a Swiss agency, provided a scholarship program to study water turbines and relevant operational skills in Europe. The agency also facilitated knowledge and technology transfer by implementing a Small Metal Entrepreneurship Development Program. This aimed at improving the technical and managerial skills of small- and medium-scale metal workshops in Bandung. The government through PLN and MEMR also began to implement micro-hydro projects in rural and remote areas.

In the early 1990s, *Deutsche Gesellschaft für Technische Zusammenarbeit* (GTZ) (later GIZ) implemented the GTZ Micro-Hydro Program (GTZ-MHPP) aimed at supporting the standardization and performance improvement of micro-hydro in Indonesia. This included introducing crossflow turbines and electronic load controllers. The program also intended to increase the capability and expertise of Indonesian micro-hydro practitioners. The reputation of micro-hydro began to revive and it became more widely known as a worthwhile technological solution for rural electrification. Following this, funding from central and local governments as well as donors and international organizations started to be allocated to SHP. These funds supported capacity building and technical assistance to improve micro-hydro related expertise and skills for project developers, turbine mechanics, and surveyor services. The growing micro-hydro market saw the establishment of several small-scale water turbine manufacturers in Bandung such as PT Cihanjuang Inti Teknik (CINTEK), PT Kramat, and PT Heksa Hydro. These companies reportedly produced more than 1,100 units totaling almost 50 MW, including crossflows, Pelton wheels, and propeller turbines. Products were exported to countries in Asia, Africa, and Europe [26].

Further international cooperation and the adoption of SHP into government policies (2000s–present)

Amid the recovery from the Asian Financial Crisis in the early 2000s and Indonesia's democratization and decentralization process, the development of micro-hydro for alternative energy and rural electrification in Indonesia, especially projects funded by the government, continued. In 2002, the government through the MEMR also issued the first regulation on distributed small-scale generation. This formally enabled communities, cooperatives, and small-scale businesses to become involved in electricity generation, sales, and purchasing.

International donors and corporate social responsibility (CSR) activities also sponsored pilot micro-hydro projects in the early 2000s. Donors increasingly focused on community capacity building, particularly to strengthen the institutional set-up of the micro-hydro sector and ensure sustainable and productive use of SHP. GTZ in cooperation with the ASEAN Centre for Energy (ACE), ENTEC AG, and the Technical Education Development Centre Bandung (TEDC) supported the development of an ASEAN Hydropower Competence Centre (HYCOM) in Bandung, expected to become an ASEAN Centre of Excellence on micro-hydro development. GTZ also worked to support the development of an operations and maintenance (O&M) center towards a sustainable micro-grid and the development of minimum technical specifications for the design, operation, maintenance, and administration of micro-hydro**.** The program was then followed by the commissioning of a Micro Hydro Power Technical Support Unit (MHP-TSU) in 2006. This provided technical assistance for the planning and construction of government-funded micro-hydro projects as well as for capacity development. In 2009, a global program Energising Development (EnDev) started its implementation in Indonesia to promote clean energy access until 2019.

Various micro-hydro projects were built in the 2000s, mainly for rural electrification. Both non-governmental (donors and international agencies) and governmental programs were responsible for implementing the projects. Among these were the Integrated Micro Hydropower Development and Application Program (IMIDAP) under the United Nations Development Program (UNDP). IMIDAP provided technical assistance and standardization for feasible micro-hydro and Government-level capacity empowerment across Indonesia [27]. Others were the 5P (Pro-Poor Public–Private Partnership) Project by the United Nations for Economic and Social Commission for Asia Pacific (UNESCAP), which provided a partial grant for community empowerment and rural electrification [28]; the Global Environmental Facility (GEF) Small Grant Programme (SGP) of the UNDP; a Japan International Cooperation Agency (JICA) program; and a program of the Korea International Cooperation Agency (KOICA).

These programs were usually supported by grants from international donors to local NGOs, which in turn served as the project-implementing entities. The NGOs included the People Centered Business and Economic Institute (IBEKA), a local organization that had been actively introducing entrepreneurship, micro-hydro for rural electrification, and community-based approaches.[6] IBEKA is known for its Cinta Mekar pilot project of cooperative-based micro-hydro funded by UNESCAP, a project that introduced the 5P concept [28, 29]. Other NGOs such as the Environmental Development Foundation (in Bahasa Indonesia: *Yayasan Bina Usaha Lingkungan*) and WWF Indonesia were also involved.

[6] IBEKA (*Institut Bisnis Ekonomi Kerakyatan*) was founded by Tri Mumpuni, a social entrepreneur and philanthropist who has been involved in the development of hydropower electricity for more than half a million people in Indonesia.

While international donors and private companies played important roles, government initiatives remained more prominent overall. By the mid-2000s the government started to institutionalize micro-hydro installations under various programs. This included the National Community Empowerment Programme (PNPM[7]) administered by the Ministry of Home Affairs (MOHA) during 2006–2014; the Energy Self-Sustained Village (DME[8]) administered by the MEMR over 2007–2012; and smaller-scale fund allocation programs by other ministries. The Ministry of Finance (MoF) and MEMR also implemented a Special Purpose Grant (DAK[9]) for rural energy in 2013–2018. The DAK has been funded through the state budget and provided opportunities for governors in Indonesia to apply for funds for the development and utilization of RE for rural electrification in their regions. Through these programs, hundreds of micro-hydro systems have been installed.

Unfortunately, due to poor data management and coordination, there are no exact records on the total number of micro-hydro systems in Indonesia, their sizes, or their exact dates of opening. According to IMIDAP [27], almost 500 units of micro-hydro totaling ~ 15 MW were built during 1980–2010. About 437 of these units (totaling about 10 MW) have capacities of less than 100 kW each. According to GIZ surveys, there were 357 micro-hydro units totaling about 9.5 MW built over 2009–2017, producing output to meet the electricity needs of almost 38,000 households [30]. Assuming capital expenditure (including the cost of logistic transportation to remote regions and network connection to each household) of USD 4000–6000 kW [31], it is estimated that around USD 40–60 million was mobilized from various sources for micro-hydro infrastructure in Indonesia over 2009–2017.

Successful cases of SHP-based rural electrification projects

There are hundreds of examples of sustainable micro-hydro projects supported by grant schemes in Indonesia. With the community at the heart of any sustainable rural electrification experience, the capacity to maintain systems has been of paramount importance. Five-dimensional sustainability risks can arise from the inability of communities to manage assets either technically (due to, for example, limited access to supply chains for spare parts), financially (e.g. the revenue based on electricity fee payment is unable to cover O&M costs), socially (e.g. a lack of sense of belonging and beneficiary unwillingness to pay for electricity), environmentally (e.g. limits to water resource availability), or institutionally (e.g. lack of knowledge and education of the community). Similar was found in previous research in Indonesia and elsewhere [4, 32–34].

A notable concern is that some micro-hydro projects have been abandoned when the grid infrastructure of the electricity utility, PLN, has reached the area. To seek to reduce this issue, MEMR Regulation No. 39/2017 (amended by MEMR Regulation No. 12/2018) was issued to enable government-funded micro-hydro projects to be connected to the grid to sell their electricity. However, a lack of understanding by communities and operators with regard to electricity sales has created challenges. Many rural communities are unfamiliar with electricity sales regulations and how to establish legal business entities such as cooperatives or village enterprises in order to conduct commercial business with PLN.[10] Moreover, delays in SHP asset handovers from the MEMR to the regional government and communities (as beneficiaries) have led to unclear asset ownership and legal statuses. By regulation, the asset handover process has to go through inspection and verification procedures of the MoF. For any asset valued at over Rp 10 billion, approval needs to be granted by the President of Indonesia [35].

Several NGOs such as IBEKA have been actively promoting community-empowered micro-hydro. This concept involves the community from planning through to operational processes so as to nurture a sense of belonging. Meanwhile, GIZ through EnDev has promoted the productive use of energy by village beneficiaries through pilot projects. By encouraging the use of electricity for income-generating activities, it is expected that communities will in turn seek to maintain the continuity of micro-hydro operations.

Two case studies were researched for this paper: Kamanggih village and Tepal hamlet. The first emerged via cooperation between HIVOS (a Dutch NGO) and IBEKA. The second was a government initiative.[11]

[7] PNPM (*Program Nasional Pemberdayaan Masyarakat)* is a national poverty alleviation program primarily based on community empowerment.

[8] DME (*Desa Mandiri Energi)* refers to the Energy Self-Sustained Village Program managed by MEMR, which has aimed at encouraging villages to meet their own energy needs, create jobs, and reduce unemployment and poverty by boosting the capacities of communities and users of local resources.

[9] DAK (*Dana Alokasi Khusus)* is a special purpose grant from the central government for the construction of specific projects.

[10] Discussion with a panel of experts including the Kamanggih Service Cooperative and a Focus Group Discussion on Rural Electrification Solution *(Solusi Listrik Desa* – "SOLID") attended by central and local government officers and local communities utilising renewables micro-grids including those from Tepal hamlet.

[11] The locations of Kamanggih and Tepal hamlet can be seen in Fig. 4.

Fig. 2 The Bakuhau micro-hydro in Kamanggih village, Sumba island (left and center). The electricity service helps communities to work on peeling candlenuts during the night-time (right)

37 kW micro-hydro in Kamanggih village, Sumba island, East Nusa Tenggara

IBEKA and HIVOS installed a 37 kW micro-hydro project in a hamlet named Bakuhau, in Kamanggih village, Sumba island, East Nusa Tenggara province. The plant was built in 2011 as an off-grid rural electrification project under the Sumba Iconic Island Initiative to provide electricity to 100 non-electrified households, a church, and a water pump as a source of clean water. It was to be operated 6 pm–6am daily. About 80 of 100 households installed a 0.5-A circuit breaker (125 VA) connection, paying a flat fee of Rp 25,000 per month for the electricity—equivalent to about USD 2/month using the 2011 exchange rate of Rp 12,500/USD. About 20 households installed a 2-A circuit breaker (450 VA), with a flat payment of Rp 85,000 per month (USD 6.8/month).

During our 2016 site visit it was observed that almost all households that were connected to the project used electricity for lighting, cell phone chargers, and television. Some also used it for other productive activities such as operating chainsaws.[12] IBEKA and HIVOS empowered a village cooperative, Kamanggih Service Cooperative, to create and facilitate community ownership of the micro-hydro. As the plant was designed to be handed over to the cooperative, the community was actively involved from an early stage, including in construction. The revenue from electricity sales was managed by the cooperative and used for O&M purposes (Fig. 2). Two young villagers received vocational high school scholarships for a course on electricity so that they could become operators.

At the end of 2013, PLN, which had previously only supplied electricity to the foothills and village center via a high-cost and old diesel power plant, began to expand its electricity service to the entire Kamanggih village. PLN sought to negotiate with the community cooperative to connect the micro-hydro to PLN's local grid under a power purchase agreement (PPA). A deal was finally agreed, with an electricity sales price of Rp 475/kWh (US 3.8 cents/kWh). In accordance with the PPA, the community cooperative would retain the responsibility to operate the micro-hydro. PLN was obliged to (i) purchase the electricity and ensure that electricity supply is available for all areas of Kamanggih, 24 h per day, and (ii) support maintenance costs towards ensuring the reliability of the micro-hydro system. Kamanggih became the first 24/7 electrified village on Sumba island, and the community cooperative could earn about Rp 50–60 million per month from PLN on average, which is a relatively sizeable sum. The micro-hydro project is able to save PLN up to Rp 300 million/year while also increasing the breadth of the entity's generation and consumer bases.[13]

25 kW and 40 kW micro-hydro in Tepal hamlet, Sumbawa island, West Nusa Tenggara

The Ministry of Cooperatives and Small and Medium Enterprises (MCSME) has implemented a micro-hydro program with the aim of improving the community's welfare under cooperatives. Electricity provision was never the sole intention. Instead, cooperative establishment is central to this program, with a power plant being perceived as an enabler for other productive activities. Under this scheme, cooperatives are responsible for managing the power plant, while ensuring its utilization is predominantly for income-generating activities.

Ngengas Multi-Business Cooperative (KSU Ngengas)[14] in Tepal hamlet is an example of a successful case. A 25 kW micro-hydro system was built in 2010 with funding from the MEMR to deliver electricity access to 279 households and 20 businesses. Three years later, the MCSME funded another system of 40 kW capacity. Tepal micro-hydro is utilized mainly to support the production of the hamlet's biggest commodity: coffee. KSU Ngengas is responsible for coordinating services and repairs.

[12] According to the site visit and also discussions with the local communities, IBEKA, and Kamanggih Service Cooperative.

[13] This calculation assumes 24-h daily electrification with a daily average load of 25 kW and alternative diesel consumption of 0.25 L/kWh cost at Rp 10,000/liter (including transportation).

[14] KSU Ngengas refers to Ngengas Multi-business Cooperative (*Koperasi Serba Usaha Ngengas).*

Table 1 Government regulations for rural electrification using renewable energy

Element	Content						
MEMR Regulation No (revision of the previous regulation)	38/2016	50/2017 (53/2018)	10/2012	Presidential Decree No. 47/2017	33/2017 (05/2018)	39/2017 (12/2018)	02/2012 03/2013 10/2015 03/2016 03/2017 36/2018
Topic	Acceleration of electrification in underdeveloped, remote, and border rural areas, and inhabited small islands through small-scale electricity supply	Utilization of renewable energy for electricity supply	Infrastructure development using renewable energy	Provision of pico PV lanterns for households without access to electricity	Provision of pico PV lanterns for households without access to electricity	Infrastructure development using renewable energy	Operational guideline for the Special Purpose Grant (DAK) for small-scale energy
Type of infrastructure	**Commercial**			**Non-commercial**			
Source of funds	Investment from the private sector and state-owned companies			National budget			Special Purpose Grant (DAK)
Type of technology	On-grid, communal off-grid systems powered by solar PV, hydro, wind, bioenergy, ocean energy			On-grid, communal off-grid systems powered by solar PV, hydro, wind, bioenergy, ocean energy, PV pico lanterns			

Source: Indonesian government regulations

When the system broke in 2014, the cooperative repaired it without external support. In 2017, an ASEAN Energy Award was given to KSU Ngengas in recognition of their success in managing the plant.

Lessons learned from micro-hydro-based rural electrification programs

The 1970s–early 2000s period was important for developing human capacity in micro-hydro technology and collaboration among actors in local and bottom-up activities, with national and international development support resulting in the establishment of many projects. The period saw labor specialization in SHP, job creation, the development of local production networks in turbine manufacturing, and institutional capacity building.

Beyond the 2000s, government initiatives have further accelerated the development of micro-hydro for rural electrification. International support has again been a significant part of the story. Pilot projects have helped to spur learning-by-doing and the boosting of institutional capacities. The projects were linked to various income-generating business schemes with the objective of creating a strong and self-reliant institutional set-up to ensure the sustainability of projects.

Not all projects have been successful, with some falling into disrepair or being abandoned. Failure of government-initiated micro-hydro projects has often been due to a focus on headline numbers rather than sustainability or service quality [36]. The cases of Kamanggih and Tepal indicate that the sustainability of these projects is linked to the economic value created by electricity-consuming activities. Thus, it is important that the development of micro-hydro and other rural electrification infrastructure consider pairing with income-generating activities. Examples from the case studies include electricity-based revenue through a PPA in Kamanggih and also the local coffee business in Tepal. The support of developmental agencies in feeding knowledge into the projects via forms of capacity building such as training, workshops, and peer-to-peer learning has also been important in both cases. Community capacity to manage the system has been vital for project sustainability.

The decision to either expand the grid to remote villages or develop off-grid SHP depends largely on the distance between the PLN grid, the hydro resource, and the rural settlements. A decentralized off-grid SHP project can be most effective for remote places that PLN's grid will not reach during the next 5–10 years under the annual PLN Electrification Plan. Another consideration is to what extent the SHP project can lower the average electricity generation cost. For reference, Table 1 presents government regulations regarding RE utilization (including hydropower) for rural electrification.

Commercial MHP schemes (early 2010s–present)

Most commercial SHP schemes are MHP projects of more than 1 MW capacity. The 2010s onwards has seen increasing private-sector interest in the development of MHP under the IPP framework for electricity sales to PLN. The trend is also partly in response to a government target to achieve a 23% renewable share in primary energy (excluding traditional biomass) by 2025 and also national greenhouse gas (GHG) emissions reduction targets. MHP is the fourth-largest contributor of renewable electricity capacity in Indonesia—after large hydropower, geothermal, and biomass—with a total (estimated) installed capacity of 486 MW (Table 2) [37]. Overall MHP capacity is more than three times the overall micro hydro capacity. Figure 3 summarizes the historical development of SHP in Indonesia.

Discussion

We here first discuss the constraints to IPP-based MHP projects in Indonesia. Key barriers from regulatory, economic-financial, and technical points of view—the three most crucial dimensions for sustainable technology adoption and use [38, 39]—are identified. We then discuss the key issues and reform options for boosting the development of SHP and renewable energy more generally in Indonesia.

Regulatory barriers

Inconsistent and unclear supporting regulations, especially regarding electricity pricing, have been a consistent feature of Indonesia's SHP sector. Since 2002, when the government via the MEMR allowed small-scale distributed generators to start selling electricity to PLN, the pricing regulations for SHP have changed as many as eight times. National energy policies were issued in 2006 (targeting a minimum of 5% RE shares of the national energy mix by 2025) and 2014 (23% RE shares by 2025).[15] Business-to-business (B2B) and feed-in tariff (FIT) arrangements have also displayed great inconsistency over time.

In relation to Table 3, the SHP project's power purchase agreement (PPA) models are not uniform. The majority apply a take-and-pay scheme that sets out that PLN has the right not to pay for the electricity to the developers for around 300 h per year (about 3.5% of the total hours in a year). This results in uncertainties in the revenue streams of developers, especially in the case that a grid outage happens during the rainy season when a

[15] The national RE target was at first regulated by the Government Regulation (GR) No. 5/2016 in which the government committed to meeting 5% by 2025. This was later amended by GR No. 79/2014 to target a 23% RE share by 2025.

Table 2 Installed capacity of non-RE (upper) and RE (lower) power plants in Indonesia (MW) (2017–2021)

Year	Coal-fired PP	Mine-mouth CFPP	Oil/gas fuel steam PP	Gas PP	Gas-steam/combined cycle	Gas machine	Diesel	Hydropower
2017	26,733.1	1975.0	2060.0	4976.2	10,418.5	2264.9	4396.4	5343.6
2018	27,486.2	2041.0	2060.0	5348.4	11,220.1	2357.7	4630.9	5399.6
2019	30,406.2	2271.0	2060.0	5348.4	11,669.5	2842.0	4779.7	5558.5
2020	32,336.9	2271.0	2060.0	5348.4	12,235.7	3177.9	4863.5	5638.7
2021	32,705.4	2271.0	2060.0	5348.4	12,411.5	3207.3	4986.6	5988.7
Year	**Mini hydro**	**Micro hydro**	**Wind**	**Biogas**	**Biomass**	**Geothermal**	**Solar PV**	**Waste-to-energy**
2017	240.6	103.8	1.5	100.6	1740.5	1808.3	50.9	15.7
2018	267.8	104.8	143.5	108.6	1758.5	1948.3	60.2	15.7
2019	311.1	106.4	154.3	112.4	1758.5	2130.7	145.8	15.7
2020	375.8	106.4	154.3	117.8	1762.0	2130.7	147.3	15.7
2021	486.7	126.4	154.3	134.8	2116.2	2286.1	201.1	28.5

PP means power plant. These numbers include both on-grid and off-grid power plants. Biogas and biomass are typically under self-use for industries and excess-power contracts. Source: [37]

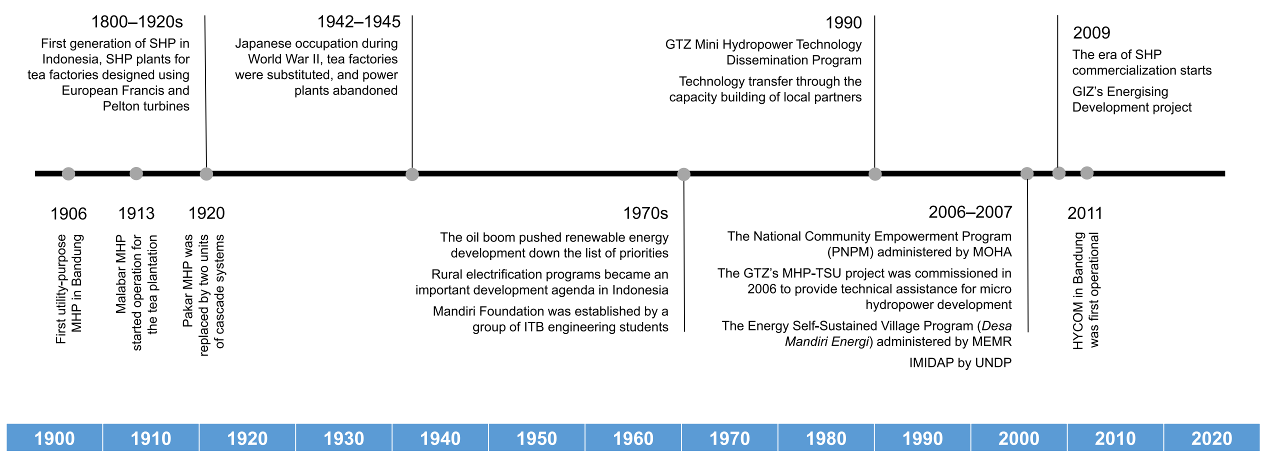

Fig. 3 Historical timeline of small hydropower development in Indonesia

run-of-river SHP project reaches optimum production. As an example, in 2020 PLN sent a negative signal to developers by curtailing SHP electricity production in North Sumatra.[16]

There have been persistent differences in perceptions on appropriate tariff settings for RE electricity pricing between the government, PLN, and investors. Quite naturally, project investors have wanted a high FIT to attain a more attractive investment return. However, a high tariff has been argued against by PLN on the grounds that it will lead to losses for the utility. The key underlying constraint faced by PLN is an inability to directly or easily pass through any increment to costs incurred when paying feed-in tariffs due to Indonesia's rigid system of retail electricity tariff setting.

In 2016, a potential breakthrough arose when the MEMR proposed an energy security fund. Under this approach, the government would collect funds via a surcharge on retail fossil fuel prices, in particular for diesel and gasoline, and use the funds for clean-energy FITs. However, the plan faced public controversy and opposition, forcing its cancellation. In late 2016, the MEMR instead proposed a budget allocation to subsidize the FIT gap. However the House of Representatives rejected the proposal, being of the view that subsidies originating from the State Budget should be for subsidizing electricity for poor families rather than subsidizing the costs of technology and electricity generation [40].

[16] See https://www.thejakartapost.com/news/2020/07/01/it-sends-a-negative-message-hydropower-players-lament-pln-power-cap-in-sumatra.html.

Table 3 Key features and comparison of regulations on SHP in Indonesia

Key features	MEMR Regulation No.[a]								PR No. 112/2022
	1122/02	02/06	05/09	31/09	04/12	12/14	19/15	50/17	
Sector targets	Small business/ cooperative	Private investors allowed							
Aims	Electrification	Commercial and business, contributing to the achievement of national RE target							Improve investment, accelerate RE and GHG emission reduction target
Procurement	Direct appointment							Direct selection	Direct Appointment or direct selection depends on the cases
Max. allowed capacity (MW)	1 MW	10 MW							Allow more than 100 MW
Tariff	Business-to-business			FIT at Rp 656/kWh multiplied by a factor of F ranging from 1.0 to 1.6 referring project location. F (Java) is 1.0, the F is higher for outside Java, esp. Eastern Indonesia		FIT at Rp 1.075/kWh multiplied by a factor of F	USD-based FIT at US 12c/kWh aiming at increasing attractiveness	Business-to-business	The tariff is set in cents USD/kWh (payment will be Rupiah denominated). The tariff is set based on capacity, staging, and multiplied by F
Asset transfer scheme	Not regulated refers to build-own-operate (BOO)							BOO and later transfer to PLN at the end of the PPA period (BOOT). Under the 2020 amendment that BOOT/BOO shall follow negotiation and not be regulated, this is also applied to PR No. 112/2022	
Additional remarks	The first RE regulation in Indonesia, known as small-scale distributed RE generation/*PSK Tersebar*	Obligation for PLN to purchase RE-based electricity		• Obligation for PLN to purchase RE-based electricity • Incentivize private investment in Eastern Indonesia with higher F • Beginning of dispute between MEMR and PLN regarding the FIT price			The regulation was ineffective and was held by PLN due to a tariff dispute	Some regions become unfavorable for the MHP project due to too-low tariffs	Covers broad ranges of capacity and types of RE technology, The F (as a location factor) is re-introduced, similar to the previous FIT regulation in 2009–2012

[a] The regulation number refers to number and year, all the regulations can be found at MEMR's regulation database at http://jdih.esdm.go.id

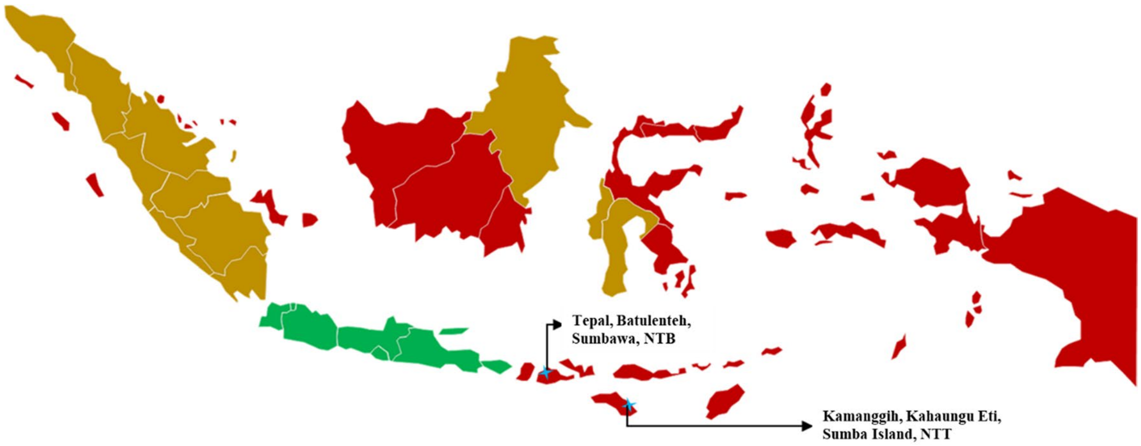

Fig. 4 Average generation cost of PLN's main areas/sub-systems across Indonesia, 2018 (referring to the MEMR Decree No. 55/K/MEM/2019). The figure shows three groups: low cost (≤ US 7 cents/kWh; green); medium cost (> 7 but < 12 US cents/kWh; gold); and high cost (≥ US 12 cents/kWh; red). The medium (gold) and low-cost areas (green) include some smaller local sub-systems with a high average generation cost. The average generation cost was US 7.86 cents/kWh. The non-subsidized PLN retail tariff was US 9.96 cents/kWh

In 2017, a new Energy Minister enacted a new tariff mechanism under MEMR Regulation No. 50/2017. The mechanism capped RE tariffs (including for MHP projects) at the local average electricity generation cost in many areas, with the determination of the exact tariff based on negotiation between PLN and investors. The regulation also obligated PLN to publish their electricity generation cost for each sub-system each year.

MEMR Regulation No. 50/2017 meant that some regions became unfavorable for MHP projects due to the low tariff that was available. Systems in Eastern Indonesia and other isolated areas remained theoretically feasible, but in fact not all were technically feasible due to low demand and limited supporting infrastructure for electricity transmission and distribution. Although some PPAs were successfully signed, many projects failed to obtain financial support [41–43]. The Minister maintained that the policy was an effort to create market fairness and that no policy could favor everyone.

Figure 4 shows average electricity generation costs in 2018. Generation costs were lowest in Java, where electricity mainly comes from large coal-fired plants. Eastern Indonesia and other isolated sub-systems are mainly dominated by high-cost power generation including diesel.

In late 2022, close to the kick-off of the G20 Bali Summit, Presidential Regulation (PR) No. 112/2022 on the Acceleration of Renewable Energy Development for Power Supply was issued, superseding MEMR Regulation No. 50/2017. The issuance of this regulation was concurrent with Indonesia signaling its prioritization of renewable energy and coming to a thermal coal phase-down over the coming decades.[17] PR No. 112/2022 combines aspects of several previous regulations and sets out the SHP tariff under a negotiation-based ceiling tariff mechanism that involves multiplication by a location factor (F) that ranges from 1.0 (Java) to 1.50 (Papua), as shown in Table 4. For some regions, the new regulation implies a more attractive ceiling tariff. Nevertheless, a negotiation process still remains, posing some uncertainties. It thus remains unclear whether the new regulation will be able to spur additional RE investment. Despite some evolutions in detail, the overall tariff regime

Table 4 Electricity purchase price from hydropower plants that utilize power from water streams/waterfalls, PR No. 112/2022

No.	Capacity	Highest benchmark price (US cents/kWh)	
		Years 1–10	Years 11–30
1	up to 1 MW	11.23 × F	7.02
2	> 1 MW up to 3 MW	10.92 × F	6.82
3	> 3 MW up to 5 MW	9.65 × F	6.03
4	> 5 MW up to 20 MW	9.09 × F	5.68
5	> 20 MW up to 50 MW	8.86 × F	5.54
6	> 50 MW up to 100 MW	7.81 × F	4.88
7	> 100 MW	6.74 × F	4.21

F is the location factor and ranges from 1.0 (Java) to 1.5 (Papua)

[17] See https://www.reuters.com/article/indonesia-climate-coal-policy-idINL5N2W10JG.

remains relatively similar to the FIT regulations that had been in place during 2012–2015.

The MEMR has also enforced a domestic market obligation (DMO) policy for coal in Indonesia. This has required 25% of domestic coal production to be reserved for electricity generation at a price capped at about USD 70/ton or below, depending on the coal type (e.g. calorific value, moisture content, ash content, and other measurement values). Among the aims is to secure domestic coal needs and reduce price volatility. The effect is to encourage the use of coal for electricity generation, slowing the adoption of cleaner generation sources.

The government has also facilitated the ramping up of coal production by increasing the annual coal production quota over time. As of 2020, this quota was 550 million tons. It was initially planned to increase rather slowly and be capped at 628 million tons in 2024 [44]. However, in 2021 the government increased the coal quota production to 625 million tons with the aim of boosting economic recovery during the COVID-19 pandemic [45]. More recently, the Government has expressed intent to ease the coal price cap policy for PLN by substituting it with a levy for coal exports that will be collected and channeled to subsidize PLN's coal price. As of early 2023 this is yet to happen, however.

Economic-financial barriers

An MHP project requires intensive capital expenditure—roughly around USD 2–2.5 million per MW, mostly for civil works and machinery (the turbine and generator). Funds must also be available to cover possible cost overruns. This can be a challenge to finance given that many MHP concessions are owned by small- or medium-sized local enterprises with insufficient capacity, experience, and capital to access financing support from banks.[18]

From the banks' perspectives, project risks mean that MHP development has often been deemed to be unattractive. Most local commercial banks typically work on the basis of mortgage asset-based lending, which requires the investor to pledge asset collateral. Non-recourse project finance is rarely available. Local banks also commonly request a sponsor's credit guarantee. The IDR-based lending interest rate is also quite high—typically 10–13.5% per annum.[19]

The establishment of PT Sarana Multi Infrastruktur (SMI), a state-owned enterprise (SOE) under the MoF, and PT Indonesia Infrastructure Finance (IIF), a joint-venture company between PT SMI and several international banks (including ADB, IFC, KfW-DEG, and SMBC), in 2009 sought to catalyze infrastructure financing in Indonesia, including in supporting renewables financing in more flexible and innovative ways.[20] Additionally, the Indonesian Financial Services Authority has also encouraged local banks, financial institutions, and emitters to diversify their financing portfolios and invest in financial instruments or projects that are in line with the implementation of sustainable finance principles and environmental social governance (ESG).[21]

Several SOEs and private entities have also started to become involved in the MHP sector for business diversification purposes and as a green project initiative. Among them are companies originally engaged in construction such as Brantas Abipraya (SOE) and Kalla Group (private); private conglomerate business groups like Tamaris Hydro and Kencana Energy (KEEN);[22] and well-known business groups in the oil, gas, coal, and large-scale power sectors such as Medco Energi [46] and Toba Bara [47]. The presence of these well-pocketed and professional parties has gradually increased local banks' appetites to finance the MHP sector.

Technical barriers

Although SHP is a mature and robust technology, technical barriers are commonly faced during project development, often resulting in cost overruns. The risk profile reduces but does not disappear as the project reaches the operational stage. Technical barriers typically include:

a. Limited technical experience and capability of project developers and project sponsors.
b. Natural-related threats such as floods, earthquakes, and landslides are highly relevant considering that SHP projects are site-specific. An interviewed project developer said that they had given up on one of three cascade SHP projects in southern West Java following a severe earthquake and landslide.
c. Insufficient and incomprehensive technical feasibility studies including geology and land investigation that result in unmitigated construction risks and cost requirements.

[18] Discussion with our panel experts including project developers, banks, and NGOs, as well as several public focus group discussions run by the Ministry of Energy and Mineral Resources.

[19] Discussion with our panel experts including several banks and project developers.

[20] PT SMI (www.ptsmi.co.id) and its subsidiary, PT IIF (www.iif.co.id), are non-bank financial institutions dedicated to support the financing, investment, and preparing national infrastructure projects.

[21] The Indonesian Financial Services Authority *(Otoritas Jasa Keuangan* – "OJK") Regulation No. 51/0217.

[22] Kencana Energy (KEEN) is one of two IPP companies (along with Terregera/TGRA) that have listed in Indonesian Stock Exchange Market, the information can be accessed via https://kencanaenergy.com.

d. Constraints on supporting infrastructure, such as road access, transmission grid links, and precipitation and discharge gauging stations, which may impact project design.
e. Limited electricity demand in areas surrounding SHP projects.

In 2017, a policy was introduced by the Ministry of Public Works (MoPW) to encourage private investors to convert existing government-owned irrigation reservoir projects to SHP projects.[23] This aimed at overcoming technical and other barriers, although any negative effects on food production would be an important consideration [48–50]. To date, one project has been in operation, the Lodagung 2×650 kW. There were 3 pilot projects to be constructed in 2021: the Batanghari 5.1 MW (West Sumatera), Titab 1.27 MW (Bali), and Pandan Duri 580 kW (Lombok, West Nusa Tenggara) [51].

There are several broad reform options for boosting the development of SHP and renewable energy more generally in Indonesia, as will now be explored.

Capacity building

Capacity building and knowledge dissemination play an important role in the adoption and sustainability of SHP projects [52, 53]. Currently, such activities are mostly scattered and lack organizational sustainability. Institutionalizing a capacity-building function for local projects is a key priority, including the establishment of vocational education, technical certification, and centers of excellence. Successful experiences with various international organizations as discussed in this paper could be built upon. NGOs can play an essential role in this endeavor.

Policy and financial de-risking

The government has various options to reduce costs and uncertainties surrounding applicable policies and risks for project developers (and banks) ("de-risking") [54]. Robust and long-term policies for RE, including pricing policy, are important.[24] Clear and transparent procurement methods, streamlining of regulation and permit procedures, and more generous rules for access to grid connections and electricity dispatch could also make a major difference. The establishment of public–private partnerships (PPPs) for RE could also be considered in some cases [55]. Indonesia could also consider a renewable portfolio standard (RPS) approach, which has spurred the uptake of distributed energy in some other countries [56]. Examples of financial de-risking include the provision of technical assistance for project due-diligence processes; risk-sharing instruments; concessional financing facilities; risk-based interest subsidy; and other insurance mechanisms. Improved ability for PLN to charge cost-reflective tariffs is also an important reform agenda.

Additionally, to deliver a better risk-sharing allocation between developers and PLN, a fairer PPA concept under a take-or-pay approach could be adopted. The PPA could be based on annual firm capacity or annual electricity output and reviewed and agreed between PLN and developers annually. During any grid outage or other event during which PLN cannot take available output (with details to be set out in the PPA), PLN would be subject to a "deemed dispatch". Other than in the case of *force majeure*, PLN would still be required to make a payment. In the other direction, PLN could also receive compensation from the developer if they fail to meet a minimum of 90% of their production declaration, for example. The higher the threshold, the more challenging for the developer—thus encouraging developers to make more precise production declarations.

The roles of stakeholders

There are many stakeholders involved in renewable energy development in Indonesia, playing either direct or indirect roles. Table 5 presents recommendations for selected key stakeholders in the Indonesian energy sector, with a focus on SHP development.

An independent electricity regulator and a renewable energy agency

The absence of an independent energy regulator or Energy Commission to oversee the planning and operation of Indonesia's electricity sector is often seen as a major issue [57, 58]. Indonesia's electricity sector is PLN-centrist, with the utility taking control of electricity planning, procurement, supply, and distribution. Transparency, accountability, and good corporate governance have come into question. The existence of an independent regulator could help to balance the needs of consumers, producers, off-takers, and other stakeholders. A renewable energy agency for planning, procurement, capacity building, research and data management, as well as securing international financing cooperation, could also be considered [59]. Malaysia has a Sustainable Energy Development Agency (SEDA) [39, 53, 60].

[23] MoPW Regulation No. No. 9/PRT/M/2017 on Procedures for the Cooperation of Business Entities in the Leasing of Dams for the Acceleration of Power Projects.

[24] Pricing could be via negotiations, a fixed feed-in tariff, or reverse auctions. However reverse auctions may introduce additional implementation and participation costs than a simpler feed-in tariff for what are small projects.

Table 5 Recommendations for selected stakeholders in the Indonesian SHP sector

Stakeholder	Tasks in the energy sector	Recommendations
National Energy Board (DEN)	Design and formulation of the National Energy Policy, and supervision of the implementation of cross-sectoral energy policies	• Include SHP in national energy planning • Provide advice on Indonesia's electricity market regulations
MEMR	Formulation, implementation, control, and supervision of energy policies	• Provide supportive and attractive regulations for SHP both for the off-grid rural electrification and commercial use • Clear pricing regulations • Ensure implementation of mechanisms that price negative externalities from fossil fuel projects
MOF	Approval for energy program budget, formulation of fiscal incentives for renewable energy, formulation of electricity subsidies, and RE pricing	• Encourage fiscal and tax incentives for SHP projects, both for private investment and the grant-based SHP for rural electrification • Tax negative externalities from fossil fuels
Ministry of Industry	Formulation of local content requirements for the power sector	• Ensure that local content regulations do not overly impede the ability of the clean energy industry to develop
State Utility, PLN	The main actor in the electricity provision with an authority over the generation, transmission, and distribution of electricity; development and implementation of the annual Electricity Development Plan (RUPTL)	• Improve the market practice of procurement and electricity sales transactions • Improve derivative regulations and market guidelines for RE project development including developing a uniform and attractive PPA model for SHPs that is fair in risk-sharing allocation
Industry associations	Networking among the members and other players in the sector, providing inputs to policymakers, and giving a collective voice to the industry	• Share best practices among members, showing best practices of successful SHP projects to the public
International development agencies	Providing technical and financial aid for policy advisory, capacity development, as well as infrastructure development	• Continue to scale up their technical and financial assistance in the SHP sector
Non-governmental organizations (NGOs)	• Empowerment of civil society to engage and participate in the implementation of energy programs • Community engagement and representation in various energy-related forums	• NGOs can play a role by disseminating good information and knowledge to the public regarding the importance of SHP development in Indonesia
Academician, researchers	Research, forward-looking think tanks, and development of innovations in technology and socio-economic aspects	• Research that aims at devising data-driven policy recommendations for SHP development

Pricing environmental externalities

A missing factor in RE policy setting in Indonesia has been that the environmental costs of fossil fuel power plants have historically been socialized rather than directly priced. Fossil fuels are a source of negative externalities in the form of global and local pollutants, causing health and other economic costs. Other countries have introduced carbon prices or charges on fossil fuel use. India, for example, has a levy on coal [61]. Japan and Singapore apply carbon taxes, and South Korea and China have emission trading schemes. Prices on emissions would ameliorate the negative effects of underpriced resource use and improve fiscal capacities. The main implementation challenges are political and institutional [62, 63].

Among recent developments, Indonesia introduced a carbon pricing policy under Law No. 7/2021 on Tax Regulatory Harmonization [64]. Delays in implementation were seen, however, although coal-fired power plants (CFPPs) were involved in a voluntary carbon trading pilot in 2021. It was not until February 2023 that Indonesia launched the first phase of a mandatory emissions trading system (ETS) for the power generation sector. This initially covers only CFPPs of at least 100 MW.[25] It remains too early to assess the effectiveness of this scheme.

Conclusions

Indonesia is rich in RE resources, yet energy access issues remain and there is a need to boost the use of clean energy. SHP is a source of clean and reliable RE with a high energy yield and a low environmental impact. It is particularly useful for generating dispatchable electricity in remote locations. The historical record of the use of SHP in Indonesia during the East Indies era, followed by the evolution of its use as a rural electrification solution and commercial scheme under the IPP framework, has highlighted how SHP can be an appropriate and reliable alternative energy supply in the context of Indonesia.

Although SHP will remain small from a macro perspective and will not exhibit the type of rapid cost reductions being witnessed for solar panels and wind turbines, it could play a more significant role than it currently does, both in Indonesia and elsewhere [65]. Key initiatives to facilitate this development could include local-level capacity building and project participation, the use of risk reduction mechanisms, and the pricing of negative externalities from fossil fuel projects. The sustainability of projects is highly important. For that, a good business model and strong local community participation in ownership and maintenance are needed.

Future research could further explore the sustainability of recent SHP projects and other distributed energy projects in Indonesia, including solar photovoltaic (PV) projects. Cost–benefit analysis for grid interconnection and studies on the potential to apply hydropower technologies with other renewable energies such as solar photovoltaics, including via small- and medium-scale off-river pumped hydro storage projects [66, 67], could also be pursued. The usefulness of SHP projects in promoting ongoing electrification in remote regions could also be explored as part of understanding pathways toward universal clean energy, including for example for cooking [68]. If clean energy projects such as SHP projects are able to perform well in terms of both adoption and sustainability, the transition away from diesel and other fossil fuels in rural and remote locations will be able to occur much more smoothly [69, 70].

[25] See https://www.reuters.com/business/energy/indonesia-launches-carbon-trading-mechanism-coal-power-plants-2023-02-22.

Abbreviations

5P	Pro-poor public–private partnership
ACE	ASEAN Centre for Energy
B2B	Business-to-business
BOO	Build-own-operate
BOOT	Build-own-operate-transfer
CFPP	Coal-fired power plant
CINTEK	*Cihanjuang Inti Teknik*
CSR	Corporate social responsibility
DAK	*Dana Alokasi Khusus*/Special purpose grant
DME	*Desa Mandiri Energi*/Energy self-sustained village
EnDev	Energising Development
FIT	Feed-in tariff
GEF	Global environmental facility
GHG	Greenhouse gas
GIZ	*Deutsche Gesellschaft für Internationale Zusammenarbeit*
GTZ	*Deutsche Gesellschaft für Technische Zusammenarbeit*
GTZ-MHPP	GTZ Micro-Hydro Program
HYCOM	Hydropower Competence Centre
IBEKA	People Centered Business and Economic Institute
IIF	Indonesia Infrastructure Finance
IMIDAP	Integrated Micro Hydropower Development and Application Program
IPP	Independent power producer
ITB	Bandung Institute of Technology
JICA	Japan International Cooperation Agency
KfW-DEG	German Investment and Development Corporation
KOICA	Korea International Cooperation Agency
MEMR	Ministry of Energy and Mineral Resources
MHP	Mini hydropower
MHP-TSU	Micro Hydro Power Technical Support Unit
MoF	Ministry of Finance
MOHA	Ministry of Home Affairs
NGO	Non-governmental organization
O&M	Operations and maintenance
PLN	*Perusahaan Listrik Negara*/State Electricity Enterprise
PNPM	*Program Nasional Pemberdayaan Masyarakat*/National Community Empowerment Programme
PPN	*Pusat Perkebunan Negara*/National Estate Center
PTPN	*PT Perkebunan Nusantara*/State Plantation Enterprise
RE	Renewable energy
ROT	Rent-operate-transfer
RPS	Renewable portfolio standard

SEDA	Sustainable Energy Development Agency
SGP	Small Grant Programme
SHP	Small hydropower
SMI	*Sarana Multi Infrastruktur*/State-owned infrastructure financing company
TEDC	Technical Education Development Centre Bandung
UNDP	United Nations Development Program
UNESCAP	United Nations for Economic and Social Commission for Asia Pacific
WSHDR	World Small Hydropower Development Report

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Author contributions
NR initiated the research during 2015–2016 and conducted field visits to several locations. PJB was involved in the write-up of the research. AS, MH, and MP contributed supporting information, especially on the topic of micro hydropower and rural electrification. NR, AS, MH, and MP worked for the GIZ Energy Programme Indonesia during 2016–2019.

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References
1. Sovacool BK, Bulan LC (2012) Energy security and hydropower development in Malaysia: the drivers and challenges facing the Sarawak Corridor of Renewable Energy (SCORE). Renew Energy 40(1):113–129
2. Paish O (2002) Small hydro power: technology and current status. Renew Sustain Energy Rev 6(6):537–556
3. Kumar A et al. (2011) Hydropower. In: Diaz Morejon C, Krug T (eds) International Panel on Climate Change (IPCC) Special Report on Renewable Energy Sources and Climate Change Mitigation, Cambridge University Press, New York: 437–496.
4. Yadoo A, Cruickshank H (2012) The role for low carbon electrification technologies in poverty reduction and climate change strategies: a focus on renewable energy mini-grids with case studies in Nepal, Peru and Kenya. Energy Policy 42:591–602
5. Mishra MK, Khare N, Agrawal AB (2015) Small hydro power in India: current status and future perspectives. Renew Sustain Energy Rev 51:101–115
6. Uddin W et al (2019) Current and future prospects of small hydro power in Pakistan: a survey. Energy Strateg Rev 24:166–177
7. Kaunda CS, Kimambo CZ, Nielsen TK (2012) Potential of small-scale hydropower for electricity generation in Sub-Saharan Africa. Int Sch Res Not 2012:132606
8. Liu D, Liu H, Wang X, Kremere E (2019) World Small Hydropower Development Report 2019. In UNIDO, World Small Hydropower Development Report 2019, International Center on Small Hydro Power, Hangzhou, China
9. Uhunmwangho R, Okedu EK (2009) Small hydropower for sustainable development. Pacific J Sci Technol 10(2):535–543
10. Nautiyal H, Singal SK, Sharma A et al (2011) Small hydropower for sustainable energy development in India. Renew Sustain Energy Rev 15(4):2021–2027
11. Yüksel I (2007) Development of hydropower: a case study in developing countries. Energy Sources, Part B 2(2):113–121
12. Kumar D, Katoch SS (2014) Sustainability indicators for run of the river (RoR) hydropower projects in hydro rich regions of India. Renew Sustain Energy Rev 35:101–108
13. World Bank & Energy Sector Management Assistance Program (2017) Small hydropower resource mapping in Indonesia: small hydro potential report
14. UNDP, UNDESA, WEC (2000) World Energy Assessment: Energy and the Challenge of Sustainability
15. Shrestha HM (2016) Exploitable potential, theoretical potential, technical potential, storage potential and impediments to development of the potential: the Nepalese perspective. Hydro Nepal J Water Energy Environ 19:1–5
16. Rospriandana N, Fujii M (2017) Assessment of small hydropower potential in the Ciwidey subwatershed, Indonesia: a GIS and hydrological modeling approach. Hydrol Res Lett 11(1):6–11
17. Setiawan D (2015) Potential sites screening for mini hydro power plant development in Kapuas Hulu, West Kalimantan: a GIS approach. Energy Procedia 65:76–82
18. Pratama YW et al (2017) Multi-objective optimization of a multiregional electricity system in an archipelagic state: the role of renewable energy in energy system sustainability. Renew Sustain Energy Rev 77:423–439
19. Widmer R, Roth M, Hayton M, Dernedde S (2001) Hydropower revival in Java's tea gardens. Mt Res Dev 21(1):14–18
20. PTPN 8 (2018) Micro and Mini Hydropower. https://www.ptpn8.co.id/pembangkit-listrik-tenaga-minihidro. Accessed 2 Aug 2021
21. Indonesia Power (2019) Press release No. 14/Release/IP/2019 on Lamajan hydropower, a great heritage for millennial era, operated since 1925. https://indonesiapower.co.id
22. Booth A, McCawley P (1981) The Indonesian economy during the Soeharto era. East Asian Soc Sci Monogr 39(2):xxv–329
23. Hill H (2000) The Indonesian economy. Cambridge University Press, New York
24. Shrestha R, Coxhead I (2018) Can Indonesia secure a development dividend from its resource export boom? Bull Indones Econ Stud 54(1):1–24
25. Munasinghe M (1988) Rural electrification: international experience and policy in Indonesia. Bull Indones Econ Stud 24(2):87–105
26. Hycom (2019) HyCom ASEAN Hydropower Competence Centre. https://energypedia.info/images/9/94/HYCOM_GerhardFischer_HPNET_Webinar_28MAR2019.pdf. Accessed 2 Aug 2021.
27. Global Environmental Facility Integrated Microhydro Development and Application Program (IMIDAP), Part I
28. Sovacool BK (2013) Expanding renewable energy access with pro-poor public private partnerships in the developing world. Energy Strateg Rev 1(3):181–192
29. Wibhawa B (2019) IBEKA's social service delivery model in Indonesia's micro-hydro power. Hum Syst Manag 37(4):387–397
30. GIZ (2020) Rural Electrification Map RE-MAP, *GIZ*, 2020. http://www.remap-indonesia.org

31. Castlerock (2012) Micro Hydro Power (MHP) Return of Investment and Cost Effectiveness Analysis Final Report, Jakarta
32. Purwanto WW, Afifah N (2016) Assessing the impact of techno socioeconomic factors on sustainability indicators of microhydro power projects in Indonesia: a comparative study. Renew Energy 93:312–322
33. Ilskog E, Kjellström B (2008) And then they lived sustainably ever after?—assessment of rural electrification cases by means of indicators. Energy Policy 36(7):2674–2684
34. Urmee T, Md A (2016) Social, cultural and political dimensions of off-grid renewable energy programs in developing countries. Renew Energy 93:159–167
35. Dias P (2017) 142 RE projects stall, presumably because the MEMR plan premature. https://bisnis.tempo.co/read/1043960/142-proyek-ebt-mangkrak-diduga-karena-rencana-esdm-tak-matang. Accessed 15 Jul 2021.
36. Derks M, Romijn H (2019) Sustainable performance challenges of rural microgrids: analysis of incentives and policy framework in Indonesia. Energy Sustain Dev 53:57–70
37. MEMR (2022) Indonesia's Electricity Statistics 2021
38. Beddoe R et al (2009) Overcoming systemic roadblocks to sustainability: the evolutionary redesign of worldviews, institutions, and technologies. Proc Natl Acad Sci 106(8):2483–2489
39. Sovacool BK, Drupady IM (2011) Examining the small renewable energy power (SREP) program in Malaysia. Energy Policy 39(11):7244–7256
40. Zatnika AM (2016) House of Rep. rejected subsidy for renewables. https://industri.kontan.co.id/news/dpr-tolak-beri-subsidi-untuk-energi-terbarukan. Accessed 13 Aug 2021
41. Sulaiman S (2018) Task force to address funding problems in renewable energy. https://www.thejakartapost.com/news/2018/04/30/task-force-to-address-funding-problems-in-renewable-energy.html. Accessed 15 Jul 2021
42. Embu W (2018) RE investors find it difficult to get credit, the government is looking for solutions. https://www.liputan6.com/bisnis/read/3572449/investor-pembangkit-ebt-sulit-dapat-kredit-pemerintah-cari-jalan-keluar. Accessed 15 Jul 2021
43. Ridwan NM (2019) Dozens of RE power plant projects still hanging. https://money.kompas.com/read/2019/04/15/100105726/puluhan-proyek-pembangkit-listrik-ebt-masih-menggantung. Accessed 15 July 2021
44. Umah A (2020) RI coal production in 2020 reach the target or not? https://www.cnbcindonesia.com/market/20201211090222-17-208336/produksi-batu-bara-ri-2020-capai-target-nggak-nih. Accessed 15 Jul 2021
45. Umah A (2021) Official! Coal production target 2021 increase to 625 million tons. https://www.cnbcindonesia.com/news/20210414113240-4-237742/resmi-target-produksi-batu-bara-2021-naik-jadi-625-juta-ton. Accessed 15 July 2021
46. Medco (2023) Operating Assets. https://medcopower.co.id/project-category/operating-assets. Accessed 11 Mar 2023
47. Suryahadi A, Julian M (2021) TBS Energi Utama subsidiary signed a power purchase agreement with PLN. https://investasi.kontan.co.id/news/anak-usaha-tbs-energi-utama-teken-perjanjian-jual-beli-tenaga-listrik-dengan-pln. Accessed 15 Jul 2021
48. Pittock J, Orr S, Stevens L, Aheeyar M, Smith M (2015) Tackling trade-offs in the nexus of Water, Energy and Food. Aquat Procedia 5:58–68
49. Taniguchi M, Endo A, Gurdak JJ, Swarzenski P (2017) Water-energy-food nexus in the Asia-Pacific Region. J Hydrol Reg Stud 11:1–8
50. Zhang X et al (2018) Impacts of climate change, policy and water-energy-food nexus on hydropower development. Renew Energy 116:827–834
51. Setiawan VN (2021) PLN to build three mini hydro 8.95 MW. https://katadata.co.id/safrezifitra/ekonomi-hijau/60cc10ba30a75/pln-bangun-3-pembangkit-listrik-minihidro-8-95-mw. Accessed 15 Jul 2021
52. Sovacool BK (2009) The importance of comprehensiveness in renewable electricity and energy-efficiency policy. Energy Policy 37(4):1529–1541
53. Muhammad-Sukki F et al (2014) Progress of feed-in tariff in Malaysia: a year after. Energy Policy 67:618–625
54. Schmidt TS (2014) Low-carbon investment risks and de-risking. Nat Clim Chang 4(4):237–239
55. Rospriandana N, Faela S (2018) Welcoming the new age of Indonesia's power business. https://www.thejakartapost.com/news/2018/12/21/welcoming-new-age-indonesia-s-power-business.html. Accessed 15 Jul 2021
56. Best R, Burke PJ, Nishitateno S (2019) Evaluating the effectiveness of Australia's small-scale renewable energy scheme for rooftop solar. Energy Econ 84:104475
57. Florian K, Kirana DVS, Faela S (2020) How Better Regulation Can Shape the Future of Indonesia's Electricity Sector. Asian Development Bank. Available: https://www.adb.org/publications/better-regulation-future-indonesia-electricity-sector. Accessed 2 Aug 2021
58. Hamdi E (2019) The Case for System Transformation in Indonesia: Time for a Full Electricity System Audit. https://ieefa.org/ieefa-indonesia-the-case-for-power-system-transformation. Accessed 21 Aug 2021
59. Burke PJ et al (2019) Overcoming barriers to solar and wind energy adoption in two Asian giants: India and Indonesia. Energy Policy 132(1):1216–1228
60. Wong SL, Ngadi N, Abdullah TAT, Inuwa IM (2015) Recent advances of feed-in tariff in Malaysia. Renew Sustain Energy Rev 41:42–52
61. Kartikeya S (2020) India's Coal Tax Is Key to Stabilizing Its Energy Transition. Center for Strategic and International Studies. https://www.csis.org/analysis/indias-coal-tax-key-stabilizing-its-energy-transition. Accessed 13 Aug 2021
62. Burke PJ, Do TN (2021) Greening Asia's economic development. Asian Econ Policy Rev 16(1):22–39
63. Burke PJ (2014) Green pricing in the Asia Pacific: an idea whose time has come? Asia Pacific Policy Stud 1(3):561–575
64. Indonesian Ministry of Energy and Mineral Resources (2021) Carbon Tax *Diterapkan di Pembangkitan per 1 April 2022*. https://www.esdm.go.id/id/berita-unit/direktorat-jenderal-ketenagalistrikan/carbon-tax-diterapkan-di-pembangkitan-per-1-april-2022. Accessed 22 Jan 2023
65. Erinofiardi GP, Date A, Akbarzadeh A, Bismantolo P, Suryono AF, Mainil AK, Nuramal A (2017) A review on micro hydropower in Indonesia. Energy Procedia 110:316–321
66. Langer J, Quist J, Blok K (2021) Review of renewable energy potentials in Indonesia and their contribution to a 100% renewable electricity system. Energies 14(21):7033
67. Silalahi DF, Blakers A, Stocks M, Lu B, Cheng C, Hayes L (2021) Indonesia's vast solar energy potential. Energies 14(17):5424
68. Burke PJ, Siyaranamual MD (2019) No one left behind in Indonesia? Bull Indones Econ Stud 55(3):269–293
69. Yuliani D (2016) Is feed-in-tariff policy effective for increasing deployment of renewable energy in Indonesia? In: Arent D et al (ed) The Political Economy of Clean Energy Transitions, Chapter 8
70. Nasution MA, Ambarita H, Siregar I (2018) Social and technical barriers that affect the growth of small-scale hydropower independent power producers in Indonesia. IOP Conf Ser Mater Sci Eng 420(1):012041

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