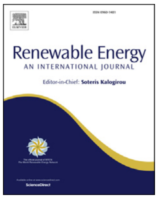
Renewable Energy 99 (2016) 410–419

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene



Energy return on investment (EROI) of mini-hydro and solar PV systems designed for a mini-grid

Noah Kittner [a, b], Shabbir H. Gheewala [c, d, e, *], Daniel M. Kammen [a, b, f]

[a] Energy and Resources Group, University of California, Berkeley, CA 94720, United States
[b] Renewable and Appropriate Energy Laboratory, University of California, Berkeley, CA 94720, United States
[c] The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi, Bangkok, 10140, Thailand
[d] Centre of Excellence on Energy Technology and Environment, PERDO, Bangkok, Thailand
[e] Department of Environmental Sciences and Engineering, Gillings School of Public Health, University of North Carolina, Chapel Hill, NC 27514, United States
[f] Goldman School of Public Policy, University of California, Berkeley, CA 94720, United States

ARTICLE INFO

Article history:
Received 4 January 2016
Received in revised form
10 July 2016
Accepted 11 July 2016

Keywords:
Energy return on energy invested
EROI
Solar PV
Mini-hydropower
Thailand
Mini-grid
Net energy analysis

ABSTRACT

With dramatic cost declines and performance improvements, both mini-hydropower and solar photovoltaics (PV) now serve as core options to meet the growing demand for electricity in underserved regions worldwide. We compare the net energy return on energy invested (EROI) of mini-hydropower and solar electricity using five existing mini-hydropower installations in northern Thailand with grid-connected solar PV simulations. Both assessments use a life cycle perspective to estimate the EROI. We find that distributed mini-grids with penetrations of solar PV up to 50% of annual generation can exceed the EROI of some fossil-based traditional centralized grid systems. The analysis will help planners and engineers optimize mini-grids for energy payback and utilize local resources in their design. The results suggest higher EROI ratios for mini-hydropower plants than solar PV, though mini-hydropower plants typically yield lower EROI ratios than their large-scale hydropower counterparts.

1. Introduction

Mini-hydropower[1] and solar PV electricity are two potential sustainable sources of electricity that may empower communities to generate their own electricity and reduce energy imports. Furthermore, there is an increased emphasis on improving electricity reliability and resilience through the use of distributed energy resources in a functioning mini-grid [1,9]. Thailand is facing growing demand for electricity and remains electricity supply constrained as referenced in the most recent Thai Power Development Plan [24]. To accommodate this increased electricity demand while maintaining environmental sustainability, increased attention has focused on decreasing Thailand's reliance on electricity imports, since more than 60% of its primary energy for electricity generation comes from abroad [26]. Thailand historically set up pilot mini-grid research projects in island regions, including Koh Jig, designed in 2004 as a prototype for island sustainability [22]. The mountainous stretches of northern Thailand similarly face rising costs in expanding centralized transmission investments and therefore have generated interest by the utilities to create mini-grid systems that utilize distributed renewable resources. Therefore, sustained interest in maintaining high penetrations of renewable energy in the grid play a key role in advancing policy support for utilizing existing mini-hydro power plants and constructing new solar plants in new mini-grid test-bed research hubs.

Large-scale hydropower, while key to many previous national development efforts, historically has generated negative social and environmental impacts by displacing people from their homes, altering livelihoods, and destroying habitats for many river-borne species. For instance, downstream impacts of hydropower development not only effect one country as in the case of Thailand, but have drastically reshaped regional watersheds [31]. Small run-of-river hydropower applications do not entail the same negative

---

* Corresponding author. The Joint Graduate School of Energy and Environment (JGSEE), King Mongkut's University of Technology Thonburi, 126 Prachauthit Road, Bangkok, 10140, Thailand.
E-mail address: shabbir_g@jgsee.kmutt.ac.th (S.H. Gheewala).

[1] We define mini-hydropower as run-of-river hydroelectric power plants with a peak capacity between 200 and 6000 kW [17].

http://dx.doi.org/10.1016/j.renene.2016.07.023
0960-1481/

externalities as mega-dams yet contribute to basic electricity supply needs [23]. However, during the summer, mini-hydropower experiences reduced levels of generation. Seasonal variability is expected to increase with climate change [19]. This makes solar PV an attractive technology to complement generation from mini-hydropower and provide supplementary electricity supply capacity. The cost of solar electricity has declined significantly enabling solar PV to emerge as a cost-effective energy source for the region. New innovations in smart control systems, battery storage, and mini-hydropower technologies are facilitating the ease at which grid operators can balance power systems with high penetrations of intermittent renewables.

Net energy analysis presents an important tool for understanding the amount of energy we need to spend to make energy. The EROI in the context of electricity generating technologies provides an accounting framework to understand the net production of electrical energy divided by the input primary energy to produce such devices [6]. This EROI metric is used as a tool comparable to other metrics developed and used in net energy analysis, namely energy payback ratio (EPR) and life-cycle inventories. The main purpose of EROI is to measure energy diverted from society to make available energy for society [2]. For instance, previous protocols developed to understand EROI of fuels highlights the advantages of EROI analysis. First, it provides a standard framework to compare the substitutability of different fuels (historically, corn ethanol and gasoline). Second, it measures resource quality. Third, it provides insights into net energy gains when extracting energy from resources, and lastly as EROI can change over time, we can understand technological development and resource changes [16]. Further, there is almost no energy return on investment (EROI) data for mini-hydropower projects and this paper uses real manufacturing inputs and electricity outputs from northern Thailand to evaluate the energy return on investment (EROI) of mini-hydro and solar PV systems designed in a mini-grid configuration. Few studies have compared the energy requirements of mini-grids and we investigate the role of solar and mini-hydro in improving overall mini-grid sustainability. From a net energy perspective, there is a growing need to understand more about the complementarity of different renewable technologies in resource-constrained areas due to seasonal changes in resource availability. Newly developed production practices in solar electricity improve its energy payback ratio, and could further improve environmental considerations depending on the manufacturing locations [16]. Few studies characterize the net energy ratio of mini-hydro power plants because they view the analysis as arbitrary and geographically dependent [7]. Table 1 summarizes reported EROI for various energy technologies and fuels as reported in the literature, however as noted, each needs further study as often EROI varies by geographic location and a lack of real data, to which this study addresses the need for realistic data by using real, observed mini-hydropower embodied energy and electric generation [8].

Table 1
Summary of reported mean EROI values for various energy technologies as reported in the literature.

Power generation technology	Mean EROI
Coal	46
Natural gas	7
Nuclear	13
Hydroelectric (large)	84
Geothermal	9
Wind	18
Solar PV	10

(Source: [8]).

Mini-hydro plants may vary in terms of output due to geographic variables, however, net energy analysis remains an important tool, especially in energy supply constrained areas, where local materials exist to construct mini-hydro power facilities, as done in northern Thailand. Furthermore, simply because few studies investigated the net energy payback ratio of mini-hydropower plants does not mean the results will be meaningless as it helps policymakers and practitioners understand the comparative costs and benefits of expanding electricity supply when choosing between renewable energy and fossil fuels. We seek to understand the implications of energy return on energy invested for mini-hydropower plants and solar PV because they will become increasingly important distributed energy resources around the world as renewable, cost-effective sources of electricity. Therefore, it becomes useful in the practice of sustainability analysis to compare the EROI of run-of-river mini-hydropower plants with solar PV and storage systems to help determine appropriateness for use in rural settings of northern Thailand. As both renewable technologies have environmental life-cycle impacts significantly less than conventional energy sources, the analysis provides insights for decision-makers in Thailand and across ASEAN to consider when developing distributed generation (DG) power [13,23]. Thailand faces renewed energy security issues and this analysis can provide some insights on how to use existing energy and resources in an efficient matter to get the most energy output for energy invested in developing mini-hydro or solar PV systems [28,29].

The remote mountainous regions of northern Thailand pose physical challenges for transmitting centralized electricity loads due to the steep physical terrain and lack of existing infrastructure. Therefore, both mini-hydro and solar power can serve as localized distributed generation options that feed the electricity grid and can improve reliability. This can be achieved by incorporating mini-hydro or solar projects into a mini-grid system or connecting the projects to the Provincial Electricity Authority (PEA) managed grid using AC inverters and other balance-of-system components to improve the flexibility of a mini-grid. This study evaluates a hypothetical islanding setup where new solar PV generation complements existing mini-hydropower stations in a new mini-grid design, that includes battery energy storage (BESS) or imported PEA-managed grid electricity to address intermittency issues. Fig. 1 details the mini-grid setup.

Both mini-hydro and solar PV technology receive policy support through the state-owned electricity authority. Thailand will seek to have 6 GW of solar online by 2036 and 324 MW of “small-scale” hydropower. Additionally, the development of mini-hydro power in Thailand remains below target levels and must catch up to meet the desired policy goals [25,26]. Solar has exceeded renewable electricity installed capacity targets due to lowered module prices imported from China and the large availability of inexpensive land to connect utility-scale solar projects on the grid. The solar power adder program received so many applications it reached its cap by the end of 2013. For instance, growth of grid-connected solar PV in Thailand grew 211% per year during 2007–2013 stopping at 782 MW of utility-scale solar. Further analysis showed that distributed rooftop solar PV in Thailand could reach $2.12 USD/W according to the National Energy Policy Commission, with utility-scale installations less than $2 USD/W [27]. Financial support through feed-in tariffs also provide between $0.19–0.22 USD/kWh, heavily promoting the use of solar in Thailand. Even further, Thailand's adder program has a $0.05 USD/kWh special adder for diesel replacement. New business models, including community solar arrays are becoming possible in Thailand [28]. Increasingly common in the context of grid extension and rural electrification, mini-hydropower and solar PV-hybrid systems are implemented in

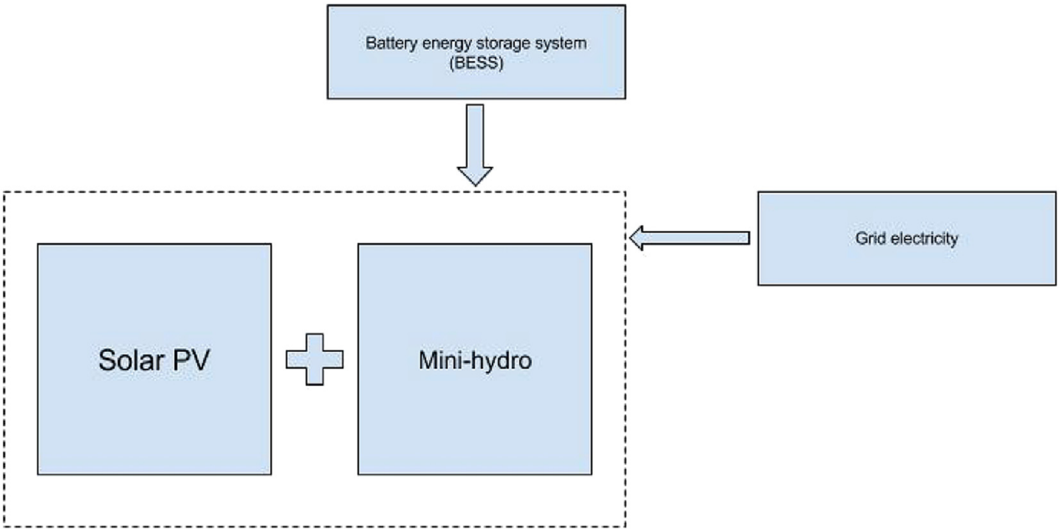


Fig. 1. Hypothetical islanding set-up where new solar PV generation complements existing mini-hydropower installations in mini-grid design supplemented by grid and/or BESS electricity.

conjunction with each other. Some types of mini-hydropower can provide dispatchable, and critical baseload generation to mitigate the variability of PV electricity. The combined suite of technologies emerges as a more common option for remote mountainous areas, with special relevance for northern Thailand due to abundant small rivers and mountainous terrain.

A growing body of work has investigated the potential value of net energy analysis [6,7,15,16]. The lack of consensus among researchers on the EROI of variable technologies including hydropower warrants further study. Therefore, we aim to elucidate some of the nuances for mini-hydropower plants specifically. Most studies focus on large-scale hydropower operations [30]. Other studies assume the hydropower plants to last very long on the order of 100–200 years, leading to potential overestimates of the energy returned on energy invested [3,30]. Using information from existing mini-hydropower plants we can estimate the EROI. Due to a growing interest in distributed energy resources, particularly small-scale run-of-river non-reservoir based hydropower power plants, the study could easily contribute to these developments across Southeast Asia. Furthermore, more research is needed for growing hybrid mini-grid systems that utilize solar PV power generation alongside mini-hydropower in place of expanding transmission lines and building large new centralized plants.

There is a wide reported range of energy payback ratios for solar PV systems [15,21]. Some problems stem from the misapplication of life cycle-based inventory energy data for EROI studies [2]. Others reflect the improvements in manufacturing technology and PV performance over time [21]. Further methodologies dispute the inclusion of expressing the electricity returned to society by PV in terms of primary energy equivalent, which makes PV directly competitive with conventional fossil fuels and sometimes fares better in terms of EROI [21]. Drawing on recent literature, this study elucidates a higher energy return on energy invested than typically perceived for solar PV and the way that both mini-hydro and solar can contribute to sustainability goals. Previous research indicates a need for more thorough investigations of the EROI on different systems [7,15]. Thus, the study clarifies many recorded values. The rapid decrease of the cost for solar electricity has altered production practices such that new modules have vastly different EROIs than modules from five-to-ten years ago.

Additionally, the EROI could help inform future systems-scale studies that investigate an entire mini-grid—potentially consisting of mini-hydro, solar, bioenergy, and battery storage. In the future, developing countries may become highly reliant on mini-grids especially in remote or mountainous areas and the total environmental impacts or energy ratios may become useful to understand how renewable energy technologies can complement or detract from each others' energy inputs and outputs when working together. This study forms the basis of comparison for mini-hydro and mini-grid-connected solar electricity, since technology assessments are rapidly changing. Furthermore, new capacity expansion is experiencing an emergence of decentralized networks for off-grid and on-grid electricity systems [1].

2. Materials and methods

2.1. Goal and scope

The goal of this study is to evaluate and compare the EROI of mini-hydropower and solar photovoltaic plants in northern Thailand. The methodology for energy return on investment (EROI) utilizes a life-cycle approach [12,20,21,23]. That means that we investigate the life-cycle embodied input energy for each technology and the usable electricity generated as energy output for the EROI metric. The study estimates the net cradle-to-grave electricity production and required input energy during the lifetime of both mini-hydro and solar PV systems and we simulate the mini-grid EROI using a scenario-based approach.

2.2. Study sites

The five mini-hydropower sites analyzed here are located in northern Thailand. They range in capacity from 1150–5100 kW. These plants produce electricity with an average capacity factor ranging from 40 to 50%. The plant details are summarized in Table 2. For the purposes of this EROI calculation, we average the five study sites and assume they are representative of typical run-of-river mini-hydropower plants in Thailand. We report a range of EROI values that represent a lower and upper bound for the run-of-river plants. The mini-hydropower plants are all located across northern Thailand and represent what we would expect future run-of-river developments may look like if new turbines are built in the

Table 2
Locations of five mini-hydropower plants in northern Thailand, their peak capacity, and composition.

Study site	Geographic location	Capacity[a] (kW)	Generator type	Land area	Design flow rate (m^3/s)	Weir dimensions	Penstock material and dimensions	Water gate and screens
Mae Thoei	Om Koi, Chiang Mai	2250	Synchronous	12 ha	2 m^3/s	Concrete; 2 m × 18 m	Steel; 1 m × 404 m	14 sets
Mae Pai	Pai, Mae Hong Son	Two sets of 1250 kW	Synchronous	23 ha	1.39 m^3/s	Concrete; 3.5 m × 21.5 m	Steel; 1.15 m × 182 m	15 sets
Mae Ya	Jom Thong, Chiang Mai	1150	Induction	6.4 ha	1.73 m^3/s	Concrete; 3.6 m × 46 m	Steel; 0.9 m × 360 m	13 sets
Nam San	Phu Rua, Loei	3000	Synchronous	9.6 ha	4.36 m^3/s	Concrete; 4 m × 55 m	Steel; 1.82 m × 250 m	19 sets
Nam Man	Dan Sai, Loei	5100	Synchronous	7.3 ha	6.0 m^3/s	Concrete 4 m × 35.5 m	Steel; 1.51 m × 304 m	17 sets

[a] Note: The average capacity factor for these plants is 40–50%, which averages that of similar-sized plants in Afghanistan (30–60%) or Malaysia (60%) [23].

coming decade. There is a vast run-of-river resource in the mountains of northern Thailand. In Sukhothai province, at Ramkhamhaeng National Park there already exists a sample PV-mini-hydro-battery hybrid system as a proof-of-concept to expand to other mini-hydro sites along different rivers in northern Thailand. Table 2 explains the locations of the five mini-hydropower plants that we consider along with their peak capacity and generator type for grid connection.

We analyze the mini- hydropower plants using real, historical data. The solar sites are simulated to be located next to the mini-hydro sites, as if to represent a future hybrid mini-grid system that combines solar photovoltaics with run-of-river mini-hydropower and battery storage. A typical solar installation in northern Thailand averages approximately 4.88 $kWh/m^2/day$ or about 1750 $kWh/m^2/year$ on a 30° south-facing plane. We also simulate a 3 MWp grid-connected solar installation with balance-of-system components and AC inverter in the same study area. The solar PV output is simulated using PVSYST for electricity output over the course of the lifetime [14]. The mini-hydropower plants and simulated solar installation comprise a potential mini-grid that would be used to meet growing demand for electricity without resorting to importing more electricity or expanding transmission capacity.

2.3. Technology

Run-of-river mini-hydropower plants, single-crystalline, multi-crystalline, and amorphous silicon solar PV are compared using net energy payback ratios. The run-of-river hydropower plants consist of two Turgo turbines except the Mae Ya mini-hydropower plant, which features an induction motor.

3. Methodology

We use tools that incorporate life cycle thinking to compare the energy ratio of mini-hydropower and solar PV. The energy return on energy invested (EROI) is the ratio of the total energy produced during a system's normal lifespan, divided by the energy required to build, maintain, and power the system. A high ratio typically indicates good energetic and environmental performance. Data come from literature values of the single-crystalline and amorphous silicon PV panels. The ratio focuses on understanding the ratio of energy output compared to energy required to construct an electricity generation technology. The methods have been developed through the literature [7,8,21]. The EROI included the use of life-cycle inventory data for the energy lifetime output and includes pre-construction land clearance, construction of the mini-hydropower plant and solar PV system, transportation of materials, operational energy production, and demolition.

Equation (1) takes the input energy for each technology and sums across the manufacturing and process energy. It also estimates the electric energy output and divides the lifetime energy output by the input energy for each technology system. We use a standard EROI approach for comparability.

$$\text{Energy Returned on Energy Invested (EROI)} = \frac{\left(\frac{E_{lifetime\ \ output}}{\eta}\right)}{E_{materials} + E_{manufacturing} + E_{transport} + E_{install} + E_{end-of-life}} \tag{1}$$

The lifetime of the mini-hydro power plant is assumed to be 50 years whereas the solar PV installation has an expected lifetime of 30 years. The life of the mini-hydro power plant is a more conservative estimate compared to recent studies that have used lifetimes of 100–200 years. Potential limitations include that we assume no physical degradation of the panels or mini-hydropower. The PV systems include frames, mounting, cabling, and inverter, but exclude embodied energy for maintenance or recycling.

3.1. System boundary

The energy included for construction of the mini-hydropower plants includes the weir, power intake, headrace, screen, penstock, river outlet, surge tank, and power house. The analysis includes energy estimated for the construction of all components listed and transportation fuel. The energy embodied in the energy return on energy invested includes energy of the materials, manufacturing, transport, installation, and end-of-life as detailed in Equation (1).

Fig. 2 details the components of the embodied manufacturing energy required for mini-hydropower and solar PV construction in this study. The EROI metric uses this information, in addition to the land clearance, transportation, and installation energy required to use mini-hydropower and solar PV in a mini-grid system.

3.2. Mini-hydropower

Table 3 summarizes the energy consumption across various life cycle stages for five different mini-hydropower plants. The plants are located in remote areas, accounting for the variation of energy consumed in transportation stages. They also use TwinJet Turgo Impulse Turbine technologies and are synchronous generators, except for the Mae Ya site which uses an induction motor. Energy for construction includes land clearances and preparation before constructing the mini-hydropower plant. Also, the manufacturing energy includes the weir, intake, headrace, penstock and power house. Data for construction information comes from construction invoices and site visits. Nam Man and Nam San plants include tunnel construction. The other plants are fixed in concrete. Energy

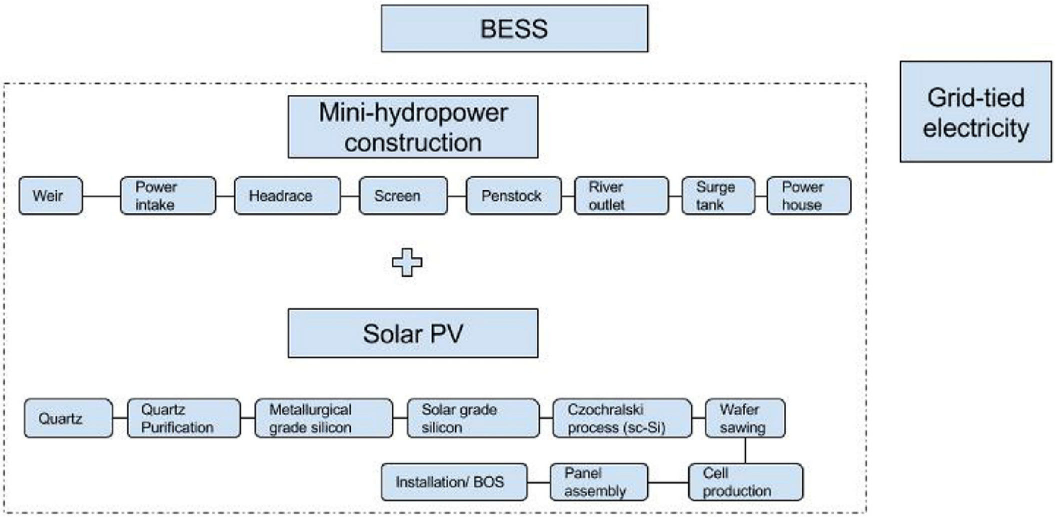


Fig. 2. System boundaries for EROI analysis including individual components of mini-hydropower and solar PV systems considered for manufacturing energy required.

Table 3
The description of energy used in each stage of the mini-hydropower plant and EROI calculation [23].

Description	Range of energy consumed for five mini-hydropower plants
Electricity produced in normal life span (MJ)	664,401,600–3,837,301,200
Energy for transportation (MJ)	6,445,987–72,400,574
Energy for construction (MJ)	1,319,984–9,133,978
Energy for operation (MJ)	1,587,917–9,554,879
Energy for demolition (MJ)	568,814–2,431,111
EROI	41–78

requirements were calculated from the bill of and site visits by discussing with project engineers and operators. The transportation energy is estimated using variety of scenarios, given the mountainous terrain and remote location of some of the plants, transportation could play a significant role in embodied energy calculations. Operation and maintenance (O&M) embodied energy includes normal maintenance and replacement of turbines, spear tips and nozzles, lubricant oil, epoxy paint, and seal plates, assuming a 25-year lifetime on turbines and spear tips and a 10-year lifetime of lubricant oil, paint, and seal plates.

The reported range (41–78) of the energy returned on energy invested (EROI) for the mini-hydropower power plant results in a ratio that is quite positive and nearly to the scale of widespread fossil fuel plants including natural gas and coal. The EROI for solar PV in our simulation is not of the same scale as the mini-hydropower plant, which is to be expected, yet remains positive.

Table 4 highlights the different effects of expanding lifespan of the mini-hydropower plant and reducing the transportation energy cost for moving materials to construct mini-hydropower plants. For instance, by manipulating the lifespan and the transportation energy costs for building a mini-hydropower plant, one could achieve an EROI of 145–284, which is quite high and more than four times greater than the base case under normal assumptions. However, this gets at an important point and probably helps explain previous literature values of EROI that utilize much higher estimated life spans for mini-hydropower plants that might not be as realistic, especially in an era of a rapidly changing energy landscape from centralized plants to distributed energy resources. Other aspects of the EROI calculation for mini-hydropower plants contain aspects of uncertainty, but we feel these parameters are contributing the most to the variation of previously published literature values, that also primarily focus on run-of-river hydropower, or larger-scale plants.

Fig. 3 highlights the significant role transportation plays in the life-cycle embodied energy of mini-hydropower plants. Reducing transportation distances to half would increase the EROI ratio by 40–70% (67–108). Construction plays the second largest contributor to life-cycle embodied energy. The implication here is that since EROI for mini-hydropower remains highly sensitive to the transport of the materials necessary to construct the plant and construction processes, more attention should be placed in a localized zone on using less energy intensive materials and shorter distances to move parts. Also, this implies that from an environmental perspective, construction managers should heed attention to site selection of mini-hydropower projects to reduce wasted energy and improve design and implementation of projects. Since previous peer-reviewed studies have used considerably longer

Table 4
Effects of lifespan and transportation energy on EROI for mini-hydropower.

Scenarios	Range of energy payback ratio (EROI)
Scenario 1: Base case, 50 year lifespan and normal transportation	41–78
Scenario 2: 50 year lifespan and 50% reduction of transportation energy	67–108
Scenario 3: 100 year lifespan and normal transportation	86–170
Scenario 4: 100 year lifespan and 50% reduction of transportation energy	145–284

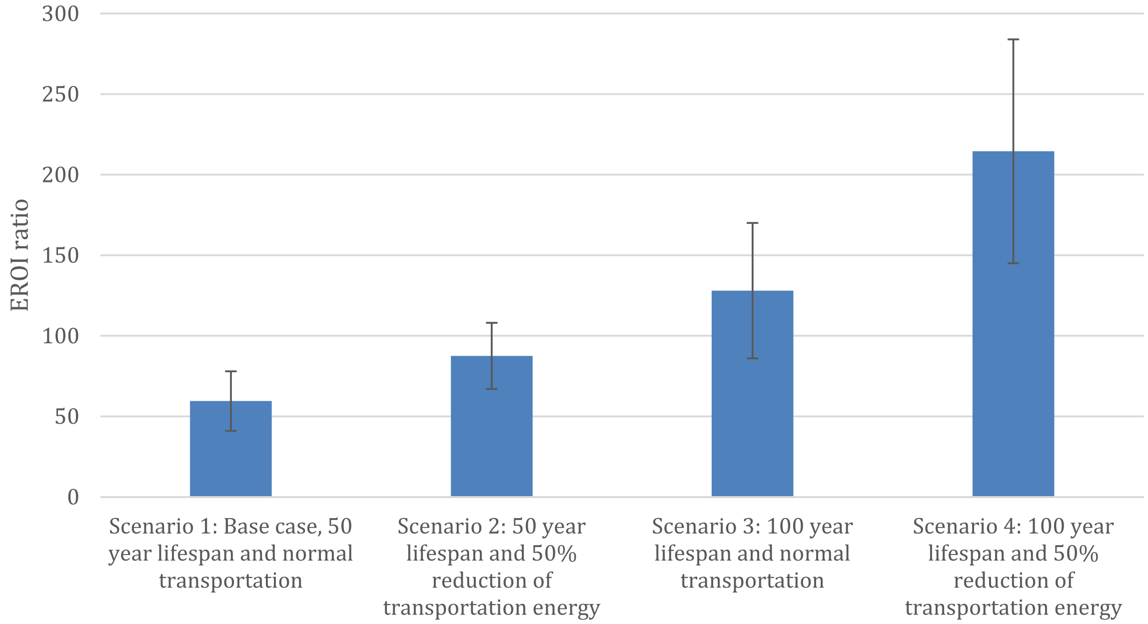


Fig. 3. Sensitivity of transportation energy on EROI ratio for mini-hydropower plants.

lifespans for the mini-hydropower plants, it became interesting and useful to understand the effect of lifespan on the EROI for mini-hydropower. We consider a number of scenarios for instance, by doubling the expected lifespan of the plant to 100 years, the EROI would become 86–170, which is a 120–150% increase.

3.3. *Solar photovoltaics*

For the solar PV plants, we use literature values for the manufacturing of different panels taken from life-cycle manufacturing energy inventories [13]. Because transportation plays a smaller role in the overall embodied energy requirements to manufacture and set up solar photovoltaic technologies, we do not account for the difference between installing the panels in a mountainous terrain versus a flat area. However, the output energy that is simulated would be captured through the level of solar insolation geographically. The EROI calculation includes the energy for construction and then uses PVSYST software to simulate the electricity generated during its lifetime. Though PV sometimes is not utilized in the system, it will not affect the EROI calculation, because during times of surplus electricity in the grid, there is available energy. If it is not utilized, however, that is a lack of efficiency in grid operations and management, and will not significantly change the EROI of the PV system itself. When we calculate the EROI of the mini-grid system in it's entirety however, this calculation assumes a well-managed grid that utilizes solar electricity as long as there is load to support the amount of solar installed. The mini-grid system takes into account solar variability because we approximate the amount of solar electricity utilized within the mini-grid over a period of 8760 hours.

Life-cycle inventory and energy estimation tools are derived from manufacturing databases including ecoinvent and literature searches [13,21].

We simulate the EROI for three different types of solar PV technologies, single-crystalline, multi-crystalline, and amorphous-silicon thin-film PV. The difference in technology is important because in tropical conditions like Thailand, often times amorphous-silicon thin-film panels can be preferred due to their predilection for diffuse radiation rather than direct insolation [13]. The conditions for the northern Thailand sites are modelled using PVSYST and literature data. The energy for construction and assembly are summarized in Table 5 along with the estimated range for EROI. These estimates are in line with other estimates for EROI of solar PV in other regions. Recent studies including [5] determine a new metric, energy stored on invested (ESOI) [4,5]. For large-scale pumped hydro storage systems, they find that there could be an ESOI ranging from 210 to 830 based on their assumptions [4,18,30]. This would drastically improve the ability for solar PV to increase its own EROI, when coupled in a hybrid system that also utilizes pumped hydro storage. In fact, it could suggest that future systems should be designed to accommodate some level of pumped hydro storage, solar photovoltaics, and run-of-river mini-hydropower plants for sustainability.

In addition to EROI, the energy stored on energy invested (ESOI) emerges as a particularly relevant metric for estimating the EROI of a flexible and adaptive mini-grid design. This relevance occurs because often times grid operators must backstop intermittent solar PV or mini-hydropower generators with some form of energy storage. Energy stored on energy invested for the purposes of this research study are reported from the literature. We define ESOI as in previous studies [4,18]. Table 6 details the ESOI values common in literature used in this analysis for various energy storage technologies including lithium-ion batteries and vanadium-redox flow batteries.

$$\mathrm{ESOI}_e = \frac{[\text{Energy discharged over lifetime}]}{[\text{Life} - \text{cycle manufacturing energy requirement}]}$$

The combination of EROI and ESOI metrics elicit useful thought experiments as grids change to utilize variable renewable generators and we can begin to compare the EROI of mini-grids with centralized grids.

3.4. *EROI for mini-grid*

We investigate the combined EROI of a mini-grid using the historic data from mini-hydropower plants in operation, simulated solar PV estimates, and literature approximates of battery

Table 5
Range of values obtained for embodied energy in construction of PV modules, LCI data from ecoinvent database and literature [13,21].

Conditions	Single-crystalline PV	Multi-crystalline PV	Amorphous-silicon PV
Insolation (kWh/m^2-yr)	1750	1750	1750
Efficiency	15%	13%	7%
Energy for construction (MJ/m^2)	2440–4070	2220–3870	640–1060
Performance ratio	0.75	0.75	0.75
System lifetime (years)	30	30	30
EROI	6–12	6–12	11–30

Table 6
Energy stored on invested from literature values for various battery technologies and pumped hydro (adapted from Ref. [18]).

Storage technology	ESOI
Lithium-ion battery	35
Sodium sulphur battery	26
Vanadium-redox flow battery	14
Zinc-bromine flow battery	15
Lead-acid battery	5.8
Pumped hydro storage	830

electricity storage and traditional grid-tied electricity. This helps understand the net energy resources gained from designing mini-grids and can serve as a comparison to national, centralized grids. However, we ignore balance of system components and principally focus on the EROI of the electricity generating and storage technologies themselves, which remains a limitation of this particular analysis. However, based on the differing distributed electricity supply mix, we can still compare the results with centralized traditionally designed grids.

Fig. 4 presents the EROI for three solar photovoltaic technologies, a lower-bound estimate for mini-hydropower turbines, and a range of EROI values for varying penetrations of solar PV in a mini-grid setup combined with mini-hydropower. The scenarios detailed investigate the changing EROI based on electricity used in a grid situation. We investigate different penetrations of electricity generated annually on a mini-grid, one with 20% of annual generation coming from solar PV and one with 50% of total annual electricity generation from solar PV. We then run sensitivity based on PV technology. The remaining 70% or 20% of annual electricity generation comes from mini-hydropower in this case. We also toggle whether the system accounts for intermittency on an hourly basis using a lithium-ion battery storage device or the central grid existing in northern Thailand which utilizes mostly coal generation from Mae Moh lignite mine-mouth plant. The results suggest that from an EROI basis, the mini-hydropower and solar PV can serve complementary roles to improve EROI ratios. Also, of strong interest is that a mini-grid receiving at least 20% of annual generation from solar PV is competitive with coal-based grids (EROI = 46) and considering that the EROI of coal is declining, this could provide further justification for renewable mini-grids from a net energy perspective. However, it is important to note the limitations of EROI and net energy, in that it does not consider environmental or climate externalities due to air pollution or CO_2 emissions. Policymakers should not use EROI estimates alone without considering environmental and social factors. The positive EROI values highlight the role mini-grids can play in meeting electricity needs to society while also providing net energy benefits to society. Lastly, the large EROI ratios for mini-grids highlight the potential for more

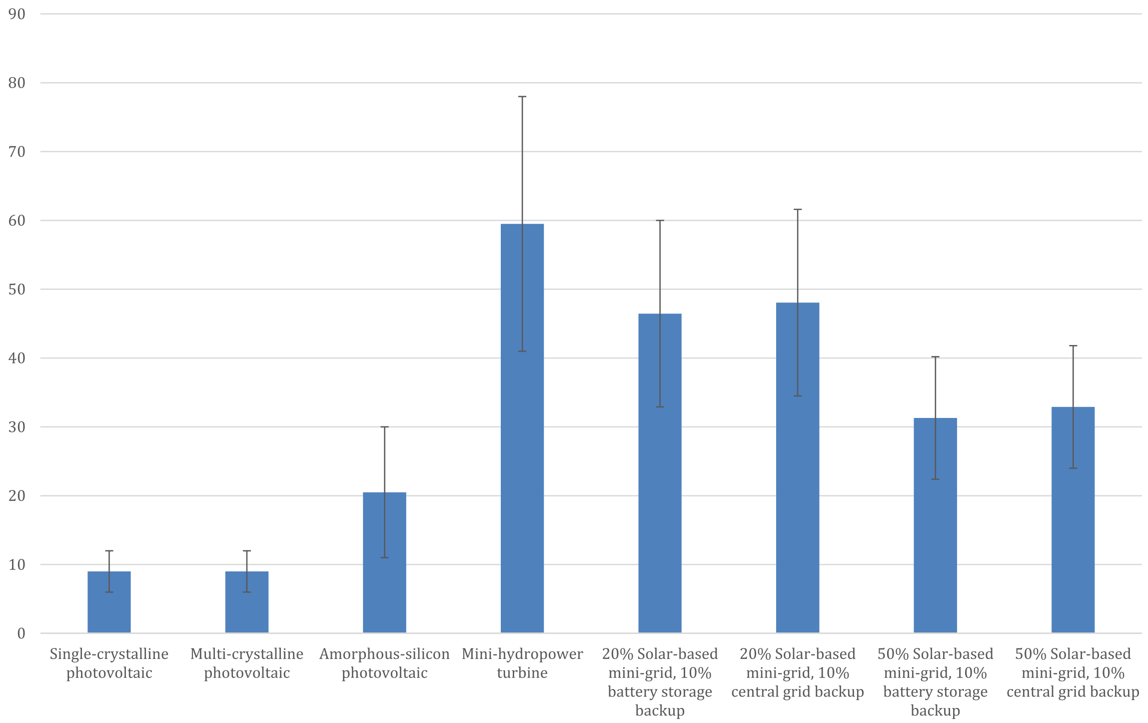


Fig. 4. EROI of mini-hydropower and solar PV technologies in Thailand, by technology and varied mini-grid setups.

distributed generation based designs to provide higher returns on energy investment than large scale centralized systems, likely because of the integrated and localized nature of distributed energy resources for electricity generation. Equation (2) describes the EROI for a mini-grid, that sums across any electricity generating or storing technology, *i* [21].

$$EROI_{minigrid} = \sum_{i} \frac{\left(\frac{E_{lifetime\ output}}{\eta}\right)_i}{E_{materials_i} + E_{manufacturing_i} + E_{transport_i} + E_{install_i} + E_{end-of-life_i}} \qquad (2)$$

It seems that combining the solar PV and mini-hydropower into a hybrid system would decrease the EROI from using only mini-hydropower plants, however, if one adds some form of pumped storage to a solar PV plant, the overall system could benefit not only from an operations perspective, but EROI as lithium-ion ESOI is about 30 compared to pumped hydro storage which can reach up to 830. The life span of the mini-hydropower plant remains an important parameter that greatly changes the results of the reported EROI ratio as evidenced by Table 3. Therefore, this should be carefully considered going forward as more mini-hydropower plants in the real world reach maturation and are decommissioned in the future. Since this is a relatively new technology, there is not much experience to draw upon for estimated lifespan. The results suggest that mini-hydropower plants can become an energetically efficient investment that will provide society with strong net energy surpluses. When combined with other net energy positive technologies, including solar PV, environmental factors like limiting pollution from energy sources can be achieved and the diversity of the system allows for better environmental outcomes and dependence on renewable energy rather than non-renewables.

4. Discussion

Photovoltaics and mini-hydropower both have high energy return on energy investment ratios that serve as useful options to strive toward sustainable energy goals. It is useful to note that mini-hydropower can utilize more local resources during the construction phase and have a higher energy payback ratio than solar PV. However, the complementary nature of solar PV and mini-hydropower can alleviate issues of intermittency when used in the same system. During the summertime, mini-hydropower experiences lower levels of production due to fewer available water resources in northern Thailand. Recent advances in power islanding within mini-grids facilitates increased flexibility for solar PV and mini-hydropower to operate either with battery or grid-tied backup power in an integrated systems. The EROI of mini-hydropower and solar PV inform future sustainability studies of systems-scale diesel/biodiesel backed-up mini-grids. Additionally, the EROI of the existing mini-hydropower system competes closely with fossil fuels including coal and oil [15]. EROI of fossil fuel resources continues to decline [8,11]. In the future, scale run-of-river hydropower plants could play a more significant role in our electricity systems as they transition from large, centralized designs to diverse, distributed sources that serve complementary roles. The addition of energy storage devices may decrease the net energy surplus from using hydro and solar dominated micro-grids. Using lithium-ion batteries for grid storage could potentially improve the energy return on invested of solar photovoltaics [18].

Run-of-river hydropower plants could also enhance sustainability by constructing the systems using local resources. Both single-crystalline and amorphous-silicon solar PV panels often are manufactured in China and imported to Thailand. However, each energy technology utilizes locally available sunlight and water resources rather than imported fuel that would power a diesel or natural gas generator.

The overall potential for solar generation is larger than mini-hydropower in Thailand. However, mountainous regions in northern Thailand could greatly benefit by co-locating solar PV with mini-hydropower plants to achieve higher energy return on energy invested ratios and also to aid in load balancing by addressing intermittency issues, though these are not captured well in EROI calculations. Both mini-hydropower and solar PV embody fewer greenhouse gas emissions than alternative diesel and fossil fuel generators [10,20]. Suitable locations for mini-hydropower should be explored further as they have very high energy payback ratios, emit few pollutants to the environment, and do not contain the same environmental externalities as mega dams. The use of mini-hydropower in northern Thailand along with solar PV will benefit energy security and environmental outcomes.

Future work may include an economic analysis to determine how the levelized cost of electricity generation between mini-hydropower at each site and solar PV compares with distributed diesel generation. The current estimated LCOE of mini-hydropower and solar PV At present the subsidy “adders” for mini-hydropower could provide up to seven years of support adding approximately $0.02/kWh to all mini-hydropower installations selling electricity back to the Electricity Generating Authority of Thailand (EGAT).

Embodied energy and resulting environmental impacts can be reduced greatly if local materials and a local manufacturing supply chain is developed for both the mini-hydropower plants and the solar photovoltaic manufacturing as evidenced by the sensitivity of transportation energy in mini-hydropower EROI. Neither industry has strongly developed in Thailand, and therefore many of the materials that need to be imported contribute to lower than necessary energy returns on investment because of transportation energy required to assemble the mini-hydropower facilities [23]. Additionally, given the amount of steel, copper, and iron necessary to construct a mini-hydropower plant, the use of recycled materials can reduce the embodied energy. After the mini-hydropower plants are decommissioned there remain opportunities for materials and systems recycling. New manufacturing of distributed mini-hydropower plants could occur from decommissioned systems. Aluminium and silicon recovery from photovoltaic panels could create a type of industrial symbiosis that would benefit the regional economy, while improving energetic and environmental performance.

Energy return on investment (EROI) along with net energy analysis is a useful energy indicator for sustainability analysis and understanding society's distribution of resources. The application of life-cycle thinking to energy systems could better help design mini-grids that advance toward sustainable energy goals. However, EROI alone should not inform policy, it should be used alongside other decision-making criteria. The rapid decline in cost of mini-hydropower systems and solar photovoltaics enables new design thinking for mini-grids, especially in mountainous areas where transportation of diesel fuel is limited and expensive. In this case, mini-hydropower capacity and solar PV are both suitable technologies that will enable sustainable energy systems, if designed appropriately with environmental, economic, and societal considerations taken into account. Mini-grids are becoming critical tools as added flexibility for power systems and to build resilient systems that can operate in cases of limited electricity supply or grid malfunctions due to power outages and blackouts. This analysis sets the stage for further work into the EROI for other distributed energy resources and mini-grids as they become more ubiquitous as a way to meet power system capacity expansion. Further work would include more extensive analyses to determine optimal sizing of PV plants within mini-grids, quantify the role of energy storage with varying power and energy capacity ratios, and the economic design and deployment of mini-grid systems.

The EROI ratio for mini-hydropower systems is higher than solar PV; however, this does not preclude distinct advantages of solar PV to meet future electricity demand. Solar PV also yields a high EROI and can serve as an electricity option in areas that may not be suitable for mini-hydropower sites. Solar PV, when sited appropriately, can also reduce the need for added investment in transmission systems and could defer distribution component upgrades by selectively providing voltage support or reactive power. Solar PV can reduce the net energy demand when coordinated with the utility to ensure proper grid integration. We highlight that a suite of low-carbon technologies can also provide financially and energetically competitive options for a mini-grid system. Diesel backup mini-grids are not the only technology option available, and mountainous regions could take advantage of locally available resources first before resorting to the use of diesel for backup. The positive EROI ratios indicate societal benefits to utilizing mini-hydropower and solar PV systems in mini-grids as they can improve the quality of energy by meeting electricity supply needs. Another upshot of the calculated EROI ratios is that they may be increasing with technological advances and improvements in performance efficiency and product lifetimes. The technological improvements in solar PV and mini-hydropower have improved the EROI ratios since earlier studies in the late 1990's and early 2000's, renewing interest in distributed energy resources, and improving the energetic balance for these emerging technologies.

Since mini-hydropower can counter power outages and help balance loads during periods of peak demand, this is a highly sought after source of electricity for rural mountainous Thailand, with spotty electricity provided by the PEA. Coupled with solar PV, both technologies will provide stability to the electricity grid while serving as net-energetically positive investments in primary energy and resources. Attention toward mini-hydropower in Thailand should grow in the future due to policy support, appropriate geologic features, and the ability to obtain a high net energy payback ratio. The feed-in tariff support toward mini-hydropower is not currently developed to its full potential. Also, the construction of more mini-hydropower plants in Thailand can provide the necessary infrastructural support that accommodates grid-connected or mini-grid-connected solar PV. The expected future decline in cost of solar PV combined with the increased demand for renewable technologies will likely spur development of mini-hydropower and solar PV systems to meet sustainability and energy goals.

5. Conclusions

First, we report the EROI of mini-hydropower systems in Thailand using real data available from five different mini-hydropower sites, that can range from 41 to 284, depending on transportation energy requirements and assumptions of lifespan. Second, we synthesize literature-based estimates and simulate EROI for three solar PV technologies and review different battery storage options for a mini-grid. We then use scenarios of annual generation for solar PV and mini-hydropower plants designed in a mini-grid setup to evaluate the EROI for mini-grids, which we find to be net positive and sometimes more competitive than fossil-based large scale centralized grids. This hinges on the fact mini-hydropower has a high EROI compared to many fossil-fuel based generators. Solar PV technologies can range from 6 to 12 in EROI and amorphous-silicon PV can be from 11 to 30. At the same time, EROI of mini-hydropower can be greater than 41 into the 100's and other mini-grid setups based on mini-hydro and solar PV range between 21 and 62. These analyses do not consider social or environmental externalities, yet provide a window into the potential societal benefits of distributed mini-grid electricity generation. The flexibility of mini-grids to meet underserved energy needs and the dramatic cost declines of mini-hydropower and solar PV technologies is driving a change toward more distributed energy systems. Our findings suggest these systems can provide net energy benefits to society, as mini-hydropower does have a high EROI and further these systems already challenge fossil-fuel based grid EROIs.

Acknowledgements

The authors wish to acknowledge JGSEE for research support. We thank Wannarat Suwanit for data collection. This work was supported by the Development Impact Lab at UC Berkeley (USAID Cooperative Agreements AID-OAA-A-13-00002 and AID-OAA-A-12-00011), part of USAID's Higher Education Solutions Network. NK was supported by the NSF Graduate Research Fellowship and the Berkeley Center for Green Chemistry SAGE-IGERT program. We also wish to thank two anonymous reviewers for their helpful comments.

References

[1] P. Alstone, D. Gershenson, D.M. Kammen, Decentralized energy systems for clean electricity access, Nat. Clim. Change 5 (4) (2015) 305–314.

[2] A. Arvesen, E.G. Hertwich, More caution is needed when using life cycle assessment to determine energy return on investment (EROI), Energy Policy 76 (2015) 1–6.

[3] R.S. Atlason, R. Unnthorsson, Energy return on investment of hydroelectric power generation calculated using a standardised methodology, Renew. Energy 66 (2014) 364–370.

[4] C.J. Barnhart, S.M. Benson, On the importance of reducing the energetic and material demands of electrical energy storage, Energy Environ. Sci. 6 (2013) 1083–1092.

[5] C.J. Barnhart, M. Dale, A.R. Brandt, S.M. Benson, The energetic implications of curtailing versus storing solar-and wind-generated electricity, Energy & Environ. Sci. 6 (10) (2013) 2804–2810.

[6] M. Carbajales-Dale, C.J. Barnhart, A.R. Brandt, S.M. Benson, A better currency for investing in a sustainable future, Nat. Clim. Change 4 (7) (2014) 524–527.

[7] A.K. Gupta, C.A. Hall, A review of the past and current state of EROI data, Sustainability 3 (10) (2011) 1796–1809.

[8] C.A. Hall, J.G. Lambert, S.B. Balogh, EROI of different fuels and the implications for society, Energy Policy 64 (2014) 141–152.

[9] A. Halu, A. Scala, A. Khiyami, M.C. Gonzalez, Data-driven modeling of solar-powered urban microgrids, Sci. Adv. 2 (2016), http://dx.doi.org/10.1126/sciadv.1500700.

[10] David D. Hsu, et al., Life cycle greenhouse gas emissions of crystalline silicon photovoltaic electricity generation, J. Industrial Ecol. 16 (s1) (2012) S122–S135.

[11] Y. Hu, C.A. Hall, J. Wang, L. Feng, A. Poisson, Energy Return on Investment (EROI) of China's conventional fossil fuels: historical and future trends, Energy

54 (2013) 352–364.

[12] N. Kittner, S.H. Gheewala, R. Kamens, Life cycle considerations for monocrystalline photovoltaics in Thailand, J. Sustain. Energy Environ. 3 (2012) 143–146.

[13] N. Kittner, S.H. Gheewala, R.M. Kamens, An environmental life cycle comparison of single-crystalline and amorphous-silicon thin-film photovoltaic systems in Thailand, Energy Sustain. Dev. 17 (6) (2013) 605–614.

[14] A. Mermoud, C. Rocker, J. Bonvin, PVSYST Version 6.43, 2016.

[15] D.J. Murphy, C.A. Hall, Year in review—EROI or energy return on (energy) invested, Ann. N. Y. Acad. Sci. 1185 (1) (2010) 102–118.

[16] D.J. Murphy, C.A. Hall, M. Dale, C. Cleveland, Order from chaos: a preliminary protocol for determining the EROI of fuels, Sustainability 3 (10) (2011) 1888–1907.

[17] O. Paish, Small hydro power: technology and current status, Renew. Sustain. Energy Rev. 6 (6) (2002) 537–556.

[18] M. Pellow, C.J.M. Emmott, C. Barnhart, S.M. Benson, Hydrogen or batteries for grid storage? A net energy analysis, Energy Environ. Sci. 8 (2015) 1938.

[19] J. Pittock, Better management of hydropower in an era of climate change, Water Altern. 3 (2) (2010) 444.

[20] H.L. Raadal, L. Gagnon, I.S. Modahl, O.J. Hanssen, Life cycle greenhouse gas (GHG) emissions from the generation of wind and hydro power, Renew. Sustain. Energy Rev. 15 (7) (2011) 3417–3422.

[21] M. Raugei, P. Fullana-i-Palmer, V. Fthenakis, The energy return on energy investment (EROI) of photovoltaics: methodology and comparisons with fossil fuel life cycles, Energy Policy 45 (2012) 576–582.

[22] C. Smith, J. Burrows, E. Scheier, A. Young, J. Smith, T. Young, S.H. Gheewala, Comparative life cycle assessment of a Thai Island's diesel/PV/wind hybrid microgrid, Renew. Energy 80 (2015) 85–100.

[23] W. Suwanit, S.H. Gheewala, Life cycle assessment of mini-hydropower plants in Thailand, Int. J. Life Cycle Assess. 16 (9) (2011) 849–858.

[24] Thai Power Development Plan 2015. Ministry of energy, Government of Thailand.

[25] S. Tongsopit, Thailand's feed-in tariff for residential rooftop solar PV systems: Progress so far, Energy Sustain. Dev. 29 (2015) 127–134.

[26] S. Tongsopit, C. Greacen, An assessment of Thailand's feed-in tariff program, Renew. Energy 60 (2013) 439–445.

[27] S. Tongsopit, S. Chaitusaney, A. Limmanee, N. Kittner, P. Hoontrakul, Scaling up Solar PV: a Roadmap for Thailand, (Thai Ministry of Energy and Chulalongkorn University), 2015. Download at Ministry of Energy or Thai Solar PV Roadmap Website, http://www.dede.go.th/ewt_dl_link.php?nid=42059.

[28] S. Tongsopit, N. Kittner, Y. Chang, A. Aksornkij, W. Wangjiraniran, Energy security in ASEAN: a quantitative approach for sustainable energy policy, Energy Policy. 90 (2016) 60–72.

[29] S. Tongsopit, S. Moungchareon, A. Aksornkij and T. Potisat, Business models and financing options for a rapid scale-up of rooftop solar power systems in Thailand, Energy Policy, (in press). http://dx.doi.org/10.1016/j.enpol.2016.01.023.

[30] D. Weißbach, G. Ruprecht, A. Huke, K. Czerski, S. Gottlieb, A. Hussein, Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants, Energy 52 (2013) 210–221.

[31] G. Ziv, E. Baran, S. Nam, I. Rodríguez-Iturbe, S.A. Levin, Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin, Proc. Natl. Acad. Sci. 109 (15) (2012) 5609–5614.