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Low-cost, low-emission 100% renewable electricity in Southeast Asia supported by pumped hydro storage

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A B S T R A C T

Rapid increases in electricity consumption in Southeast Asia caused by rising living standards and population raise concerns about energy security, affordability and environmental sustainability. In this study, the role of short-term off-river energy storage (STORES) in supporting 100% renewable electricity in Southeast Asia is investigated. Large-scale integration of off-river, closed-loop pumped hydro storage is a new approach to providing system flexibility facilitating high penetration of variable renewable energy in electricity systems. The features of STORES include large storage potential, high technology maturity and a long service life. Energy generation, storage and transmission are co-optimised based on long-term, high-resolution chronological energy data. A comparative analysis is undertaken between the scenarios with and without an intercontinental Asia-Pacific Super Grid. The results show that, with support provided by STORES, the Southeast Asian electricity industry can achieve very high penetration (78%–97%) of domestic solar and wind energy resources. The levelised costs of electricity range from 55 to 115 U.S. dollars per megawatt-hour based on 2020 technology costs. In the Super Grid scenarios, the costs change by −4% to +7% while the storage requirements reduce by 50%–89%. Renewable energy supported by STORES can be a cost-effective solution for Southeast Asia's energy transition, delivering long-term, substantial environmental benefits.

1. Introduction

1.1. Energy and environmental challenges

Southeast Asia has one of the highest growth rates of electricity consumption in the world. In 2018, the total electricity demand in Southeast Asia was about 1,100 TWh, which represented a 60% increase from 2010 and a 200% increase from 2000 [1]. The dramatic increases in the demand for electricity were mainly driven by economic and population growth, urbanisation and industrialisation [2]. In 2018, the per-capita electricity consumptions in the Southeast Asian countries were (MWh per person per year, low to high): Timor-Leste 0.1, Myanmar 0.4, Cambodia 0.6, the Philippines 0.9, Laos 1.0, Indonesia 1.1, Vietnam 2.5, Thailand 3.0, Malaysia 5.3, Singapore 9.2 and Brunei 10.0. This can be compared with Australia (10), China (5), the European Union (6) and the United States of America (14) [1]. In light of the low electricity consumption in most Southeast Asian countries, the upward trend in electricity consumptions is likely to continue, despite the current disruptions of COVID-19 to the economy. For example, if all the Southeast Asian countries reach a per-capita electricity consumption of 3 MWh per year, equivalent to the 2018 level in Thailand, then the annual electricity consumption will rise above 2,600 TWh across the region. Further, if the Southeast Asian countries achieve a per-capita electricity consumption of 9 MWh per year (similar to Singapore), then the annual electricity consumption will rise above 7,500 TWh, which represents 7-fold increase from today.

Expectations for the rapid growth in electricity consumption raise significant concerns about energy security and affordability in Southeast Asia. At the end of 2019, the proved reserves of coal and natural gas in Southeast Asia were 44 gigatonnes and 4.6 trillion cubic metres, respectively [3], which can support about 142,000 TWh of electricity in total assuming a thermal efficiency of 33% for coal-fired and 50% for natural gas-fired power plants. This is equivalent to only 19 years of electricity demand in the high electricity consumption scenario (9 MWh per capita per year). Therefore, if the current energy mix in Southeast Asia stays unchanged (coal plus natural gas > 75%), then a large fraction of energy supply would rely on imports of fossil fuels for the foreseeable future. The

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expected huge increases in electricity production could have a large impact on the environmental sustainability. If the carbon intensity of electricity remains at its current level, then greenhouse gas (GHG) emissions from electricity and heat production would increase from 644 Mt CO2-e in 2018 [1] to beyond 4,400 Mt CO2-e in the high electricity scenario, comparable to China's current emissions from electricity and heat production in the global GHG emissions inventory. Meanwhile, the premature deaths caused by the air pollutants emitted from burning of thermal coal could rise above 100,000 every year [4].

1.2. 100% renewable electricity

An effective solution to the above energy and environmental challenges is energy change, transitioning away from fossil fuels to renewable energy. In recent years, 100% renewable electricity has become a highly discussed research topic, both on a global/continental level and at a country/state level. Bogdanov et al. [5] modelled a global energy transition to 100% renewable electricity by 2050. A portfolio of electrical energy storage technologies was integrated, including lithium-ion battery for short-term, diurnal energy storage and power-to-gas (synthetic natural gas) for long-term, seasonal energy storage. The analysis was further extended to include transport, heating and desalination sectors in Bogdanov et al. [6]. Lund et al. [7] developed a Smart Energy System concept, which was applied to countries such as Denmark [8], Germany [9], Italy [10] as well as a European Union-wide study [11]. In the Smart Energy System, the flexibility of energy systems is created by the synergy of multiple energy sectors including electricity, transport, buildings and industry. Variable renewable energy resources can be converted into renewable electro-fuels and thermal energy through bridging energy technologies. Jacobson et al. [12] investigated 100% wind, water and sunlight scenarios for the world's energy systems, where 72% of the energy demand was assumed to be flexible: half from thermal storage (heating & cooling), and half from demand response and flexible hydrogen production. In addition, large-scale deployments of concentrated solar power were required to match renewable energy supply and energy demand. Frew et al. [13] and Schlachtberger et al. [14] examined the benefits of building a continental transmission network in the 100% or near-100% renewable electricity scenarios for the United States and Europe, respectively. They concluded that aggregation of renewable energy resources over large geographic areas can help significantly reduce the costs of the renewable energy systems. Matsuo et al. [15] demonstrated a trade-off between the requirements for hydrogen energy storage and sodium-sulphur battery in the 100% renewable electricity futures for Japan. Zero-carbon hydrogen was assumed to be either produced from domestic renewable energy sources or imported from overseas. Dranka & Ferreira [16] modelled 100% renewables in the Brazilian electricity system, where the hydropower resources are abundant and can contribute to half of the electricity generation in 2050. Elliston et al. [17] discussed the feasibility of utilising biogas-fuelled open-cycle gas turbines to balance solar and wind energy achieving 100% renewable electricity in Australia.

All of the above existing literature demonstrated that 100% renewable electricity is technically feasible and can be economically competitive, although both sides of the argument existed such as Heard et al. [18], Heuberger & Mac Dowell [19], Brown et al. [20] and Diesendorf & Elliston [21]. However, these 100% renewables studies differed in geographic coverages, temporal and spatial resolutions, inclusion of energy sectors, transition paths and model types as noted by Hansen et al. [22]. Importantly, a variety of methods were utilised to increase the flexibility of energy systems facilitating high penetration of variable solar and wind energy as summarised in Table 1, based on the different energy resources and electricity consumption patterns in different regions.

As shown in Table 1, a major shortcoming in all of these studies is the limited use of pumped hydro energy storage, despite the fact that pumped hydro constitutes 97% of rated power and 99% of storage energy volume of the global energy storage market [23] because it is mature and low cost. Reasons provided for this exclusion is that conventional hydropower energy resources are extremely limited in many parts of the world, and the construction of on-river hydroelectric schemes is usually associated with a wide variety of environmental concerns, such as the impacts on biodiversity, nutrient flows and landscape destruction [24]. However, pumped hydro storage is not necessarily to be confined to rivers and can operate in a closed loop, which avoids damming of rivers. Since rivers only occupy a small fraction of the landscape, restricting pumped hydro storage opportunities to rivers only identifies a small fraction of the opportunities. A first-of-its-kind global atlas of short-term, off-river energy storage (STORES) was recently developed at the Australian National University [25], which discovered 616,000 cost-effective sites around the world, with the enormous storage potential of 23 million GWh in total. STORES refers to closed-loop pumped hydro systems located away from rivers, which are to be built on large flat lands or within enclosed dry gullies separated by large altitude difference, typically >300 m [26]. Unlike conventional on-river hydropower, STORES features low water consumption, relatively low environmental footprints and a shorter lead time for design and construction. Consequently, it shares the advantages and technology of on-river hydropower but without the severe disadvantage of being confined to rivers.

In this study, we utilise STORES as a primary storage medium to support high penetration of variable renewable energy resources in Southeast Asian electricity systems. Compared with other energy storage technologies modelled in the existing literature, the STORES technology has a variety of competitive advantages to be utilised for short-term, diurnal energy storage. Firstly, STORES has high technology maturity and had been deployed over 167 GW worldwide at the end of 2020, compared with only 1.8 GW and 2.4 GW of global deployment for battery and thermal energy storage, respectively [23]. Secondly, the round-trip efficiency of STORES is relatively high: typically 80% of energy can be recovered using modern hydropower technology [27]. By contrast, energy storage through hydrogen or synthetic natural gas has a low round-trip efficiency of only 30% or less, due to the large energy loss in electrolysers, storage and fuel cells (or gas turbines) collectively [28]. Thirdly, STORES features a long service life of typically 30–60 years. In comparison, lithium-ion batteries can only be operated for about 10 years [29], and therefore a large amount of battery waste will need to be properly managed at the end of their technical life, which can be a significant environmental issue. In addition, as will be discussed in Section 2 and Section 3, the STORES technology is not constrained by factors relating to resource availability and accessibility or raw materials supply (concrete, steel, water etc.).

Southeast Asia is located in the Sunbelt (lower than $\pm$ 35° of latitude), where the solar radiation is high, and the seasonal variations in solar resource are relatively low [30]. Unlike much of Europe, North America and Northeast Asia, there is no significant heating load in winter, and the demand for cooling is generally in alignment with the high solar irradiance in summer. Therefore, the need for short-term, diurnal energy storage is large while the need for long-term, seasonal energy storage is low [5]. STORES offers vast opportunities to access low-cost and mature energy storage on timescales of hours to a few days, which can enable a cost-effective renewable energy transition in Southeast Asia.

Table 1
A summary of the methods to increase the flexibility of 100% renewable energy systems in the existing literature.

Method	Energy balancing strategies
Electrical energy storage	Large-scale storage technologies for energy time-shifting, including grid-scale batteries [5], concentrated solar power [12] and power-to-gas (e.g. hydrogen [15] and synthetic natural gas [5]). Short-term, diurnal energy storage is often required in the regions with low seasonal variations in renewable energy resources e.g. the Sunbelt, while long-term, seasonal energy storage is usually necessary for the high-latitude regions.
Energy sector integration	Electricity, transport, buildings and industry sectors are fully integrated through bridging technologies e.g. power-to-gas and power-to-heat. Variable renewable energy resources are converted into renewable electro-fuels (e.g. methane, methanol and dimethyl ether), which can be stored in existing oil and gas storage facilities [7–11].
Demand response	Assuming a significant proportion of electrical loads are flexible and can be shifted or shed based on energy balancing requirements [12]. Demand flexibility can be sourced from the existing residential, commercial and industrial sectors or from the future electrified transport and heating, where electric car batteries and hot water storage can contribute significant storage capacity.
Electricity grid interconnection	Large-scale interconnection between the electricity grids using high-voltage direct-current or alternating-current transmission can increase the diversity of renewable energy resources [13,14]. Local weather can be effectively smoothed out through the aggregation of widely dispersed renewable energy resources over millions of square kilometres.
Dispatchable renewable energy resources	Hydropower and other flexible energy resources can be strategically dispatched to fill the gaps between renewable energy supply and electricity demand. However, this strategy is only applicable to the countries where there are significant hydropower resources such as Brazil [16].

1.3. Objectives

In this study, we investigate the role of STORES in supporting Southeast Asia's energy transition to 100% renewable electricity futures. The objectives of this study are: (i) assess the potential for renewable energy and storage to support the rapidly growing demand for electricity in Southeast Asia; (ii) examine the reliability and affordability of 100% renewable electricity systems dominated by variable renewable energy and with support provided from STORES; (iii) investigate the impact of building a fully interconnected electricity system across Southeast Asia through high-voltage direct-current transmission. The study is expected to provide relevant input into policy discussion on the Association of Southeast Asian Nations' target of a 23% renewable energy share in the total primary energy supply and a 35% renewable energy share in the electricity generation capacity by 2025 [31].

In addition to the integration of STORES, this study includes the following features which are different from existing models of renewable energy futures for Southeast Asia:

- Energy generation, storage and transmission are co-optimised based on long-term (10 years), high-resolution (60-min) chronological energy data. Consequently, the interannual variability in renewable energy resources can be effectively captured, together with the weather events which occur occasionally with extremely low availability of renewable energy supply. In comparison, Gulagi et al. [32], Bogdanov et al. [5] optimised the 100% renewable electricity systems based on one year's energy data, while Huber et al. [33] only modelled 12 weeks with each week representing a month of the year.
- The future electricity demand is projected according to 3 MWh (low), 6 MWh (medium) and 9 MWh (high) per capita of electricity consumption, which represent 2-fold, 4-fold and 7-fold increases from the 2018 electricity demand, respectively. Modelling of the low, medium and high electricity consumption scenarios allows the uncertainty of future electricity growth to be incorporated, for example, due to rapid economic growth or large-scale uptake of electric vehicles. In comparison, the International Energy Agency's Southeast Asia Energy Outlook [2] modelled a Sustainable Development scenario in 2040, where the electricity demand was doubled only.
- Solar photovoltaics and wind turbines constitute 100% of new generation capacity while the capacity of fossil fuel electricity assets is assumed not to grow above their current levels. Existing fossil fuel generation is retained based on the fact that many existing coal plants in Southeast Asia were built after the 2000s, such as in Indonesia (26 GW) and Vietnam (19 GW) [34], which are likely to continue to operate in the next decades. The legacy fossil fuel assets will be gradually phased out from the energy mix as they reach the end of technical lifetime. In the long term, as the uptake of electric vehicles becomes significant, the smart charging will contribute large demand flexibility and is able to support the complete replacement of fossil fuels for energy balancing [35]. Additionally, uptake of electric vehicles reduces emissions from vehicles which offsets emissions from legacy power stations.
- All the energy technologies included in the modelling have high technology readiness level and have been deployed on a large scale worldwide (>100 GW of installed capacity). Accordingly, the levelised costs of 100% renewable electricity are calculated based on 2020 technology costs rather than on the predictions of future technology costs as the case in many studies. In this way, a credible “upper bound” of the costs for 100% renewable electricity systems can be obtained from the modelling, which can be directly compared with that of existing fossil fuel energy systems. In light of the rapidly falling price of solar photovoltaics as expected by the International Renewable Energy Agency [36], renewable energy and storage would be the least-cost solution for the Southeast Asian energy industry in the next decades.

This article is structured into the following sections: Section 2 describes the methodology for electricity demand projections (Section 2.1), energy resource assessments (Section 2.2), modelling of the Asia-Pacific Super Grid (Section 2.3), energy balance modelling (Section 2.4) and other modelling assumptions (Section 2.5). Section 3 presents the modelling results, including the levelised cost of electricity (Section 3.1), electricity generation mix (Section 3.2), energy storage requirements (Section 3.3) and emissions reduction (Section 3.4). Section 4 includes the conclusions drawn from the analyses.

2. Methods

2.1. Electricity demand projections

As noted in Section 1, electricity demand in Southeast Asia is growing rapidly. In this work, a “per-capita” method was adopted in the projections of future electricity demand, which assumed a per-capita electricity consumption of 3 MWh (low), 6 MWh (medium) and 9 MWh (high) per year across the Southeast Asian countries. The low, medium and high electricity scenarios are comparable to the 2018 per-capita energy consumptions in Thailand, Malaysia and

Singapore, respectively. The underpinning projections of population growth in Southeast Asia were obtained from the Medium Variant scenario for 2050 in the United Nations' World Population Prospects 2019 [37]. As shown in Table 2, the annual electricity demand in Southeast Asia increases from only 1,101 TWh in 2018 to 2,652 TWh, 5,038 TWh and 7,524 TWh in the low, medium and high electricity scenarios, respectively. The hourly distributions of electricity consumption were simulated using the 2019 electricity data in Singapore obtained from the Energy Market Authority of Singapore [38]. This is because Singapore represents an equatorial industrialised country with a high per-capita income and a mature energy market, to which other countries may aspire.

2.2. Energy resource assessments

Solar energy, wind energy and off-river pumped hydro resources in Southeast Asia are illustrated in Fig. 1.

2.2.1. Solar energy

High-resolution meteorological data were downloaded from Solcast [41], including solar irradiance, wind speed and direction, temperature, relative humidity and atmospheric pressure. Solar energy conversions were calculated on an hourly basis for the years 2010–2019, using 315 W-DC modules and a 2,200 kW-DC inverter in the National Renewable Energy Laboratory (NREL)'s System Advisor Model [42]. Solar panels were assumed to be ground-mounted, south-facing (except for the locations in the southern hemisphere such as some areas of Indonesia) and tilted according to the latitudes of location without tracking systems. An overall loss factor of 15% was assumed in the energy conversion, which included the losses from soiling, module mismatch, diodes and connections, degradation, wiring and transformer. The calculations showed that the capacity factors of solar photovoltaics ranged from 12% in Hanoi, Vietnam to 18% in Timor-Leste and achieved a 10-year average of 15% across Southeast Asia. In comparison, the capacity factors in northern Australia can reach 22% (fixed) to 26% (single-axis tracking). This is the competitive advantage of Australian renewable energy and is the motivation to explore the connection of Australia, Indonesia and Singapore through a submarine power cable [43]. Importantly, the solar resources in Southeast Asia have low seasonal variations. The mean absolute deviations of daily solar energy output are less than 4% across Southeast Asia except for some regions like Hanoi and Yangon, which are located at higher latitudes and affected by orographic precipitation. The low seasonality of solar energy resources means that hours or a few days of energy storage are required to cope with the variability in solar energy rather than long term, costly seasonal energy storage.

2.2.2. Wind energy

Significant wind energy resources are widely distributed in Laos, Myanmar, the Philippines, Thailand and Vietnam, but only exist in a few regions in Cambodia, Malaysia and Indonesia [44]. Based on the meteorological data from Solcast, the wind energy outputs were calculated on an hourly basis using a 3 MW wind turbine model in the System Advisor Model. A mean wind speed of 8 m/s at a 150 m hub height was assumed, which translated to a capacity factor of 43% on average. Wind energy is often complementary with solar in energy production. In particular, solar and wind energy are complementary on a seasonal basis in many regions of Southeast Asia, due to the northeast monsoon in winter. Consequently, the integration of wind energy can substantially reduce the reliance on energy storage to stabilise the electricity systems when solar energy is not sufficient. However, compared with solar energy, the seasonal variability in wind energy in Southeast Asia is large. A standard deviation of 20%–32% is observed from the daily averaged wind energy outputs. In the modelling, the optimal mix of solar and wind energy was decided by the mathematical optimisation as is described in Section 2.4. The capacity limits on wind energy development in each Southeast Asian country were decided based on the GW figures included in an NREL report [44]: 69 GW in Cambodia, 13 GW in Laos, 482 GW in Myanmar, 217 GW in the Philippines, 239 GW in Thailand and 311 GW in Vietnam. These GW figures were assumed for windfarms with a levelised cost of electricity less than US$150/MWh.

2.2.3. Hydropower and other renewables

Existing hydropower plants are mostly located in the Greater Mekong Subregion. Based on the Global Power Plant Database [45], hydropower has a total installed capacity of 37 GW in Southeast Asia: Vietnam 16.8 GW, Indonesia 4.6 GW, Thailand 3.8 GW, the Philippines 3.4 GW, Laos 3.1 GW, Myanmar 2.7 GW, Malaysia 2.0 GW and Cambodia 0.9 GW. According to the International Energy Agency's Outlook [2], hydropower in Southeast Asia is likely to be expanded in the next couple of decades. However, in this work, a conservative assumption was made that there will be no further expansion of existing hydropower in Southeast Asia, neither in its current capacity, nor in annual energy production. One reason for this assumption is the high environmental cost of river-based

Table 2
The current and projected electricity demand (terawatt-hours per year) in Southeast Asia.

	Population in 2018 (million)[a]	Electricity demand in 2018[b]	Per-capita electricity use in 2018[c]	Projected electricity demand[d]		
				Low	Medium	High
Brunei	0.4	4	10.0	5	5	5
Cambodia	16	10	0.6	69	138	207
Indonesia	268	286	1.1	1,045	2,090	3,135
Laos	7	7	1.0	30	60	90
Malaysia	32	168	5.3	228	256	384
Myanmar	54	23	0.4	197	393	590
Philippines	107	99	0.9	456	913	1,369
Singapore	6	53	9.2	62	62	62
Thailand	69	208	3.0	208	416	625
Timor-Leste	1.3	0.1	0.1	6	13	19
Vietnam	96	242	2.5	346	692	1,038
Total	655	1,101		2,652	5,038	7,524

[a] Data source: United Nations' World Population Prospects 2019 [37].
[b] Data source: International Energy Agency [1]; WorldData.info (for Timor-Leste only).
[c] Megawatt-hour per person per year.
[d] A transmission and distribution loss of 5% is included.

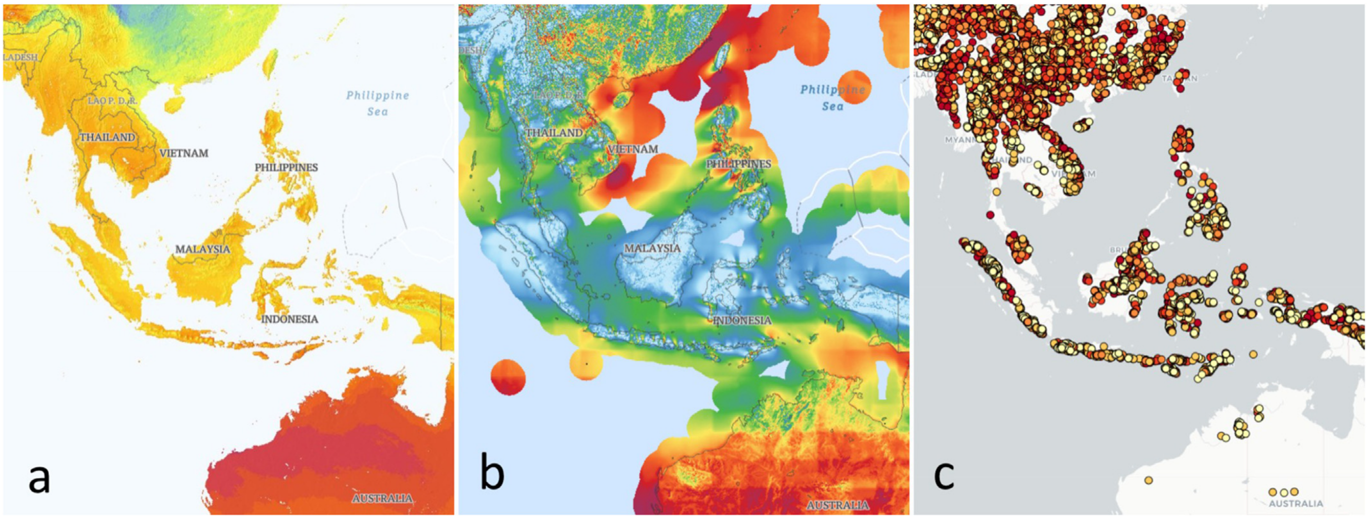

Fig. 1. Renewable energy resources in Southeast Asia: (a) Global horizontal irradiance as denoted by the blue-yellow-orange-red colour scheme (low to high solar radiation); (b) Mean wind speed at 150 m height with the excellent wind energy resources (>8 m/s) highlighted in red; (c) Potential sites for off-river pumped hydro, classified into A (dark red), B (red), C (orange), D (yellow) and E (light yellow) based on the construction costs (low to high). Image source: Fig. 1-a obtained from the Global Solar Atlas 2.0 [39], developed and operated by Solargis on behalf of the World Bank Group, with funding provided by the Energy Sector Management Assistance Program (ESMAP). Fig. 1-b obtained from the Global Wind Atlas 3.0 [40], developed, owned and operated by the Technical University of Denmark. The Global Wind Atlas 3.0 is released in partnership with the World Bank Group, utilising data provided by Vortex, using funding provided by the ESMAP. Fig. 1-c obtained from the Australian National University's Global Pumped Hydro Atlas [25]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

hydropower developments [46]. In the modelling, half of the existing hydropower was assumed to be fully dispatchable (with storage reservoirs) based on energy balancing requirements, while the annual energy production stayed unchanged from the current level (127 TWh p.a.). In fact, hydropower cannot keep pace with the rapid deployments of solar and wind energy. Rather, they contribute to energy security and reliability as a last resort through energy balancing and providing ancillary services such as frequency control. Other renewable energy resources such as geothermal and biomass contribute about 3% (30 TWh p.a.) of the annual electricity generation in Southeast Asia, which is a small fraction. In the modelling, these power plants were assumed to be operated at the current capacity.

2.2.4. Pumped hydro energy storage (off-river, closed-loop)

A particular type of hydropower is pumped hydro storage, which entails a pair of adjacent reservoirs located at different altitudes and connected via conduits or a tunnel. Due to the limited resource potential of hydropower and environmental considerations, the opportunities for new river-based pumped hydro are scarce. However, the potential sites for off-river pumped hydro in Southeast Asia are enormous [25], except in Singapore and Brunei. As noted in Section 1, off-river, closed-loop pumped hydro was utilised as a primary method for large-scale energy storage. Due to the geographic constraints, in Brunei and Singapore, however, battery storage systems were used and responsible for the energy time-shifting.

The availability of effectively unlimited low-cost technically mature storage in the form of off-river pumped hydro is critical for these renewable electricity scenarios. Pumped hydro is by far the most cost-efficient solution for electrical energy storage on timescales ranging from hours to a few days [47]. A good off-river, closed-loop pumped hydro system comprises a pair of closely spaced reservoirs each with area of 1 square kilometre, an average depth of 20 m, a water volume of 20 GL and a height difference ("head") of 500 m. Such a system can operate at a power of 1 GW for 24 h and would have a capital cost of about US$1.8 billion [25]. The water is not consumed during power generation; rather, it is cycled between the upper and lower reservoirs. Therefore, the consumption of water is modest (initial fill and evaporation minus rainfall), and there is no or low interaction with the ecosystem of main stem rivers, which means the environmental footprints are relatively low. Pumped hydro systems can also be built utilising existing reservoirs and old mining pits, like Snowy 2.0 and the Kidston Pumped Storage Hydro Project in Australia.

2.3. Asia-Pacific Super Grid

In this study, a set of renewable electricity scenarios were modelled for the Southeast Asian countries: Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, Timor-Leste and Vietnam. In addition to the scenarios for each Southeast Asian country, two Super Grid scenarios were modelled, including a high-voltage direct-current (HVDC) backbone across Southeast Asia (Fig. 2). The interconnection of the electricity grids allowed: (i) the variability in both renewable energy and electricity demand to be smoothed out over a large geographic area, and (ii) sharing of excellent wind energy and hydropower resources in the Mekong region across Southeast Asia. In the first Super Grid scenario (Super Grid-1), the electricity grids in the Southeast Asian countries were interconnected via overhead, underground or submarine HVDC transmission. In comparison, in the second scenario (Super Grid-2), the Super Grid was further extended to north Australia, northeast India and southwest China (such as Guangxi and Yunnan) to allow access to renewable energy resources beyond Southeast Asia.

2.4. Energy balance modelling

Energy supply and demand balance was carefully examined

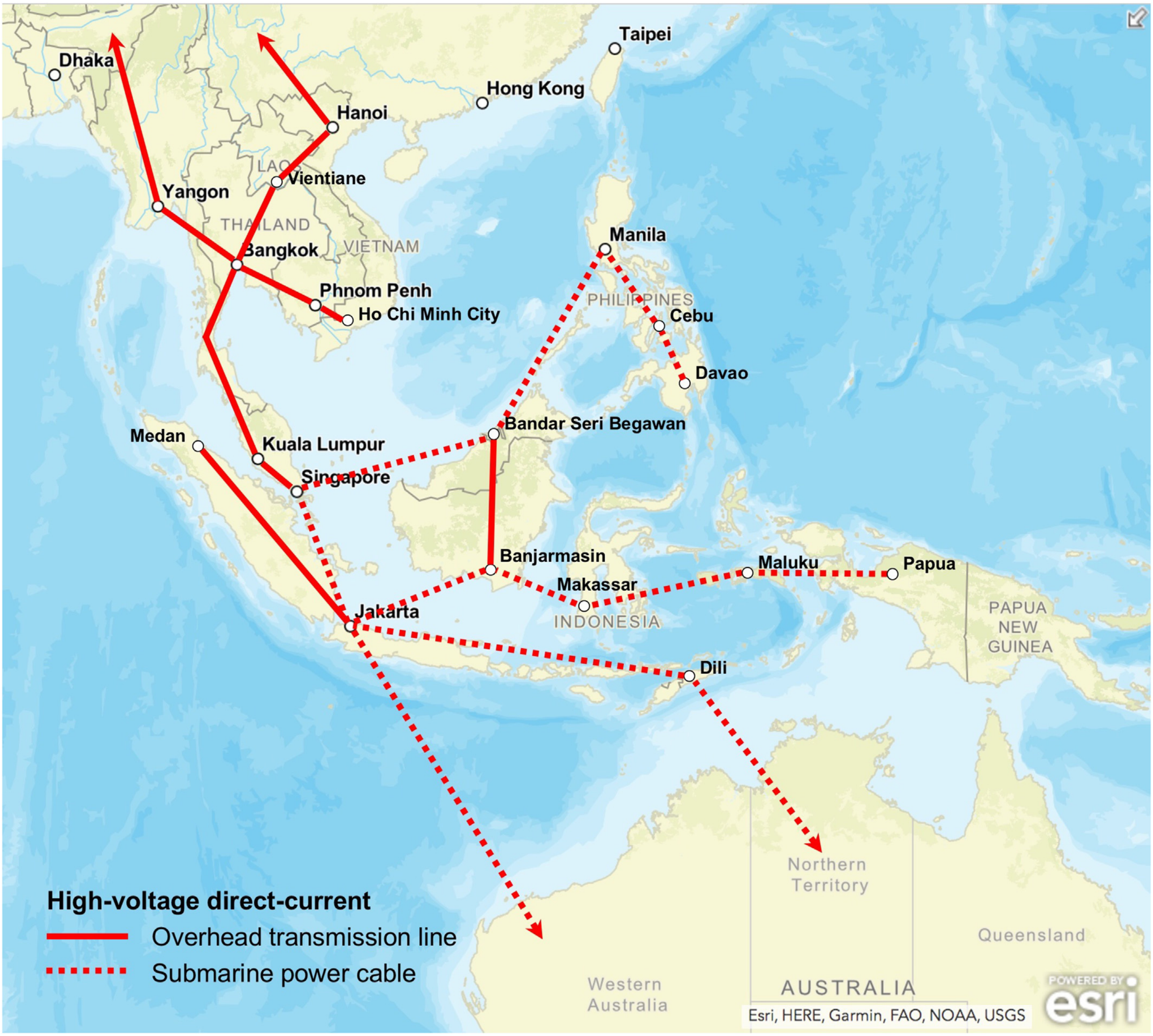

Fig. 2. The Asia-Pacific Super Grid: a high-voltage direct-current backbone in the Super Grid scenarios.

through an hour-by-hour analysis of energy generation, storage and transmission in the renewable electricity scenarios. A "net load" approach was used in the modelling where the net load is defined as the difference between electric load and renewable energy supply on an hourly basis as shown in Eq. (1). Energy storage is key to achieving high levels of balanced renewable energy supply. As shown in Eqs. (2)–(4), when the net load was greater than zero, the electricity system experienced a deficit, and hence energy storage was operated as generators to fill the gaps. In contrast, if the net load was negative, then there was a surplus of energy supply, and energy storage was operated as pumps to absorb the excess power. The round-trip efficiency was assumed to be 80% for pumped hydro and 90% for battery systems, respectively. In Eq. (5), existing hydropower and other renewables were strategically dispatched to mitigate of the difference between energy supply and demand while subject to the energy constraints.

$$\sum_{i=0}^{I} E_{NLoad}(i,\ t) = \sum_{i=0}^{I} E_{ELoad}(i,\ t) - \sum_{i=0}^{I} G_{PV}(i,\ t) - \sum_{i=0}^{I} G_{Wind}(i,\ t) - \sum_{i=0}^{I} G_{Hydro}(i,\ t) - \sum_{i=0}^{I} G_{Fossil}(i,\ t) \tag{1}$$

$$\sum_{i=0}^{I} D_{Storage}(i,\ t) = min\left(max\left(0,\ \sum_{i=0}^{I} E_{NLoad}(i,\ t)\right),\ \sum_{i=0}^{I} C_{Discharge}(i),\ \sum_{i=0}^{I} S_{Storage}(i,\ t-1)\right) \tag{2}$$

$$\sum_{i=0}^{I} CH_{Storage}(i,\ t) = min\left(-1 * min\left(0,\ \sum_{i=0}^{I} E_{NLoad}(i,\ t)\right),\ \sum_{i=0}^{I} C_{Charge}(i),\ \left(\sum_{i=0}^{I} C_{Storage}(i) - \sum_{i=0}^{I} S_{Storage}\left(i,\ t-1\right)\right) \Big/ EF_{Storage}\right) \tag{3}$$

$$\sum_{i=0}^{I} S_{Storage}(i,\ t) = \sum_{i=0}^{I} S_{Storage}(i,\ t-1) - \sum_{i=0}^{I} D_{Storage}(i,\ t) + \sum_{i=0}^{I} CH_{Storage}(i,\ t) * EF_{Storage} \tag{4}$$

$$E_{Import}(i,\ t) = E_{ELoad}(i,\ t) + CH_{Storage}(i,\ t) + E_{Spillage}(i,\ t) - G_{PV}(i,\ t) - G_{Wind}(i,\ t) - G_{Hydro}(i,\ t) - G_{Fossil}(i,\ t) - D_{Storage}(i,\ t) - E_{Deficit}(i,\ t) \tag{5}$$

where:

E_{NLoad}, E_{ELoad}, $E_{Spillage}$, $E_{Deficit}$ represent the net load, electrical load, energy spillage and energy deficit; G_{PV}, G_{Wind}, G_{Hydro} and G_{Fossil} represent the energy generation from solar photovoltaics, wind turbines, existing hydropower and other renewables, and legacy fossil fuel assets; $D_{Storage}$, $CH_{Storage}$, $S_{Storage}$ and $EF_{Storage}$ represent the discharge, charge, state-of-charge and the round-trip efficiency of energy storage facility, while $C_{Discharge}$, C_{Charge} and $C_{Storage}$ represent the rated power (discharge and charge) and the storage volume, respectively. Region i ranges from 0 to I, and time interval t ranges from 0 to T.

The economics of renewable electricity systems were measured using the levelised cost of electricity (LCOE) figures, as shown in Eqs. (6)–(9). The configurations of energy generation, storage and transmission technologies were optimised using the Differential Evolution algorithm (SciPy) to find the lowest-cost solutions for the energy systems. For example, it was cost-effective to allow occasional energy spillage rather than to build excessively large storage facilities to store all the surplus energy. However, energy spillage can be used to heat industrial thermal stores or even for hydrogen production (not included in this study) provided the cost of electrolysers becomes insignificant in the hydrogen cost.

$$LCOE = Cost\ /\ Energy \tag{6}$$

$$Energy = \sum_{i=0}^{I} \sum_{t=0}^{T} E_{ELoad}(i,\ t) \tag{7}$$

$$Cost = \sum_{i=0}^{I} \sum_{j=0}^{J} Cost(\ i,\ j) \tag{8}$$

$$Cost(i,\ j) = C(i,\ j) * CC(i,\ j) * Y\ /\ AF(i,\ j) + C(i,\ j) * FOM(i,\ j) * Y + G(i,\ j) * VOM(i,\ j) \tag{9}$$

where:

C, G represent the capacity and the electricity generation/storage/transmission of energy technologies; CC, FOM and VOM represent the capital cost, the fixed and variable operating and maintenance (O&M) costs of energy technologies; AF is the present value annuity factor; Y is the number of years. Energy technology j ranges from 0 to J.

In Fig. 3, the load profiles and generation mix in the high electricity consumption scenario are illustrated for a typical day in Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, Timor-Leste, Vietnam and the two Super Grid scenarios.

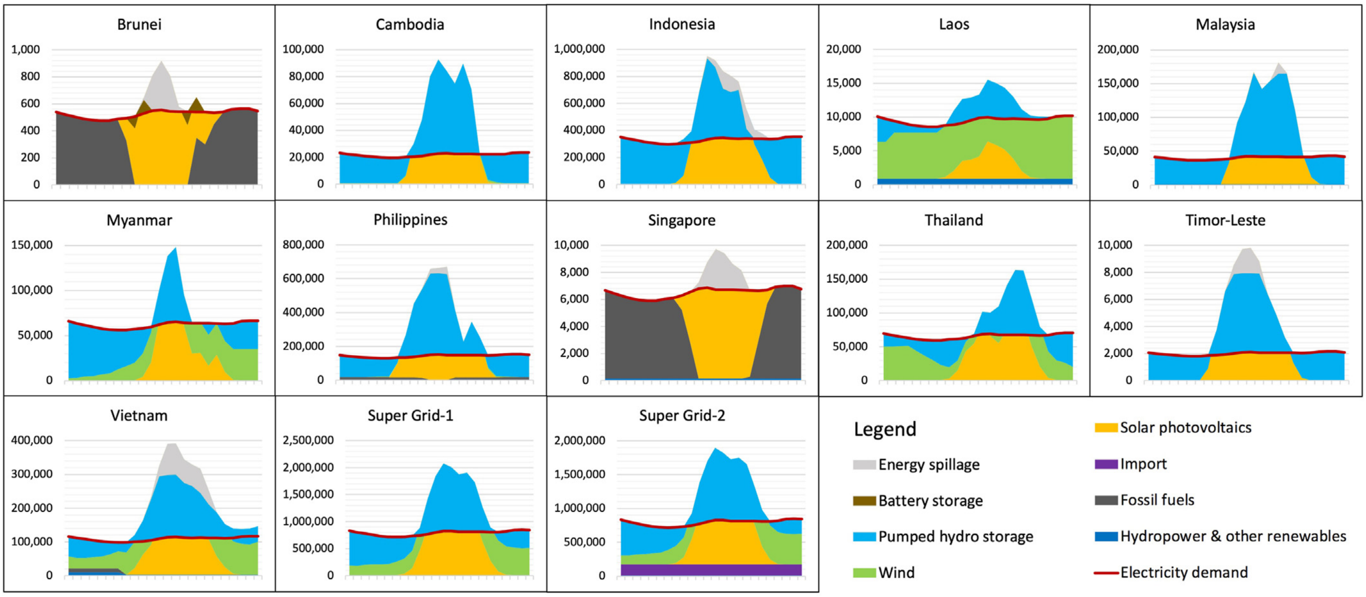

Fig. 3. Energy supply-demand balance for a typical day in the Southeast Asian countries and two Super Grid scenarios.

Table 3
Cost assumptions for new electricity generation, storage and transmission technologies in 2020 U.S. dollars. Data source: IRENA [48], Lazard [49], Statnett [50], Blakers et al. [51], Lu et al. [35].

Technology	Capital cost	Fixed O&M cost	Variable O&M cost	Lifetime (years)
Solar photovoltaics	$850/kW (DC)	$10/kW p.a. (DC)	0	25
Wind turbines	$1,400/kW	$25/kW p.a.	$2/MWh	25
Pumped hydro storage[a]	$560/kW $50/kWh	$7/kW p.a.	0	50
Battery storage[a]	$70/kW $330/kWh	$3/kWh p.a.	0	15
High-voltage direct-current (overhead)[b]	$220/MW-km $110,000/MW	$2.2/MW-km p.a. $1,100/MW p.a.	0	30, 50[b]
High-voltage direct-current (submarine)[c]	$2,000/MW-km	$20/MW-km p.a.	0	30
High-voltage alternating-current[d]	$1,000/MW-km	$10/MW-km p.a.	0	50

Note.
[a] $/kW for power components plus $/kWh for storage components.
[b] $/MW-km for transmission lines (50 years) plus $/MW for a converter station (30 years).
[c] Including submarine power cables and converter stations.
[d] Including transmission lines and substations.

2.5. Modelling assumptions

The assumptions in the modelling include:

- In this study, only the electricity sector was modelled. However, deep decarbonisation of the remaining energy sectors is achievable through electrification of heating (via electric heat pumps and appliances), transport (via electric vehicles), manufacturing (via electric furnaces) and mining (via electric mining and construction equipment). Integration of electric vehicles and hot water storage can increase the flexibility of energy systems and further facilitates the uptake of variable renewable energy resources [7].
- Perfect weather and load forecasts were assumed. Nevertheless, weather and load forecasts are imperfect by its nature, and hence operating reserves are required to cope with the forecast errors. Unlike existing fossil fuel energy systems where the reserve resources are sourced from additional generation capacities, in the renewable electricity systems, energy storage and responses from demand-side participation will contribute to large reserve margins. For example, pumped hydro can be dispatched from idle to full capacity within a few minutes in response to changes in the energy systems.
- An “N-1” redundancy was assumed for the HVDC transmission backbone. In the renewable energy systems, the impact of loss of widely distributed kW to MW-scale solar panels and wind turbines is much less than the loss of a large, centralised thermal unit in the existing fossil fuel energy systems. Rather, the risk of failures of GW-scale HVDC transmission will be significant. Consequently, a 25% redundancy was incorporated for the overhead HVDC transmission lines and converter stations to cope with the failure of transmission network and maintenance requirements.
- Transmission and distribution (T&D) network was operated in a “business-as-usual” mode. T&D network is a large component in the electricity bill. Augmentations of the existing T&D network are required to accommodate growing electricity demand, but the per-unit figure ($/kWh) may reduce thanks to the demand

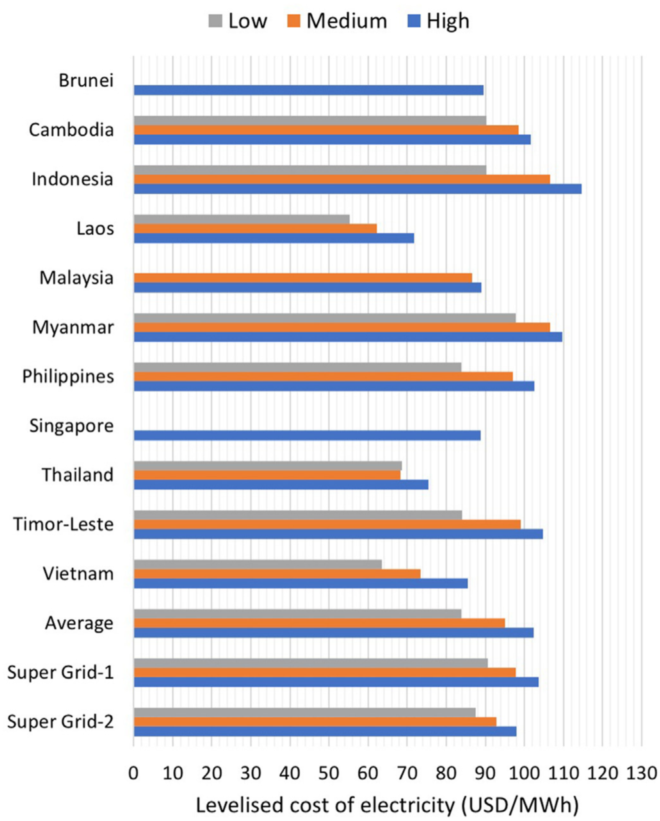

Fig. 4. The levelised costs of electricity in the low, medium and high electricity consumption scenarios.

flexibility enabled by distributed energy storage. In addition, new transmission lines to connect solar and wind farms were included in the cost calculations.

- Reliability standard: the loss of electric load was constrained to zero. This exceeds the current reliability standards in the Southeast Asian electricity industry and ensures high levels of energy security and reliability. In the Super Grid scenario (Super Grid-2), energy imported from Australia, China or India was less than 5% (each) of the total electricity consumption in Southeast Asia, while the interconnections amongst the Southeast Asian countries were not constrained.
- The cost assumptions for new energy generation, storage and transmission technologies are included in Table 3.

Electricity generated by the legacy fossil fuel assets was valued at $100/MWh, which is comparable with the current cost from new combined-cycle gas turbines in Southeast Asia [52]. A purchase price of $50/MWh was assumed for the renewable energy imports and the hydropower [48]. The capital costs of battery storage in Table 3 can be translated to about $400/kWh and $350/kWh for 1 h and 4 h of energy storage, respectively. In comparison, the Hornsdale Power Reserve (100 MW, 129 MWh) [53] developed in South Australia in 2017 costed about €56 million, equivalent to $486/kWh. It is expected that the cost of battery storage system will continue to drop rapidly: for example, a latest figure of $150/kWh was claimed by BloombergNEF [54]. In this study, the LCOE figures were expressed in 2020 U.S. dollars. The assumed exchange rates for Australian dollar/U.S. dollar and Euro/U.S. dollar were 0.7 and 1.12, respectively. The discount rate was 5% (real).

3. Results and discussion

3.1. Levelised cost of electricity

The LCOE figures in the low, medium and high electricity consumption scenarios are shown in Fig. 4 and included in Table A of Appendix. As illustrated, the LCOE figures are in the range of $55-$98/MWh (low), $62-$107/MWh (medium) and $72-$115/MWh (high) across Southeast Asia. The LCOE figures are relatively low in Laos ($55–72/MWh), Thailand ($68–75/MWh) and Vietnam ($63–85/MWh), because: (i) they have access to excellent wind resources which are complementary to solar energy, and (ii) they have large hydropower capacity in the Mekong region which is more flexible and can be dispatched in response to energy deficits. By contrast, the LCOE figures in Cambodia ($90–102/MWh), Indonesia ($90–115/MWh) and Myanmar ($98–110/MWh) are significantly higher than other countries as there is no significant hydropower resource available, and the growth in the future electricity demand is high, driven by the current low electricity consumption on a per-capita basis. For Brunei and Singapore, only the LCOE figures for the high electricity scenario are included in Fig. 4 as they have already exceeded a per-capita electricity consumption of 9 MWh per year. Similarly, the LCOE figures for Malaysia are only for the medium and high electricity scenarios in Fig. 4. Overall, the volume-weighted average of LCOE in Southeast Asia are $84/MWh (low), $95/MWh (medium) and $102/MWh (high), respectively. In comparison, the LCOE figures in the Super Grid scenarios are $87–91/MWh (low), $93–98/MWh (medium) and $98–104/MWh (high). This means, despite a large investment in the HVDC transmission backbone, the LCOE figures are not evidently increasing in the Super Grid scenarios. In addition, the LCOE figures are rising as the per-capita electricity consumption increases from low to medium and high electricity scenarios. The reason for the increasing cost of electricity as demand increases is that the fixed amount of existing hydropower and legacy fossil fuel assets is progressively diluted.

As noted in Section 1, these LCOE figures are calculated based on the 2020 costs of renewable energy technologies. According to the BloombergNEF analysis [54], solar photovoltaics has already become the cheapest option of new electricity generation in many parts of the world. Even compared with existing coal-fired power with large sunk costs and low marginal costs, solar photovoltaics is becoming cost-competitive according to the International Renewable Energy Agency's report [48]. The cost of solar photovoltaics is expected to be halved by 2050 according to the International Renewable Energy Agency's report [36], and therefore the LCOE figures in Fig. 4 would further decrease by $20–30/MWh accordingly. By contrast, the unsubsidised LCOE of new combined-cycle gas turbines in Southeast Asia were in the range of $80–110/MWh in 2019 [52]. Consequently, the renewable electricity scenarios can be fully cost-competitive compared with new natural gas-fired power generation and would be comparable to new coal ($60–90/MWh) in the near future.

3.2. Electricity generation mix

The annual electricity generation and the proportions of solar photovoltaics, wind, hydropower & other renewables and fossil fuels in the energy mix are shown in Fig. 5, for the high electricity scenario only. The complete energy data for the low, medium and high electricity scenarios are included in Table A of Appendix.

As illustrated, solar energy is the major source of electricity in the hypothetical renewable energy scenarios, which contributes to 30%–99% in the energy mix across Southeast Asia with a volume-weighted average of 82%. In comparison, wind energy only makes

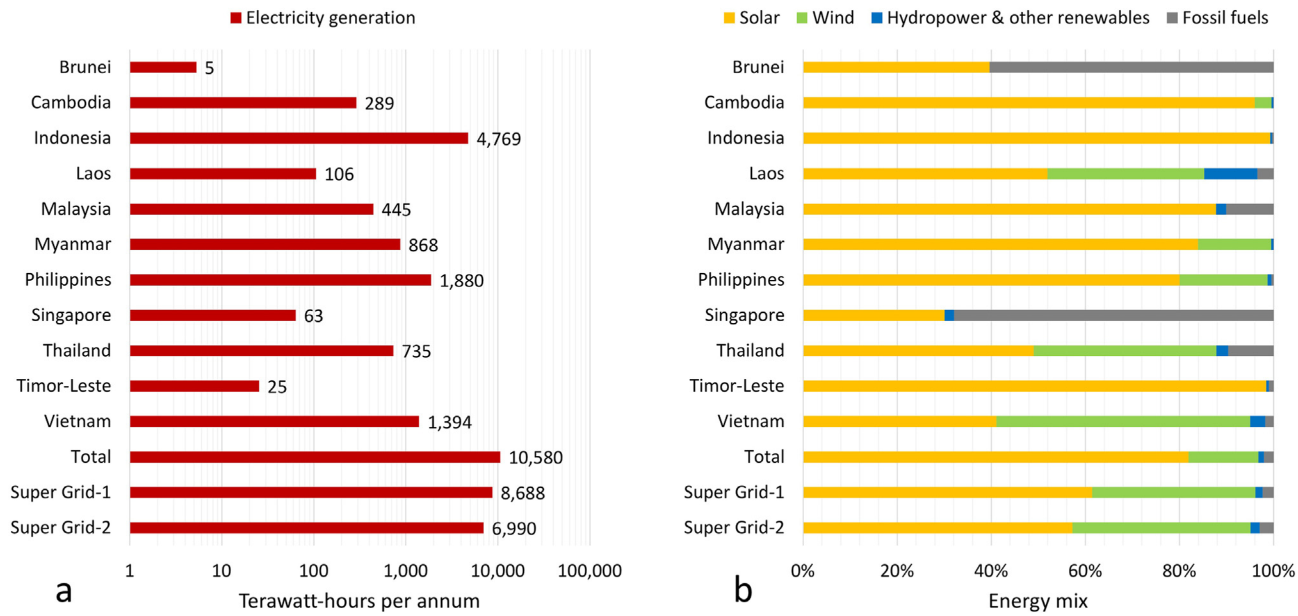

Fig. 5. The electricity generation (a) and the energy mix (b) in the high electricity consumption scenario.

significant contributions in the energy mix of Laos, Thailand and Vietnam, as well as in the Super Grid scenarios. It is highly likely that solar photovoltaics will dominate the market for future renewable energy development in Southeast Asia, due to lack of constraints relating to cost competitiveness, environmental impact, raw material supply, resource availability, security concerns and social factors. Existing fossil fuel assets locally contribute from 0 to 68% of the total electricity generation across Southeast Asia, with a volume-weighted average of only 2%. The fractions of fossil fuels are significant in Brunei (60%) and Singapore (68%) because they lack off-river pumped hydro resources, while using battery storage systems for energy balancing is more expensive than natural gas. Hence, their requirements for natural gas are large.

In Fig. 5-a, the annual electricity generation across Southeast Asia is 10,580 TWh compared with 8,688 TWh and 6,990 TWh in the Super Grid scenarios. This is because the renewable energy supply as well as the electricity demand are smoothed out over a large geographic area with large-scale interconnection of the electricity grids. Hence, the energy spillage is effectively reduced. In addition, the difference between the two Super Grid scenarios is due to the electricity imports from Australia, China and India in the Super Grid-2 scenario.

Huber et al. [33] concluded that an integrated electricity system in Southeast Asia can reduce the system costs by 5%–40%, and the Southeast Asian countries cannot build zero-carbon electricity independently without cross-border electricity trade. In this study, a different conclusion is observed from the results: STORES provides large-scale low-cost storage and hence enables a high level of energy independence in the Southeast Asian countries. This reduces the benefit of geographical smoothing provided by strong regional interconnection. A Super Grid would not result in a significant increase or decrease in the LCOE compared with the scenarios where the electricity grids are not interconnected. In the Super Grid scenarios, there is less storage, and the contributions of wind energy become significant accounting for 35%–38% in the energy mix. This is because the hypothetical Asia-Pacific Super Grid allows the moving of wind energy across Southeast Asia: from north to south where the wind energy resources are scarce.

The land use figures are calculated in Table A of Appendix based on the assumptions of 20 m^2/kW-DC for solar photovoltaics (energy conversion efficiency 20%, ground cover ratio 0.3, and DC/AC 1.2), and 333 m^2/kW for wind turbines (3 MW wind turbines with 1 km by 1 km of spacing), respectively. Overall, the land requirements for solar photovoltaics to provide the electricity needs are only a small fraction (1%–3% in total) of the land area in Southeast Asia, except in Singapore. Deployment of solar photovoltaics can be readily scaled to accommodate increasing electricity demand in Southeast Asia. In addition, there is large potential for floating solar photovoltaics to be deployed in inland reservoirs and the territorial waters, and "Agrivoltaics" [55] allows co-location of large amounts of solar photovoltaics with agriculture. In comparison, the land spanned by wind turbines is large in Vietnam and the Philippines, especially in the high electricity consumption scenario, although the area actually alienated for towers and access roads is only a small fraction. The development of offshore wind provides access to a much larger wind resource. The area of land flooded by a STORES system is about 100 km^2 per TWh of storage volume. Thus, 90-4,500 km^2 of land will be alienated for the storage systems in the various scenarios listed in Table A. This is less than 0.1% of the land area of the countries included in our analysis and is 30–108 times smaller than the area alienated by the solar panels which the pumped hydro storage supports. The water requirement comprises initial fill plus makeup water for evaporation less rainfall. Southeast Asian countries generally have high rainfall, and only a small fraction of available water is required.

Solar photovoltaics and STORES are not constrained by raw materials availability or supply issues. Today, crystalline silicon photovoltaics constitute the vast majority (>95%) of the world's solar photovoltaics markets. Silicon is one of the most abundant elements on the earth. Based on the analysis by Carrara et al. [56], there will be no severe pressure on the global silicon supply chain even when a seven-fold increase occurs in the currently annual deployment of solar photovoltaics worldwide. In addition, the intensities of some specific materials in solar photovoltaics such as silver are expected to decline significantly as the technology advances. Concrete, steel, aluminium, copper and glass used in solar energy and storage are general construction materials and only account for a small proportion of the global supply chains. In

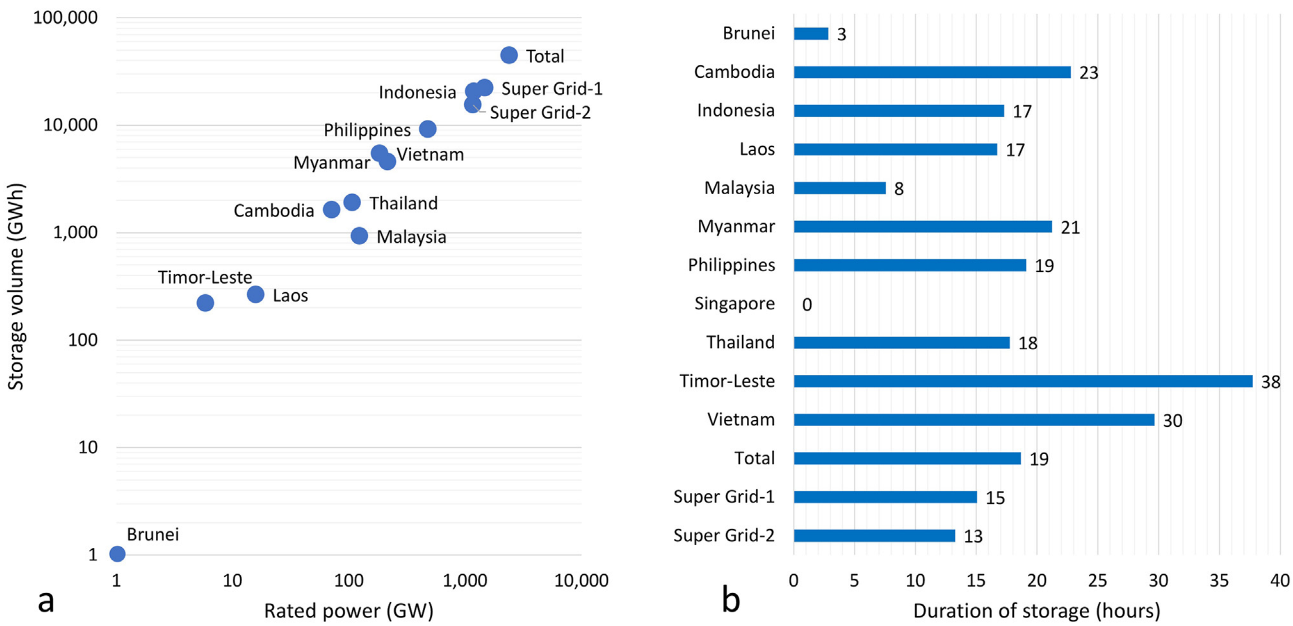

Fig. 6. The storage requirements (a) and the duration of energy storage (b) in the high electricity scenario.

Table 4
A comparison of the storage requirements in different 100% renewables studies for Southeast Asia.

	Electricity demand p.a.	Solar and wind energy integration	Storage requirements
Huber et al. [33]	1,862 TWh	~60%	• Battery 1,000–2,000 GWh • Pumped hydro (limited)
Bogdanov et al. [5]	4,013 TWh	88%	• Battery 5,289 GWh (6 h) • Power-to-gas & gas storage 59 GW, 80,533 GWh • Power-to-heat & thermal storage 180 GW, 615 GWh • Compress air 215 GWh (100 h) • Pumped hydro 8 GWh (8 h)
Jacobson et al. (Case A) [57]	7,721 TWh	94%	• CSP 615 GW, 5,314 GWh • Battery 1,580 GW, 3,065 GWh • Thermal storage 6,293 GW, 1,458,084 GWh • Pumped hydro 76 GW, 1,065 GWh
This study: Low, Medium and High scenarios	2,652 TWh (Low) 5,038 TWh (Medium) 7,524 TWh (High)	78%–85% (Low) 91%–94% (Medium) 95%–97% (High)	• STORES 169–644 GW, 916-8,326 GWh (Low) • STORES 606-1,445 GW, 7,215–25,037 GWh (Medium) • STORES 1,170-2,394 GW, 15,506–44,707 GWh (High) • Battery 0.2 GW, 0.6 GWh

Note. Australia and New Zealand were included in Bogdanov et al.'s definition of Southeast Asia, which accounted for 9% of the total; Bangladesh was included in Jacobson et al.'s definition of Southeast Asia, which accounted for 5% of the total.

comparison, there would be increasing pressure on the supply of rare earths (dysprosium, neodymium, praseodymium, terbium) for wind turbines, though alternative design without permanent magnets is a solution. By contrast, if the current energy mix stays unchanged, the coal and natural gas will heavily rely on imports to cope with the rapidly growing demand for electricity in Southeast Asia, which raises significant concerns about energy security and independence.

3.3. Energy storage requirements

The storage requirements for the high electricity scenario are illustrated in Fig. 6. In Fig. 6-a, the horizontal and vertical axes represent the rated storage power (GW) and the storage energy volume (GWh), respectively. In general, the storage requirements increase both in GW and GWh as the size of the electricity system increases. The total requirements for energy storage are 2,394 GW and 44,707 GWh, while in the Super Grid scenarios, the storage requirements reduce to 1,170–1,480 GW and 15,506–22,299 GWh. Therefore, the Super Grid substitutes for part of energy storage and can significantly reduce the needs for energy storage by 50%–65% in the high electricity consumption scenario. In the low and medium electricity consumption scenarios as included in Table A of Appendix, the storage requirements reduce by 87%–89% and 62%–71%, respectively. In other words, there is a trade-off between energy storage (energy time-shifting) and electricity transmission (energy geo-shifting) in balancing of the renewable energy systems. The GW-km figures of the HVDC overhead, HVDC submarine and HVAC transmission are included in Table A of Appendix. Note that in the Super Grid-2 scenario, the interregional connections to Australia, China and India are constrained as noted in Section 2.3, to ensure a high level of energy independence in Southeast Asia. In the Super Grid-1 scenario, no connections to Australia, China and India are assumed.

From Fig. 6-a, the duration of storage can be calculated, which is the ratio of the storage volume (GWh) to the rated power (GW) as shown in Fig. 6-b. The duration of storage is a useful indicator of the "depth" of energy storage required to support high penetration of

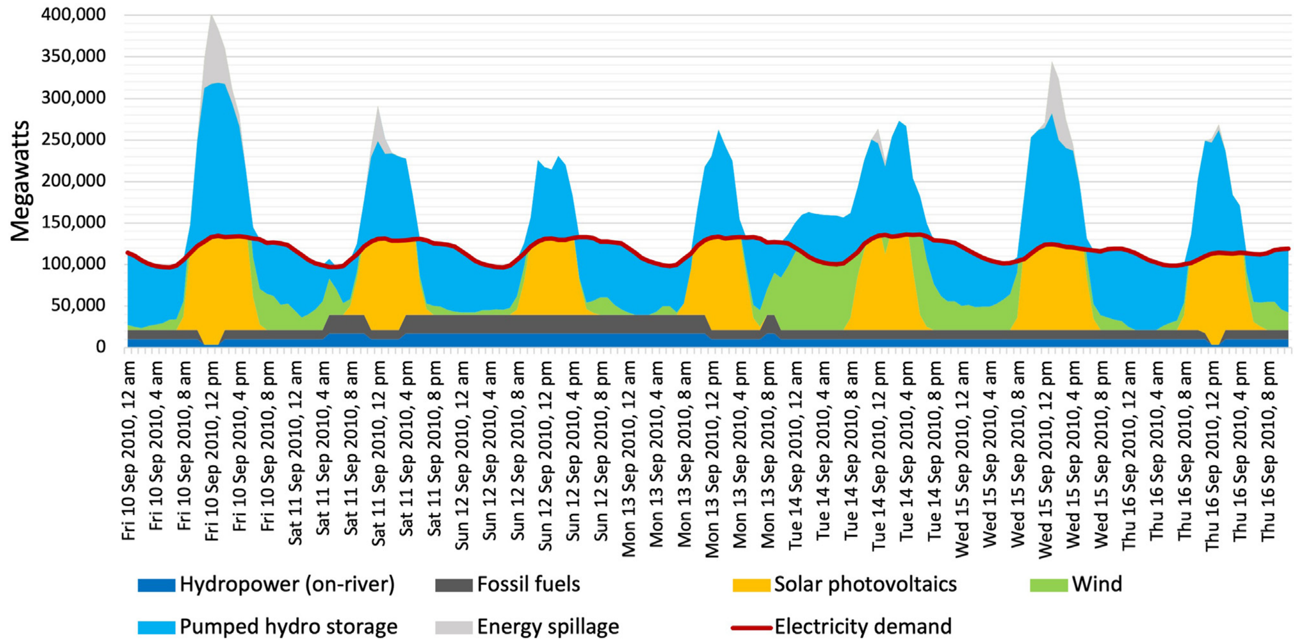

Fig. 7. A snapshot of the energy supply-demand balance for a stressful week with low availability of renewable energy supply in Vietnam.

renewable energy resources. Within all the scenarios, the duration of storage is in the range of 0–38 h, which means hours or days of short-term energy storage are required in Southeast Asia rather than weeks or months of long-term, seasonal energy storage. This is highly likely to be true in the other Sunbelt countries, where the variations in solar resources are low, and there is no significant winter heating load [30].

A comparison of the storage requirements in different 100% renewables studies for Southeast Asia is included in Table 4. As demonstrated, a significant feature of this study is the large-scale deployment of STORES as a primary storage medium, compared with battery, power-to-gas and concentrated solar power in the other studies. As noted in Section 1.2, STORES has a variety of competitive advantages including a high technology readiness level, a high round-trip efficiency, a long service life and is not constrained by raw materials supply. This means it can be a long-term, low-cost solution enabling a rapid renewable energy transition in Southeast Asia. The storage volume required to support this renewable energy integration is only 0.8%–2.2% of the total STORES storage potential in Southeast Asia (2 million GWh). However, unlike batteries which are modular and can be deployed from a kWh-scale, the STORES systems are usually developed on a GWh-scale which requires hundreds of millions of dollars in investment. Therefore, effective mechanisms and energy policies will need to be in place to facilitate the financing, land acquisition and project approval processes.

Fig. 7 illustrates a snapshot of the energy supply-demand balance in the high electricity consumption scenario for a "stressful" week with low availability of renewable energy supply in Vietnam. As demonstrated, the renewable energy supply and electricity demand are effectively balanced on an hourly basis through large-scale energy time-shifting by STORES, supplemented by existing hydropower and legacy fossil fuel assets. STORES can be strategically operated in pumping/charging mode (above the demand curve) to absorb the excess energy from solar and wind farms or in generation/discharging mode (below the demand curve) to fill the gaps between renewable energy supply and electricity demand. Long-term, chronological energy supply-demand balance can be observed from the modelling for all the renewable energy scenarios throughout the simulated period 2010–2019 and are included in Data Availability.

3.4. Emissions reduction

Electricity and heat production contributed to 644 Mt CO2-e, about 43% of the annual greenhouse gas emissions in Southeast Asia in 2018 [1]. If the current emission intensities stay unchanged, the annual GHG emissions from electricity and heat production would increase to 1,551 Mt, 2,947 Mt and 4,401 Mt CO2-e in the low, medium and high electricity scenarios, respectively. Alternatively, if the Southeast Asia countries start deploying renewable energy systems over the coming decades instead of building new coal, then thousands of megatonnes of carbon emissions can be avoided in future electricity and heat production. Further, renewable energy and storage will help improve the air quality, avoiding the fine particulate matter (PM2.5) and ozone concentrations formed by the emissions from coal-fired power plants. Koplitz et al. [4] estimated that the premature mortality due to the coal combustion-related respiratory and cardiovascular diseases can reach about 70,000 by 2030, with the operation of existing and planned coal-fired power plants in Southeast Asia. The death toll would largely increase as the electricity demand grows, if coal still plays a significant role in the future electricity production.

The lifecycle energy use of renewable energy and storage is only a negligible fraction of that of fossil fuels and nuclear energy. The lifecycle emissions of carbon and air pollutants (SO_2, NO_x and PM) from solar photovoltaics manufacturing, installation, operation and recycling can be very low. Compared with thermal power generation, solar photovoltaics only consumes a small amount of water, mainly for cleaning the panels. Solar panel recycling would not be a significant challenge to the existing recycling industry [58]. The STORES systems have low water consumption and moderate environmental footprints. In fact, renewable energy is the most environmentally friendly pathway towards low-emission energy futures, compared with alternative options such as existing fossil fuels with carbon capture and storage (which has negligible global deployment) or nuclear energy [59] (which has net global annual deployment that is two orders of magnitude smaller than for solar photovoltaics and wind turbines). If Southeast Asia starts to build renewable energy and storage instead of new coal to cope with the future electricity growth, then catastrophic damage to the environment can be effectively avoided.

In addition, renewable energy and storage would help reduce environmental and social costs associated with on-river hydropower. These external costs from losses of capture fisheries and from sedimentation, biodiversity reduction and social impacts resulting from the development of 11 mainstream hydropower dams in the Lower Mekong Basin were estimated at about US$18 billion[60]. It would also reduce the risk of insufficient water availability for dam operations in the dry season due to climate change-induced droughts in the Mekong region in recent years.

4. Conclusions

Large-scale integration of STORES is a new approach to providing the system flexibility required for high penetration of variable solar and wind energy in electricity systems. Compared with battery storage, power-to-gas and other storage technologies, STORES has a variety of competitive advantages which can enable a rapid renewable energy transition in the electricity industry. This study is the first to explore the benefits of utilising STORES as a primary storage medium to support 100% renewable electricity futures in Southeast Asia. STORES can facilitate high penetration of variable solar and wind energy in electricity systems through energy time shifting and load levelling. Large-scale integration of low-cost solar and wind energy allows affordable low-emission electricity systems to be built, supporting the future economic growth in Southeast Asia. In addition, STORES is capable of providing a wide range of ancillary services such as frequency control and black start. Hydroelectric generators can contribute significant synchronous inertia and can quickly ramp up or down in response to the variations in renewable energy outputs as well as electricity demand. Consequently, the integration of STORES can effectively enhance the resilience of the electricity grids dominated by variable solar and wind energy. Importantly, pumped hydro storage has a high technology readiness level and is not constrained by the availability of resources or raw materials, which means it can be widely deployed on a large scale, enabling a rapid energy transition in Southeast Asia.

As demonstrated in the modelling, the benefits of the energy transition to renewable energy and storage systems in Southeast Asia are multiple. Firstly, by transitioning to renewable energy futures, Southeast Asia can achieve high levels of energy security and independence. Solar, wind and storage are domestic and are scarcely constrained by factors relating to resource availability, land availability, seasonality, accessibility, raw materials availability and security. Secondly, renewable energy and storage systems are reliable and affordable. The energy balance between renewable energy supply and electricity demand can be met every day and every hour through the energy day-night shifting by STORES. A high-voltage direct-current Super Grid can substitute for part of the energy storage and can significantly decrease the requirements for energy storage at the cost of increased cost of transmission. Thirdly, renewable energy and storage are environmentally friendly and sustainable energy systems, which can deliver long-term and substantial environmental benefits.

Southeast Asia is a typical Sunbelt region, where the solar energy resources and the electricity consumption patterns are significantly different from much of Europe, North America and Northeast Asia. Deployments of renewable energy and storage, primarily solar photovoltaics with support provided by STORES, can be readily scaled and can be a cost-effective way to accommodate rapidly increasing electricity demand in the coming decades. Deep decarbonisation of the entire energy sector can be achieved through direct or indirect electrification of heating, transport, manufacturing and mining, which will be included in a future study. In light of some common characteristics in the Sunbelt (where three quarters of the world's population lives), such as high solar radiation, low seasonality of both solar energy and electricity demand, this strategy is likely to be applicable to the other regions with a tropical or subtropical climate.

Data Availability

The hourly energy supply-demand balance data for the renewable energy scenarios are available from: https://www.dropbox.com/sh/dwn36cp8g6hzm1b/AADpUoN61fsdn4b6tHD96_JYa?dl=0.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A
Energy generation, storage and transmission information.

Country	Electricity demand (TWh)	HVDC loss (TWh)	Solar photovoltaics			Wind			Hydro & others		Fossil fuels		Import		Energy storage		Transmission (1,000 GW-km)			LCOE ($/MWh)
			GW	TWh	Land use	GW	TWh	Land use	GW	TWh	GW	TWh	GW	TWh	GW	GWh	Overhead DC	Submarine DC	AC	
Per-capita electricity consumption: 3 MWh p.a.																				
Brunei	5	0	1	2	1%	0	0	0%	0	0	1	3	0	0	0.2	1	0	0	0.01	89
Cambodia	69	0	57	84	1%	1	2	0.1%	1	1	1	0.4	0	0	22	414	0	0	1	90
Indonesia	1,045	0	853	1,118	1%	0	0	0%	6	25	43	87	0	0	331	4,172	0	0	9	90
Laos	30	0	4	6	0.04%	3	12	0.5%	3	14	2	1	0	0	1	11	0	0	1	55
Malaysia	228	0	166	208	1%	0	0	0%	2	9	27	43	0	0	63	341	0	0	2	87
Myanmar	197	0	156	209	0.5%	13	50	1%	3	6	1	1	0	0	60	1,321	0	0	4	98
Philippines	456	0	297	390	2%	36	131	4%	5	19	14	21	0	0	121	1,544	0	0	10	84
Singapore	62	0	16	19	44%	0	0	0%	0.2	1	14	43	0	0	0	0	0	0	0.2	89
Thailand	208	0	32	43	0.1%	32	121	2%	4	20	34	54	0	0	15	125	0	0	7	69
Timor-Leste	6	0	5	7	1%	0	0	0%	0.04	0.1	0.3	0.3	0	0	2	37	0	0	0.05	84
Vietnam	346	0	22	29	0.1%	64	243	7%	17	65	23	59	0	0	25	360	0	0	13	63
Total	2,652	0	1,610	2,116	1%	150	558	1%	41	162	159	313	0	0	644	8,326	0	0	46	84
Super Grid-1	2,652	100	587	782	0.3%	464	1,726	4%	41	150	159	293	0	0	263	1,084	617	329	99	91
Super Grid-2	2,652	95	462	613	0.2%	333	1,242	3%	41	164	159	366	48	420	169	916	493	341	71	87
Per-capita electricity consumption: 6 MWh p.a.																				
Brunei	5	0	1	2	1%	0	0	0%	0	0	1	3	0	0	0.2	1	0	0	0.01	89
Cambodia	138	0	122	179	1%	2	7	0.4%	1	1	1	0.2	0	0	46	1,056	0	0	2	99
Indonesia	2,090	0	2,224	2,918	2%	0	0	0%	6	20	43	22	0	0	742	12,278	0	0	22	107
Laos	60	0	15	21	0.1%	8	29	1%	3	13	2	5	0	0	6	63	0	0	2	62
Malaysia	256	0	187	235	1%	0	0	0%	2	10	27	47	0	0	72	384	0	0	2	87
Myanmar	393	0	350	469	1%	24	89	1%	3	5	1	0.4	0	0	139	2,955	0	0	8	107
Philippines	913	0	717	938	5%	60	220	7%	5	18	14	13	0	0	300	5,645	0	0	19	97
Singapore	62	0	16	19	44%	0	0	0%	0.2	1	14	43	0	0	0	0	0	0	0.2	89
Thailand	416	0	84	114	0.3%	65	244	4%	4	21	34	94	0	0	37	464	0	0	14	68
Timor-Leste	13	0	11	16	1%	0	0	0%	0.04	0.1	0.3	0.3	0	0	4	123	0	0	0.1	99
Vietnam	692	0	249	305	2%	115	432	12%	17	56	23	44	0	0	98	2,068	0	0	25	73
Total	5,038	0	3,975	5,216	2%	273	1,019	2%	41	144	159	273	0	0	1,445	25,037	0	0	94	95
Super Grid-1	5,038	182	2,214	2,951	1%	627	2,342	5%	41	139	159	235	0	0	843	9,533	1,044	658	148	98
Super Grid-2	5,038	188	1,563	2,061	1%	560	2,087	4%	41	148	159	283	98	862	606	7,215	952	698	128	93
Per-capita electricity consumption: 9 MWh p.a.																				
Brunei	5	0	1	2	1%	0	0	0%	0	0	1	3	0	0	0.2	1	0	0	0.01	89
Cambodia	207	0	189	278	2%	3	10	1%	1	1	1	0.1	0	0	71	1,625	0	0	2	102
Indonesia	3,135	0	3,607	4,733	4%	0	0	0%	6	19	43	17	0	0	1,188	20,534	0	0	36	115
Laos	90	0	39	55	0.3%	10	35	1%	3	12	2	4	0	0	16	264	0	0	2	72
Malaysia	384	0	310	390	2%	0	0	0%	2	9	27	45	0	0	123	933	0	0	3	89
Myanmar	590	0	543	729	2%	36	135	2%	3	5	1	0.2	0	0	216	4,580	0	0	13	110
Philippines	1,369	0	1,150	1,504	8%	96	351	11%	5	17	14	8	0	0	480	9,179	0	0	31	103
Singapore	62	0	16	19	44%	0	0	0%	0.2	1	14	43	0	0	0	0	0	0	0.2	89
Thailand	625	0	266	361	1%	76	285	5%	4	18	34	71	0	0	107	1,905	0	0	18	75
Timor-Leste	19	0	16	25	2%	0	0	0%	0.04	0.1	0.3	0.3	0	0	6	220	0	0	0.2	105
Vietnam	1,038	0	468	572	3%	199	752	21%	17	44	23	25	0	0	184	5,466	0	0	45	85
Total	7,524	0	6,606	8,668	3%	420	1,568	3%	41	127	159	217	0	0	2,394	44,707	0	0	150	102
Super Grid-1	7,524	280	3,979	5,338	2%	808	3,013	6%	41	133	159	204	0	0	1,480	22,299	1,580	984	201	104
Super Grid-2	7,524	305	3,021	3,999	1%	712	2,649	5%	41	134	159	208	160	1,405	1,170	15,506	1,372	1,064	173	98

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