 DOI 10.1515/green-2012-0013 — Green 2012; 2(4): 189–202

Andrew Blakers*, Joachim Luther and Anna Nadolny

Asia Pacific Super Grid – Solar electricity generation, storage and distribution

Abstract: This paper explores the large scale transmission of solar electricity to Southeast Asia from Australia. Despite the expense and losses incurred in long distance transmission of Australian solar electricity, it appears to be competitive with locally produced solar electricity because of high insolation levels in Australia. Supplementation of locally produced electricity (both from renewable and conventional sources) with power from Australia, together with substantial integrated energy storage, would allow a high solar electricity fraction to be achieved in Southeast Asia.

Keywords: solar energy, HVDC, photovoltaics, energy storage, renewable energy

PACS® (2010). 88.05.Lg

***Corresponding author: Andrew Blakers:** Australian National University, Centre for Sustainable Energy Systems
E-mail: andrew.blakers@anu.edu.au
Joachim Luther: Solar Energy Research Institute of Singapore (SERIS), E-mail: joachim.luther@ise.fraunhofer.de
Anna Nadolny: University of NSW
E-mail: anna.nadolny@hotmail.com

1 Introduction

Rapidly falling costs of solar electricity generation, coupled with rising concern about anthropomorphic greenhouse gas emissions, suggest a bright future for solar energy technology.

The 12 contiguous Southeast Asian countries of Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Papua New Guinea, Philippines, Singapore, Thailand, Timor-Leste and Vietnam comprise about 600 million people, about 9% of the world's population (1). The average population density is 120 people per square kilometer, similar to that of Europe, and well above that of Africa, Australia and the Americas. Southeast Asian countries have rapidly growing economies leading to rapidly growing energy demand (2). The continent of Australia has a population of 23 million people and an average population density of 3 people per square kilometer. Australia is well endowed with indigenous energy resources. In particular, Australia has immense solar energy resources in the centre and northwest (3).

A glance at the South East Asian page of a world atlas shows a long and narrow chain of islands between Australia and the Malay Peninsula. Major desert regions exist to the north (central China) and south (central and north west Australia). This dipole suggests the possibility of transporting large quantities of solar electricity to South East Asia via high voltage cables from large solar farms located in Australia, and solar and wind farms in China. The latitudes are 20°S and 40°N respectively, which would provide seasonal balance to the solar resource from each region. In addition to this such a cable could also distribute solar electricity produced within South East Asia in an effective way.

The distance between the desert regions of NW Australia and central China is about 9000 km, with Malaysia being equidistant between the two. Countries to the north of Malaysia could be supplied predominantly from China, while Australia could supply the southern countries. The population centres of SE Asia and the deserts of China have the same longitude, which is 30° (two hours) behind the deserts of NW Australia. This causes a modest time shift of the daily peak of Australian solar production into the afternoon in SE Asia.

This paper explores the possibility of the supply of solar electricity by a high voltage DC (HVDC) power line from northern Australia to four SE Asian countries. The line could run via Timor-Leste, Indonesia, Singapore and Malaysia. Each of these four countries is narrow and lies approximately in a straight line, allowing efficient delivery and distribution of electricity from Australia via a "backbone" HVDC cable. Other Southeast Asian countries, notably the Philippines, also could benefit from the supply of solar electricity via HVDC. However, distances to population centres are greater, populations are smaller and the countries are less "linear". This study could be extended to other Southeast Asian countries at a later time.

The distance involved is 4500 km, including a minimum 500 km undersea cable. This would be a major engineering feat by today's standards. However, the required technology already exists, and will continue to improve.

In undertaking the study, the following major aspects were considered:
- Current and future electricity demand in Southeast Asia;
- Energy options for Southeast Asia;
- Solar electricity generation in Australia and SE Asia;
- Transportation of the electricity via HVDC cable;
- Short term storage of a substantial fraction of the generated solar energy locally within Australia in order to even out the load on the HVDC cable and to mitigate solar energy intermittency.

These aspects are considered in turn. The feasibility and cost of providing one third of the required electricity for these countries by HVDC cable from Australia by 2050 is then estimated. The fraction one third was selected for this scenario on the basis that it is substantial but would still allow room for diverse electricity sources within each country to maintain robustness.

The feasibility of transporting large quantities of renewable electricity has been considered for other regions, notably by the Desertec foundation and the Desertec Industrial Initiative (Dii), who propose to transport solar and wind generated electricity from North Africa to Europe (4).

Fig. 1: Planned route for HVDC backbone.

2 Electricity demand

2.1 Regional Populations and energy demand

South East Asia comprises mostly developing countries, as characterised by per capita electricity consumption. Indonesia is by far the largest SE Asian nation, and has the fourth largest population worldwide (5).

2.2 Current and projected electricity consumption

SE Asian countries have historically had low electricity consumption compared with industrialized countries, as listed in Table 1 – currently in the range of 10% of the per capita electricity consumption of industrialized countries such as Australia. Millions of people within this region still do not have access to centrally generated electricity (Table 2).

	Area (Mm^2)	**Population (millions) 2010**	**Population density (km^{-2})**	**Population projection (millions) 2050**
Timor-Leste	15	1.1	76	3
Indonesia	1911	240	126	294
Singapore	0.7	5	7169	6
Malaysia	331	28	86	44
PNG	463	7	15	14
Brunei	6	0.4	69	0.6
Philippines	300	93	311	155
Total/Average	**3026**	**375**	**124**	**517**
Australia	7692	22	3	31

Table 1: Area and population for selected SE Asian countries. (The data for electricity consumption is sourced from (5); the 2010 and 2050 populations from (6)). PNG = Papua New Guinea.

Country	Percentage Electrification
Cambodia	16
Indonesia	53
Malaysia	97
Myanmar	5
Philippines	87
Singapore	100
Thailand	99
Vietnam	76
Papua New Guinea	46
Timor-Leste	22

Table 2: Percentage electrification for selected SE Asian countries (7).

Rising living standards and rapid industrialization are correlated with rising per capita electricity consumption and rising rates of electrification. Rapid growth in electricity consumption can be expected in Southeast Asia over the next few decades. For example, the demand for electricity in Indonesia is rising at around 7% p.a. (8).

Substantial improvements in energy efficiency over the next few decades may allow per capita electricity consumption in industrialized countries to fall, following the long-term trend of reductions in electricity per unit of economic output observed in most OECD countries. Over the next forty years it is expected that the difference in per capita electricity consumption between non industrialized and industrialised countries will sharply decline. The scenario selected for this study entails an increase in per capita electricity consumption of 5% p.a., saturating at a consumption rate of 8 MWh per year per capita (which is the current per capita annual consumption in Singapore and Brunei). This results in a 5-fold increase in average per capita consumption of electricity across the seven selected countries shown in Table 3, and a 7-fold increase in total consumption.

3 Electricity generation

3.1 Energy options for Southeast Asia

Current electricity generation in Southeast Asia is overwhelmingly from natural gas and coal, supplemented by hydroelectricity, geothermal electricity and oil burning. There is no nuclear generation (9), (10), (11), (12), (13), (14), (15).

Reductions in greenhouse gas emissions from electricity generation could cause a substantial shift to renewable energy generation. Wind energy resources are limited in tropical regions. However, there is substantial scope for greater use of biomass, hydroelectricity and geothermal electricity (e.g. 2). Philippines and Indonesia are ranked second and third in installed geothermal capacity respectively after the United States of America (16). The substantial hydroelectric potential is tabulated in Table 4. Large scale use of biomass, hydroelectricity and geothermal electricity entail substantial conflict with environmental,

Country	Gross Theoretical Capability	Technically Exploitable Capability	Economically Exploitable Capability
Australia	265	100	30
Cambodia	88	34	5
Indonesia	2147	402	40
Malaysia	230	123	
Papua New Guinea	175	53	15
Philippines	47	20	18
Thailand	18	16	15
Vietnam	300	123	100
Total	**3270**	**871**	**223**

Table 4: Hydroelectricity potential for selected Southeast Asian countries (2008, TWh pa) (17).

	Total (TWh p.a.) 2010	Per capita (MWh p.a.) 2010	Total (TWh p.a.) 2050	Per capita (MWh p.a.) 2050
Timor-Leste	0.6	0.6	12	4
Indonesia	126	0.5	1140	4
Singapore	42	8	48	8
Malaysia	102	4	352	8
PNG	3	0.4	47	3
Brunei	3	8	5	8
Philippines	59	0.6	726	5
Total/Average	**335**	**0.9**	**2330**	**4.5**
Australia	261	12		

Table 3: Electricity consumption for selected SE Asian countries (5). PNG = Papua New Guinea.

cultural and economic values due to competing land use (17). For this reason, the Sustainably Exploitable Capability is likely to be considerably smaller than the Economically Exploitable Capability.

As with most countries, by far the largest indigenous energy resource is solar energy. Despite its tropical location, solar insolation is substantially lower in Southeast Asia than for dry temperate regions such as Australia, although it is considerably higher and has less seasonal variation than higher latitude regions such as Germany (17).

In order to gauge the feasibility of transmission of substantial solar electricity from Australia to Southeast Asia, we assume that one third of demand in 2050 is met from Australian solar energy, one third from indigenous solar energy, and one third from conventional energy sources. Under this scenario, the consumption of Australian-sourced electricity in Timor-Leste, Indonesia, Singapore and Malaysia in 2050 would be 517 TWh per year.

Under the scenario described in more detail in later sections, the area of land required in northern Australia, taking into account storage and transmission losses, is about 3200 km^2 (0.04% of Australia's land area). The area of land required for solar energy collectors in Timor-Leste, Indonesia, Singapore and Malaysia is about 4000 km^2 (0.17% of the land area). The ability to locate solar energy converters on buildings could substantially reduce the area of land alienated by mass deployment of solar electricity generation. The fact that only part of a typical solar farm area is covered by solar energy converters, with the balance being available for some forms of agriculture, further mitigates the environmental impact of solar energy conversion.

3.2 Solar electricity generation in Australia

The northern and western regions of Australia are arid, lie within the tropics, and have very high insolation. The global insolation on a fixed module mounted facing north at an angle of 20° to the horizontal is about 2500 kWh/m^2 per year, and on a north-south single axis tracking surface the global insolation is about 3400 kWh/m^2 per year (18). Resources for wind energy, hydroelectricity, biomass, geothermal and other renewable energy sources are relatively poor in northern Australia.

For solar electricity generation three mature technologies are available: flat plate photovoltaics (PV, tracking and non-tracking the sun's position), photovoltaics under (high) optical concentration (CPV) and tracking concentrating solar thermal power plants (STP). By far the highest system efficiency values are achieved using CPV technologies. However, flat plate PV currently has better cost effectiveness. Concentrating solar thermal systems generate electricity at efficiency values similar to those of flat plate PV but advantageously incorporate (thermal) energy storages into the systems (19), (20). Both concentrator technologies operate efficiently under direct beam solar radiation only. In central and northwestern Australia the direct beam insolation on a tracking surface exceeds 80% of the global insolation on a tracking surface over the course of a year. However, in tropical areas this ratio is only 50–70% due to more abundant atmospheric water vapour and clouds. Thus the deployment of CPV and STP systems is restricted to high direct beam radiation regimes.

Flat Plate PV tracking systems can be efficiently applied almost everywhere. They have the substantial advantage that solar energy production is spread over more hours of the day (21). This reduces the ratio of peak to average power production and hence reduces the cost of DC to AC inversion, storage and transmission systems, although at the cost of slightly increased operations and maintenance cost.

In this study we assume for simplicity that the solar energy converters are non-concentrating PV modules mounted on single axis tracking systems. Large professionally managed PV systems are likely to achieve performance ratios above 75%. That is, the average AC power production (kW_{AC}) under standard irradiation (1 kW/m^2) is above 75% of the nameplate DC capacity (kW_{DC}). The as-

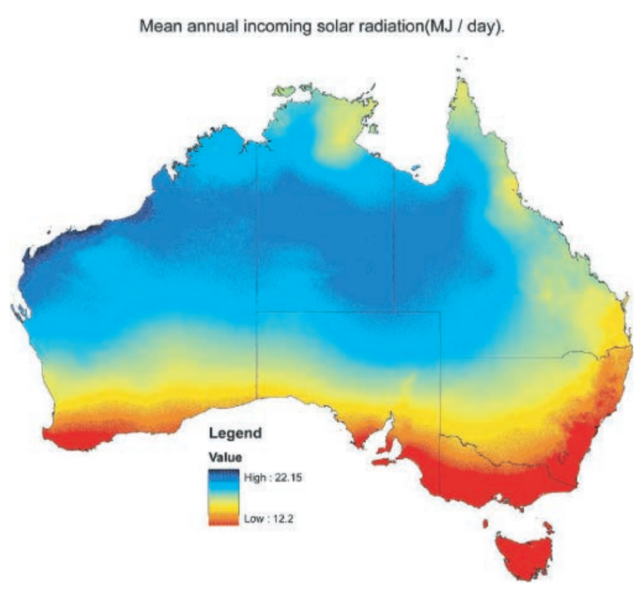


Fig. 2: Mean annual Australian solar irradiation (MJ/day) on a horizontal surface (22).

sessed performance ratio accounts for losses associated with the elevated temperature of the modules, soiling, losses in the DC to AC inverters, resistive losses, variable spectral content, system non-availability, and an expected slow annual decline in module performance. The expected annual output of a non-concentrating Megawatt rated PV system in NW Australia under these assumptions is about 1900 and 2500 MWh (AC) for fixed and single axis tracking systems respectively.

In this study we assume an average efficiency of PV modules under standard conditions of 21%, which is similar to the efficiency achieved by the best commercial solar PV modules today. A land occupation factor of one third is assumed (to allow for service areas and to minimize self shading). These assumptions yield a nominal system efficiency of 7% (i.e. a nominal DC capacity of 70 MW per km^2 under standard conditions). The realistic average energy yield of this system is 0.18 TWh (AC) per year per km^2.

Seasonal variability of insolation on tracking surfaces is modest in central and Northwestern Australia, generally in the range +/– 15% about the mean (Figure 3). This is because of the subtropical latitude and the absence of a wet season away from the coastline. This small variability reduces the size of a solar farm required to meet a given minimum seasonal load.

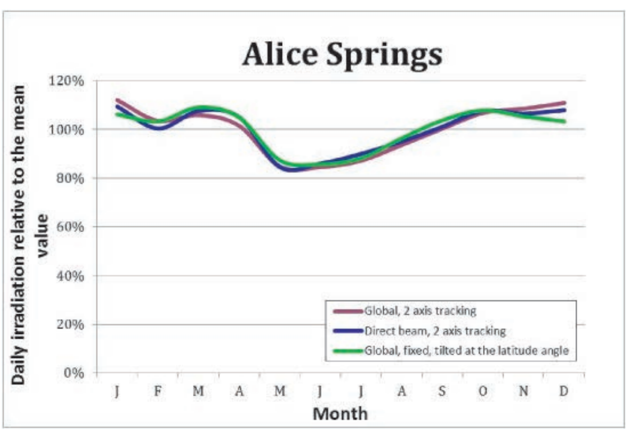


Fig. 3: Seasonal variability of irradiation at Alice Springs (18).

3.3 Solar generation in Southeast Asia

Southeast Asia has poorer solar resources than northern Australia despite its tropical location. Seasonal variations, including monsoons, mean that insolation is low for significant periods of the year. Table 5 tabulates the radiation incident for various locations within South-East Asia and Australia. In this study, the solar availability in Southeast Asia is assumed to be 70% of that in northern Australia.

3.4 Cost of solar generation

The cost of PV modules has declined by a factor of five, and annual sales have grown by a factor of 100, since 2000 (23). The industry has followed a logarithmic experience curve for 35 years whereby the cost of PV modules declines by about 20% for each doubling of cumulative production.

Retail grid parity is now widespread, whereby the levelised cost of electricity from PV systems is below the domestic and commercial retail electricity tariffs (20). As costs continue to fall, ever more regions of the world will achieve grid parity, and industrial grid parity will also become widespread. It is widely expected that large further reductions in PV module costs will be possible in the future, caused by further technical improvements and continued rapid growth in sales (and hence production

City	Latitude	MJ/m^2 day		Relative	GJ/(m^2 yr)
Singapore	1	15.8	Global, horizontal plane	64%	5.8
Bangkok	14	17.3	Global, horizontal plane	70%	6.3
Kuala Lumpur	3	17.6	Global, horizontal plane	72%	6.4
Canberra	35	17.6	Global, horizontal plane	72%	6.4
Canberra	35	20.1	Global, latitude angle	82%	7.3
Port Hedland	20	22.9	Global, horizontal plane	93%	8.4
Port Hedland	20	24.6	Global, latitude angle	100%	9.0
Port Hedland	20	34.6	Global, 2-axis tracking	141%	12.6
Port Hedland	20	28.6	Direct beam, 2-axis tracking	116%	10.4

Table 5: Insolation at selected sites in Australia and Southeast Asia. The column labeled Relative tabulates annual insolation relative to that of a plane inclined at the latitude angle at Port Hedland in northwestern Australia (defined as 100%).

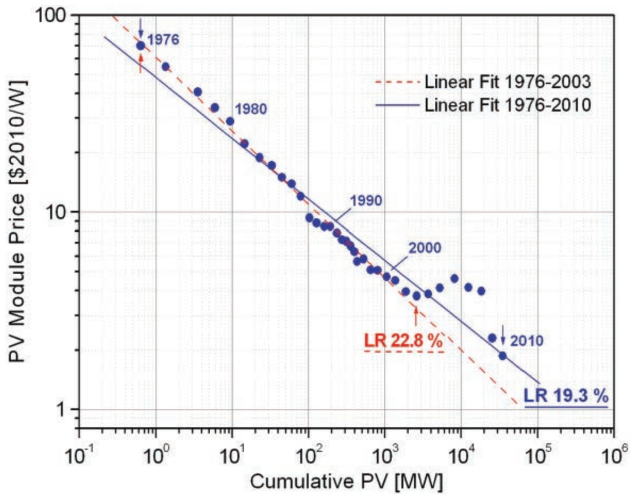


Fig. 4: Decrease in photovoltaic price with increased installation (23).

experience). Eventually of course the rate of cost reductions will decline.

High quality PV systems can be purchased today for a price of less than US$3000 per kW nominal power under standard conditions (23). It is not possible to reliably predict the price of PV systems decades into the future. In this study we adopt the conservative assumption that the purchase price of large PV systems declines by 2% per year from $3000 per kW, reaching $1300 per kW in 2050. We assume a 30 year system life and an annual operations and maintenance cost of 1% of the capital cost. In this study the cost PV generation in both Australia and Southeast Asia is modeled with similar assumptions, and is presented in Table 7.

4 High voltage DC transmission

4.1 Benefits of Long Distance Transmission

Current transmission grids within industrialized countries are based around a relatively small number of large fossil, nuclear and hydro power stations (24). Load management is practised by offering reduced prices at times of low demand. Increasing scale of interconnection confers robustness of supply, allows smoothing of total demand by increasing the variety and timing of loads, and allows the incorporation of more varied power sources including pumped hydroelectric storage. Continent-wide transmission grids are emerging and are being strengthened for sound economic reasons. Long distance transmission increases competition within markets (25), (26), (27).

Greater penetration of fluctuating renewable electricity sources is occurring, particularly from wind and solar. When compared with conventional generation, these energy resources have quite different characteristics. Although PV allows distributed generation of electricity, renewable energy generation is often far removed from cities, and energy must be transmitted over long distances. Examples include offshore wind generation and solar generation in desert regions (28), (29).

Transmission of electricity over long distances generally utilizes high voltage direct current (HVDC) technology. Since the power transmission capacity scales with the square of the transmission voltage, voltages in the range of hundreds of kilovolts are used. High voltage and power alternating current transmission is technically infeasible over long distances (25). HVDC has additional advantages relating to reduced transmission easements (30), (31) and reduced induced current flowing through people living and working near DC overhead transmission lines (30).

4.2 HVDC technology

HVDC technology was first used to link Gotland with mainland Sweden in 1954. This link was capable of transporting 20 MW, at 100 kV, over a 98 km underwater cable (32). Since this installation, distances spanned, voltages attained and power transmitted have all experienced massive increases. The longest HVDC line to date is in China, connecting the Xiangjiaba Dam to Shanghai, spanning a distance of 2071 km and transmitting up to 6400 MW at ± 800 kV (33). The ± indicates that the transmission line is bipolar.

The two main types of HVDC technology are Current Source Converters and Voltage Source Converters. The former is the more mature technology, and is otherwise referred to as HVDC Classic, or LCC HVDC. Thyristor valves are used, and the system is line commutated. As a more established technology, the voltages and power transmission capability is much greater than its younger counterpart.

Voltage Source Converter HVDC was introduced in the late 1990s. These systems are self-commutated and make use of insulated-gate bipolar transistors. VSC HVDC has better controlling technology than LCC HVDC, such that the active and reactive power can be swiftly controlled without dependence upon the other. There is no restriction upon the minimum short-circuit capacity. This means DC-AC converters can be positioned at any point in the AC network. Black starts are possible, because of the self-commutation (34), (35).

	Area (Mm^2)	Population projection (millions) 2050	Electricity consumption (TWh p.a.) 2050	Cable length (km)
Timor-Leste	15	3	12	1200
Indonesia	1911	294	1140	2900
Singapore	0.7	6	48	3900
Malaysia	331	44	352	4200
Population-weighted average (2050)				**3100**

Table 6: Summary of parameters of the distance between the Tanami Desert (Australia) and the capital city of four selected countries.

Underground cabling has environmental and aesthetic benefits, and the transmission easement is much smaller. However, underground cables that are capable of transmitting more than ± 500 kV, and 2000 MW, have not yet been developed (31). Mass-impregnated cables cannot be practically utilized underground, and no extruded polymer cable has been capable of carrying such high voltages. Underground cabling can cost up to ten times that of overhead lines (36).

HVDC cables can be configured in several ways. Monopolar systems involve a single cable, with the midpoint grounded, and earth or metallic return. Submarine monopolar cables can be designed to have sea return, but this can produce corrosion in underwater infrastructure, and also cause chlorine gas to form at the terminals (37), (38). Bipoles are simply two monopoles joined together, and can also have metallic return. These cables can be built in parallel in order to transmit more power. Back-to-back systems are built to join two asynchronous AC grids, for example linking between separate regional transmission systems within the US (39). This can also be beneficial for weak AC systems (40), (41).

The right of way needed for HVDC is substantial. On land, corridors of around 60 m width are necessary for the installation of a 5 GW cable (31). Obtaining access rights is a significant impediment to HVDC transmission. Underground cables require a much narrow corridor, but are more expensive and less capable of transmitting large amounts of power.

Feasibility studies suggest that ± 800 kV HVDC systems are currently the most economically efficient way to transmit large amounts of power over long distances (42), (43). The transmission losses associated with an 800 kV DC power line with 5 GW capacity is quoted by Siemens as 3% per 1,000 km (44). In addition, there is a few percent conversion loss at the two ends of the cable (38), (45).

In order to derive an effective transport distance the population-weighted cable length was calculated from the product of the distance from northwest Australia to the capital city of each country, and the population of that country, normalized by total population of Southeast Asia. The population-weighted length of a cable running from northwestern Australia to Malaysia is 3,100 km (Table 6). The cable capacity could be stepped down to match the required capacity as it passes various load centres – although in practice the benefits of strongly interconnecting Indonesia with other parts of Southeast Asia could mean that a large-capacity transmission system is extended to the north of Indonesia. In summary, 10–15% power losses can be expected in a cable running from Australia to Malaysia via Indonesia. In this study a transmission and conversion power loss of 12% is adopted.

Undersea HVDC cables are technically challenging compared with HVDC cables on land, and so the length of undersea cable should be minimized. The minimum distance between northern Australia and Timor is 500 km, which is less than the length of the NorNed undersea cable between Holland and Norway (580 km). The NorNed cable is a 700 MW cable beneath shallow seas transmitting at +/– 450 kV DC (46).

The Timor Trench is a significant technical obstacle to a direct Australia-Timor link, with depths of up to 3300 m. However, careful route choice would limit maximum depths to 1800 m. Research suggests that deep sea transmission is possible to depths of 2000 m (47). The machines currently used to lay cables work to a depth of 1000 m (48).

Alternative routes exist between Australia and Southeast Asia that traverse only shallow water. One option would be from the Northern Territory to West Papua, and another would be from the tip of Queensland to Papua New Guinea. The deepest water encountered in these routes is only 55 m. However, they are considerably longer than the route to Timor-Leste, and do not traverse substantial population centres.

Water depths and distances between the Indonesian islands are relatively small. Connections could be underwater or could utilise overhead cables supported by towers, depending upon distance.

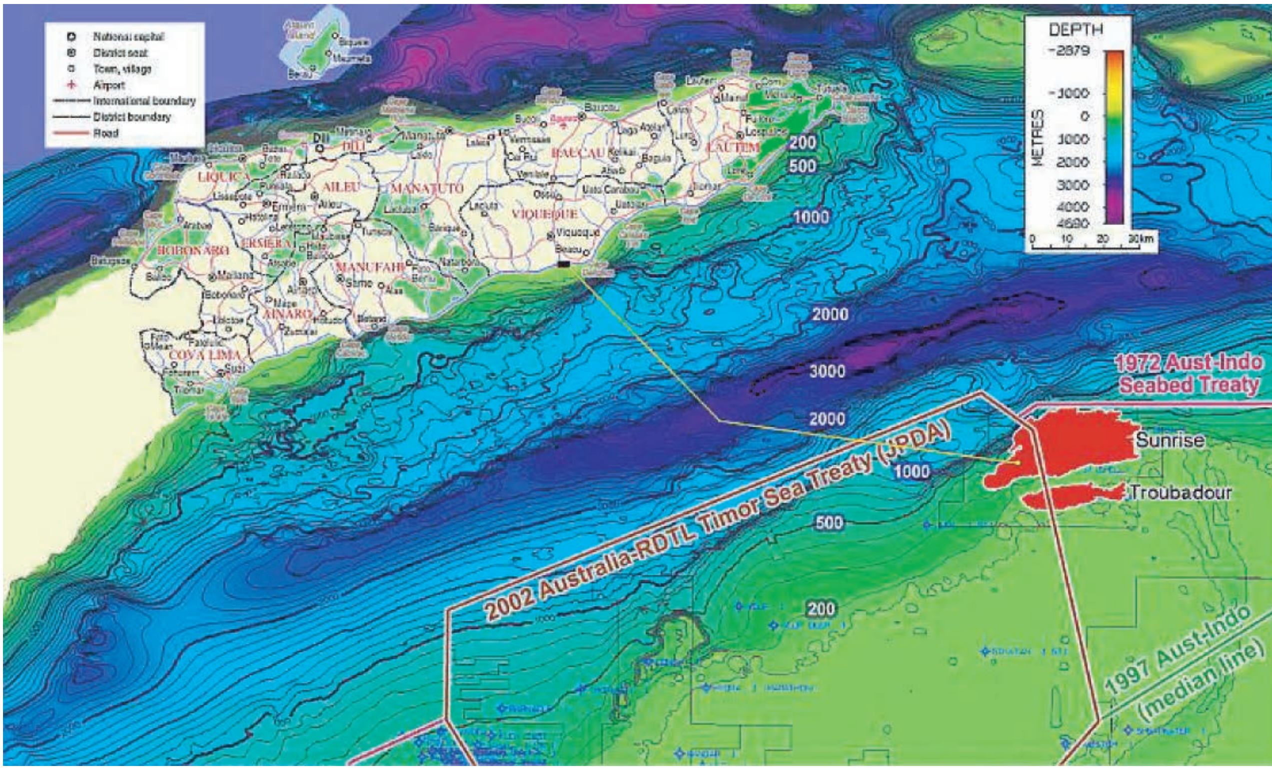


Fig.5: Ocean depth between Australia and Timor (49).

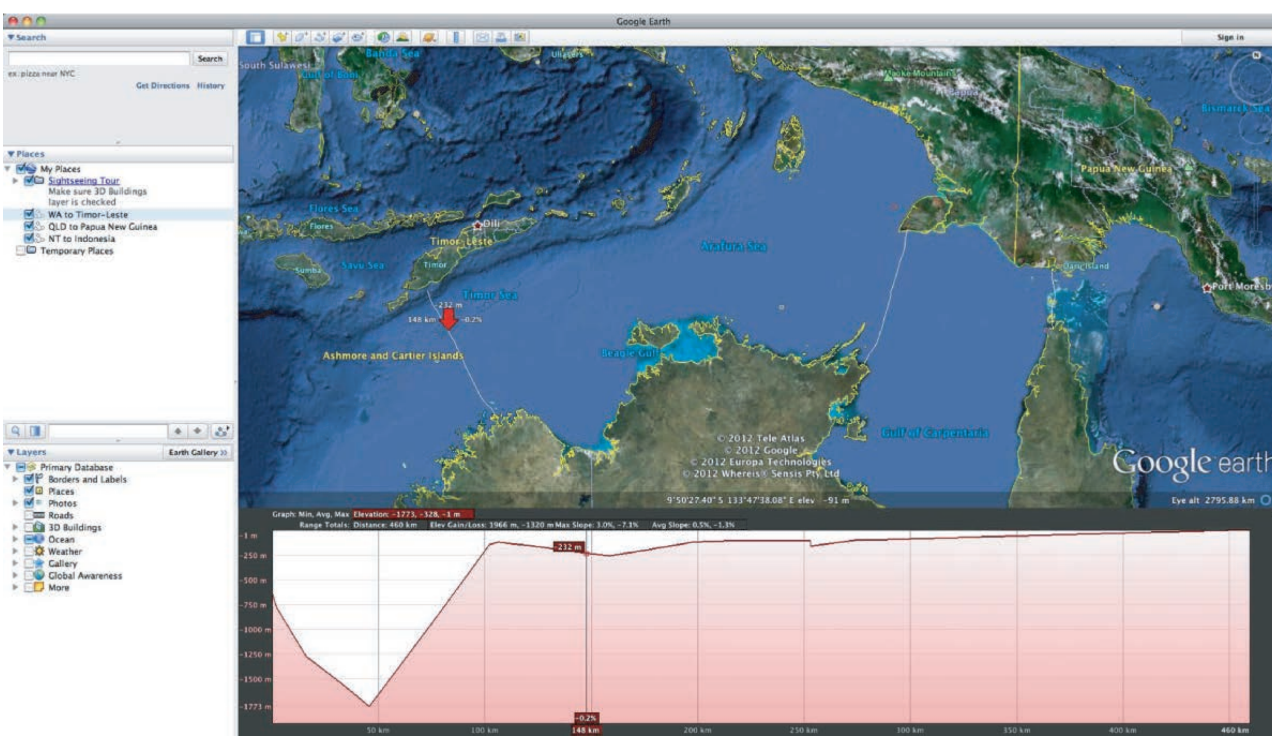


Fig.6: Potential pathway for HVDC line modelled in Google Earth.

4.3 Cost of HVDC cables

The cost of HVDC cables can be conveniently referred to in terms of dollars per megawatt-kilometer (US$/MW km). It is to be expected that US$/MW km costs will generally be lower for long and large power cables due to more effective amortization of fixed costs. More recent cables are expected to have lower costs than earlier cables due to rapid technical developments and learning experience gained from rapid proliferation of long high-power cables.

Reliable estimates of the cost of HVDC cables are difficult to find in the literature. Many of the HVDC projects around the world are located in China (50). The world's largest HVDC project was recently announced, to connect eastern Xinjiang with the central city of Zhengzhou. This cable has a capacity of 8 GW, a length of 2200 km and a reported cost of US$3.7 billion (US$210/MW km) (51). Costs quoted by various sources for high-power long-distance HVDC cables are in the range US$110–500 per MW km (31), (33), (46), (51), (52), (53), (54), (55), (56), (57), (58), (59). Costs of large HVDC cables can be expected to decline substantially as many more are constructed in coming decades.

In this study an average figure of US$300 per MW km is adopted. This accounts for future reductions in cost arising from far greater utilization of HVDC, and the substantial cost of the 500 km undersea cable between Australia and Timor.

5 Local storage

5.1 Benefits of local storage

Long distance power transmission cables are expensive, and so it is desirable that they operate near full capacity for most of the time. Solar insolation peaks during the day and is zero at night. Short term storage within Australia would allow continuous flow of power at close to the capacity of the transmission system over the full 24 hour cycle. This would allow the capacity of the transmission system to be reduced by a factor of up to 4 for a given daily energy transmission compared with the case without storage. Additionally, it would effectively convert solar electricity to dispatchable electricity. A high solar fraction, regardless of whether it is produced locally or imported, will require daily storage to stabilize supply in the face of variable demand and solar intermittency. Demand management and solar forecasting mitigate storage requirements.

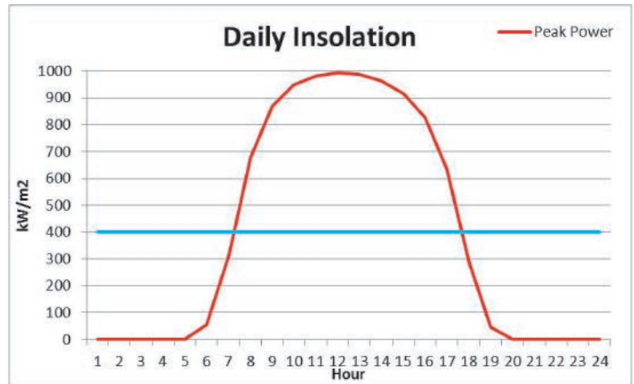


Fig. 7: Comparison of electricity output of a solar system under clear sky conditions (red) and average electricity generation (blue) (18).

Storage will also be required for solar energy production in Southeast Asia in order to ensure reliability. This storage will be more expensive than an Australian equivalent because of the far higher cost of land and the higher variability of solar insolation (i.e. the larger ratio between peak and average electricity production).

5.2 Pumped hydro storage

Pumped hydro energy storage (PHES) is by far the largest scale energy storage technology currently deployed, with a combined world wide capacity of ~130 GW (60), (61) (99% of worldwide storage capacity for the electricity industry). Water can be pumped to an upper reservoir during periods of low electricity demand and returned to a lower reservoir through a turbine during periods of high electricity demand. The lower reservoir can be a dam, the sea or deep underground caverns (62), (63). A common application of PHES is arbitrage between periods of high and low electricity demand, corresponding to periods of high and low electricity value respectively (64).

Most PHES systems are combined with hydroelectricity production from a river. However, PHES systems can also be constructed independently of a river, since water is recycled between upper and lower reservoirs. The only water requirement during operation is to replace the difference between rainfall and evaporation. The civil infrastructure of PHES systems has a lifetime in the range of 100 years. The main environmental impact of PHES is the alienation of land covered by lakes (65). An advantage of off-river PHES is that the expense of coping with floods is avoided.

PHES provides very rapid response (< 1 minute) to support fluctuating solar availability and consumer demand (66). PHES is capable of supplying voltage regulation, spinning reserve, frequency control and system restart (67). A round trip efficiency of 70–90% is achievable (i.e. 10–30% of the stored energy is lost during pumping and generation) (60), (66). For the application studied in this study, daily rather than seasonal storage is required, which means that relatively small and low cost lakes are required. For this study, storage is assumed to utilise PHES.

Several other large scale energy storage technologies may be available by 2030–2050. These include compressed air in caverns, advanced batteries and solar thermal storage by means of molten salt. Should the cost of these technologies decline rapidly then they may become competitive with pumped hydro. Thermal storage would be a key element of any large scale solar thermal electric generation in NW Australia (68), (69), (70). However, none of these storage technologies have been deployed at significant scale, and future costs and technical feasibility are more speculative than for PHES. In this study, storage is assumed to utilise PHES.

Because daily rather than seasonal storage is primarily required, pumped hydro storage costs are heavily weighted towards the cost of power production (turbines, pumps and pipes) rather than the cost of energy storage (large dams and lakes) – it is necessary to move energy in and out quickly rather than store energy for the long term. A lake with a useable depth of 20m is able to store 15 GWh per km^2 assuming a round trip efficiency of 80% and an elevation difference between upper and lower lakes of 300 m.

Lake Argyle is a large (1000 km^2) artificial lake on the Ord River in the coastal region of NW Australia, with the water surface at an altitude of 87 m. The Ord River is fed by monsoonal rain and has an average annual flow of 3.9 km^3. It lies close to the likely path of a transmission cable between the Tanami desert in northern Australia and Timor. There is a substantial area of land nearby at an altitude of around 400 m. This 300 m elevation difference suggests the possibility of large scale pumped hydro energy storage. Other storage solutions, including PHES at other sites, are also possible.

Storage of half of the daily Australian electrical energy production to be transmitted to Southeast Asia is modeled in this study. Utilizing PHES with an elevation difference of 300 m between upper and lower lakes, would require an upper lake with depth, area and volume of 20 m, 55 km^2 and 1.1 km^3 respectively. The upper lake is rather small compared with the modeled generation capacity (118 GW) and does not have to cope with floods. Most of the cost is in the power systems (pumps, turbines, pipes and tunnels) rather than the energy storage system (the lake). For comparison, the Three Gorges Dam in China has generation capacity of 23 GW, maximum depth, area and volume of 180 m, 1045 km^2 and 39 km^3 respectively, and must cope with large floods.

Fig.8: Lake Argyle (71).

5.3 Cost of pumped hydro storage

The cost of PHES systems is site-specific, and depends upon geography, scale, cost of land, cost of interconnection to the grid and availability of related infrastructure. A literature search suggests that the cost of PHES systems is in the range US$600–1800 per kilowatt (62), (72), (73), (74), (75), (76). A very large scale PHES system constructed several decades hence, and utilizing small lakes relative to power capacity, as envisaged in this study, is likely to have costs at the lower end of this range. The cost adopted in this study for PHES is US$600 per kW.

6 The cost of large-scale supply of Australian solar electricity

In calculating levelised costs, a 5% real (inflation free) discount rate is used, together with a 30 year system life and an annual operations and maintenance cost of 1% of the capital cost. The cost of land acquisition for solar farms, PHES reservoirs and transmission corridors is included at a rate of US$5 and US$5,000 per hectare in Australia and Southeast Asia respectively. However, the cost of land is a trivial fraction of overall system cost.

Solar energy does not require fuel. Once the system has been installed, the only extra costs are those of operations and maintenance. Thus the price of solar power will not be dependent upon international fuel prices. This

	Australian electricity	SE Asian electricity
SE Asian consumption (TWh/day)	1.4	1.4
Storage fraction	50%	50%
Area of land (km^2) and % of the landmass	3140 and 0.04%	3940 and 0.17%
Required nameplate PV production capacity (GW)	262	328
HVDC transmission capacity (peak) (GW)	144	–
PV cost (US$billions)	350	440
Storage cost (US$billions)	71	89
HVDC cost (US$billions)	134	–
Total (US$billions) (incurred over 30–40 years)	558	533
Levelised electricity cost (US$/kWh)	0.080	0.077

Table 7: Summary of system costs.

provides a measure of stability to a solar investment. On the other hand, interest rates may vary with time.

Under the assumptions noted above, the parameters listed in Table 7 are calculated for 2050. Bulk electricity could be supplied for about US$0.08 per kWh from both Australia and Southeast Asia. Under the assumptions used in this study, including that per capita consumption of electricity rises to that of Singapore today, the capital cost of supply of two thirds of Southeast Asian electricity consumption from solar energy is about US$3200 per capita, including generation, storage and high voltage transmission, but not including low voltage distribution. It should be noted that solar electricity is capital intensive with low running cost.

7 Conclusion

This paper has modeled a Southeast Asian electricity system in which one third of demand in 2050 is met from Australian solar energy, one third from indigenous solar energy, and one third from conventional energy sources. Large scale generation and transmission of solar electricity to SE Asia from Australia appears to be both technically and economically feasible over the next 40 years. Despite the expense and losses incurred in long distance transmission of Australian solar electricity, it is competitive with indigenous solar electricity because of high insolation levels in Australia. Supplementation of locally produced electricity with power from Australia, together with substantial storage, would allow a very high solar electricity fraction. The high voltage DC transmission backbone would also facilitate distribution of non-dispatchable electricity from renewable sources generated in South East Asia.

Received: July 26, 2012. Accepted: August 13, 2012.

References

[1] United Nations. World Population Prospects The 2008 Revision Highlights. New York: 2008.

[2] Koh SL, Lim YS. Meeting energy demand in a developing economy without damaging the environment—A case study in Sabah, Malaysia, from technical, environmental and economic perspectives. Energy Policy [Internet]. 2010 Aug [cited 2012 Jan 9];38(8):4719–28. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0301421510003186

[3] ABARE. Australian Energy Resource Assessment. Canberra: 2010.

[4] Zickfeld F, Wieland A. 2050 Desert Power Executive Summary [Internet]. Munich: 2012. Available from: http://www.dii-eumena.com/fileadmin/flippingbooks/dp2050_exec_sum_engl_web.pdf

[5] CIA. World Factbook 2008 Revision [Internet]. 2008. Available from: https://www.cia.gov/library/publications/the-world-factbook/

[6] United Nations Department of Economic and Social Affairs. World Population Prospects: The 2010 Revision [Internet]. New York: 2011. Available from: http://esa.un.org/unpd/wpp/

[7] Urmee T, Harries D, Schlapfer a. Issues related to rural electrification using renewable energy in developing countries of Asia and Pacific. Renewable Energy [Internet]. 2009 Feb [cited 2011 Aug 13];34(2):354–7. Available from: http://linkinghub.elsevier.com/retrieve/pii/S096014810800205X

[8] Reza M, Andreasson L, Persson G, Bostrom A. HVDC and FACTS Potentials for Indonesian Electrical Grid Infrastructure. In: 2011 International Conference on Electrical Engineering and Informatics. Bandung: 2011. p. 5–8.

[9] BP. BP Statistical Review of World Energy June 2011 [Internet]. 2011. Available from: http://www.bp.com/sectionbodycopy.do?categoryId=7500&contentId=7068481

[10] Thavasi V, Ramakrishna S. Asia energy mixes from socio-economic and environmental perspectives. Energy Policy [Internet]. 2009 Nov [cited 2011 Aug 10];37(11):4240–50. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0301421509003449

[11] IEA. Electricity generation by fuel: Singapore. Statistics. 2010;:2010.

[12] IEA. Electricity Generation by Fuel: Indonesia [Internet]. 2011. Available from: http://www.iea.org/stats/pdf_graphs/IDELEC.pdf

[13] IEA. Electricity Generation by Fuel: Philippines [Internet]. 2011. Available from: http://www.iea.org/stats/pdf_graphs/PHELEC.pdf

[14] IEA. Electricity Generation by Fuel: Malaysia [Internet]. 2011. Available from: http://www.iea.org/stats/pdf_graphs/MYELEC.pdf

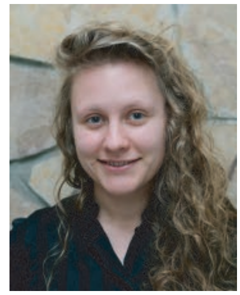
[15] IEA. Electricity Generation by Fuel: Australia [Internet]. 2011. Available from: http://www.iea.org/stats/pdf_graphs/AUELEC.pdf
[16] Bertani R. Geothermal Power Generation in the World 2005–2010 Update Report. In: Proceeding World Geothermal Congress 2010. 2010. p. 1–41.
[17] Gadonneix P, Frei C. 2010 Survey of Energy Resources. 2010.
[18] Lee TR, Oppenheim D, Williamson TJ. Australian Solar Radiation Data Handbook. 2nd ed. Manuka ACT: Australian and New Zealand Energy Society; 2005.
[19] Jacobson MZ. Review of solutions to global warming, air pollution, and energy security. Energy & Environmental Science [Internet]. 2009 [cited 2011 Jul 17];2(2):148. Available from: http://xlink.rsc.org/?DOI=b809990c
[20] Denholm P, Mehos M. Enabling Greater Penetration of Solar Power via the Use of CSP with Thermal Energy Storage. 2011.
[21] Koussa M, Cheknane a., Hadji S, Haddadi M, Noureddine S. Measured and modelled improvement in solar energy yield from flat plate photovoltaic systems utilizing different tracking systems and under a range of environmental conditions. Applied Energy [Internet]. 2011 May [cited 2012 Jul 21];88(5):1756–71. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0306261910005088
[22] ABARES. Australian Mean Annual Incoming Solar Radiation [Internet]. 2011; Available from: http://www.daff.gov.au/abares/publications_remote_content/all-publications?sq_content_src=%2BdXJsPWh0dHAlM0ElMkYlMkYxNDMuMTg4LjE3LjIwJTJGYW5yZGwlMkZEQUZGU2VydmljZSUyRmRpc3BsYXkucGhwJTNGZmlkJTNEcGFfbW1pc3JyOWNsX18wMzUxMWExMy54bWwmYWxsPTE%3D
[23] Breyer C, Gerlach A. Global overview on grid-parity. Progress in Photovoltaics: Research and Applications [Internet]. 2012; Available from: http://dx.doi.org/10.1002/pip.1254
[24] Greenpeace, EREC. [r] enewables 24/7. 2009.
[25] Andersen B. HVDC transmission-opportunities and challenges [Internet]. In: The 8th IEE International Conference on AC and DC Power Transmission, 2006. ACDC 2006. IET; 2006 [cited 2012 Jan 31]. p. 24–9.Available from: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1633606
[26] United Nations Department of Economic and Social Affairs. Multi Dimensional Issues in International Electric Power Grid Interconnections. 2006.
[27] Hammons TJ. Integrating renewable energy sources into European grids. International Journal of Electrical Power & Energy Systems [Internet]. 2008 Oct [cited 2012 Jul 22];30(8):462–75. Available from: http://www.sciencedirect.com/science/article/pii/S0142061508000306
[28] Crabtree G, Misewich J, Ambrosio R, Clay K, James R, Lauby M, et al. Integrating Renewable Electricity on the Grid [Internet]. In: AIP Conference Proceedings. 2011. p. 387–405. Available from: http://dx.doi.org/10.1063/1.3653865
[29] Garrity TF. Getting Smart. Power and Energy Magazine IEEE [Internet]. 2008;6(2):38–45. Available from: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4457958&isnumber=4457931
[30] Kutuzova NB. Ecological Benefits of DC Power Transmission. Power Technology and Engineering. 2011;45(1):60–66.
[31] Alberta Energy. Assessment and Analysis of the State-Of-the-Art Electric Transmission Systems with Specific Focus on High-Voltage Direct Current (HVDC), Underground or Other New or Developing Technologies. 2009.
[32] Peake O. The history of high voltage direct current transmission *. In: Australian Journal of Multi-disciplinary Engineering. 2010. p. 47–55.
[33] Hammons TJ, Lescale VF, Uecker K, Haeusler M, Retzmann D, Staschus K, et al. State of the Art in Ultrahigh-Voltage Transmission. Proceedings of the IEEE [Internet]. 2011 [cited 2012 Jan 31];(99):1–31. Available from: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5910129
[34] Flourentzou N, Agelidis VG, Demetriades GD. VSC-Based HVDC Power Transmission Systems: An Overview. Power Electronics, IEEE Transactions on [Internet]. 2009;24(3):592–602. Available from: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4773229&isnumber=4812314
[35] Bahrman MP. HVDC Transmission Overview. Power. 2008:1–7.
[36] Silva RD, Robbie A. Network Extensions to Remote Areas Part 1 – Planning Considerations. Melbourne: 2009.
[37] Kim C-K, Sood VK, Jang G-S, Lim S-J, Lee S-J. HVDC Transmission: Power Conversion Applications in Power Systems. Singapore: John Wiley & Sons; 2009.
[38] Westerweller TH, Price JJ. Crossing the divide [Basslink HVDC interconnector]. Power Engineer [Internet]. 2006;20(5):42. Available from: http://link.aip.org/link/PEJOEE/v20/i5/p42/s1&Agg=doi
[39] Bahrman M, Johnson M. The ABCs of HVDC Transmission Technologies. IEEE Power and Energy Magazine. 2007;5(2):32–44.
[40] Westerweller T, Price J. Basslink HVDC interconnector-system design considerations [Internet]. In: AC and DC Power Transmission, 2006. ACDC 2006. The 8th IEE International Conference on. IET; 2006 [cited 2011 Dec 8]. p. 121–4. Available from: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1633626
[41] Pritamsatsangi K, Sandeepkumar K. Advanced Technologies in Power Transmission System. In: IET-UK International Conference in information and Communication Technology in Electrical Sciences (ICTES 2007). 2007. p. 30–2.
[42] Asplund G. Ultra High Voltage Transmission. 2007.
[43] Siemens. Ultra HVDC Transmission System. Siemens Newsletter. 2009:1–4.
[44] Siemens. Factsheet Energy Sector. Abu Dhabi: 2012.
[45] Johnstone H. Latest development in HVDC transmission. Power Engineering International. 2011;19(3):16.
[46] Koreman K, Pääjärvi B, Worzyk T, Andersröd T. The NorNed Cable Link: A Power Transmission Highway Between Norway and the Netherlands. 2006.
[47] Gevorgian V. Renewable Energy and Inter-island Power Transmission. Energy. 2011.
[48] Rourke FO, Boyle F, Reynolds A. Marine current energy devices: Current status and possible future applications in Ireland. Renewable and Sustainable Energy Reviews [Internet]. 2010 Apr;14(3):1026–36. Available from: http://www.sciencedirect.com/science/article/pii/S1364032109002743

[49] La'o Hamutuk. Depth of Timor Trench [Internet]. 2012; Available from: http://www.laohamutuk.org/Oil/LNG/images/fig11Bathy780.jpg
[50] Licheng L. Ultra HVDC Transmission Technology in China and Application of High Power Electronics. In: IPEMC-2012 ECCE-Asia. 2012.
[51] Xinhua. China starts laying record capacity power cables [Internet]. China.org.cn. 2012 [cited 2012 Jul 25]; Available from: http://www.china.org.cn/business/2012-05/14/content_25374700.htm
[52] Bahrman M. HVDC Transmission: An economical complement to ac transmission. In: WECC Transmission Planning Seminar. 2009.
[53] Faulkner R. Hybridizing HVDC transmission with non-local energy storage and large dispatchable loads for load leveling [Internet]. In: Power and Energy Society General Meeting, 2011 IEEE. IEEE; 2011 [cited 2012 Feb 1]. p. 1–8. Available from: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6039730
[54] ABB. Comparison of HVDC and EHV Transmission. 2011.
[55] TenneT. NorNed [Internet]. Arnheim: 2008. Available from: http://www.tennet.org/images/NorNed – Europe's link for the future_tcm41-18745.pdf
[56] ABB. North-East Agra [Internet]. 2012 [cited 2012 Jul 25]; Available from: http://www.abb.com/industries/ap/db0003db004333/9716a8ac9879236bc125785200694f18.aspx
[57] Bahrman M. HVDC Transmission [Internet]. 2006. Available from: http://pnwer.dataweb.com/tables/jointables/meetingparticipantjoin/files/presentation/Michael Bahrman.pdf
[58] Bahrman M. HVDC Transmission. Power [Internet]. 2006; Available from: http://www.ieee.org/portal/cms_docs_pes/pes/subpages/meetings-folder/PSCE/PSCE06/panel2/Panel-02-1_Overview_of_HVDC_Transmission.pdf
[59] Bahrman M. Cost Comparison of AC & DC Transmission Alternatives [Internet]. 2007. Available from: http://www.ece.uidaho.edu/hvdcfacts/Presentations/MBahrman07.pdf
[60] Pittock J. Viewpoint – Better Management of Hydropower in an Era of Climate Change. Water Alternatives. 2010;3(2):444–52.
[61] NHA, HRF, ORNL. Pumped Storage Hydropower. Washington, DC: 2010.
[62] Deane JP, Ó Gallachóir BP, McKeogh EJ. Techno-economic review of existing and new pumped hydro energy storage plant. Renewable and Sustainable Energy Reviews [Internet]. 2010 May [cited 2011 Jul 25];14(4):1293–302. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1364032109002779
[63] Pickard WF. The History, Present State, and Future Prospects of Underground Pumped Hydro for Massive Energy Storage. Proceedings of the IEEE [Internet]. 2012 Feb;100(2):473–83. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5942141
[64] IEA. Renewable Energy Essentials: Hydropower. 2010.
[65] Altinbilek D, Seelos K, Taylor R. HYDROPOWER ' S ROLE IN DELIVERING SUSTAINABILITY. Energy and Environment. 2005;16(5):815–24.
[66] Francois-Xausa M, Havard D, Czerwinski F, Teller O. Hydroelectricity – An answer to energy needs. In: World Energy Council 2010. 2010. p. 1–14.
[67] Taylor RM. Future Power Systems – Where does Hydro fit? 2006.
[68] Ibrahim H, Ilinca a, Perron J. Energy storage systems—Characteristics and comparisons. Renewable and Sustainable Energy Reviews [Internet]. 2008 Jun [cited 2011 Jul 25];12(5):1221–50. Available from: http://linkinghub.elsevier.com/retrieve/pii/S1364032107000238
[69] Toledo OM, Oliveira Filho D, Diniz ASAC. Distributed photovoltaic generation and energy storage systems: A review. Renewable and Sustainable Energy Reviews [Internet]. 2010 Jan [cited 2011 Jul 26];14(1):506–11. Available from: http://linkinghub.elsevier.com/retrieve/pii/S136403210900207X
[70] IEA. Technology Roadmap Concentrating Solar Power. Paris: 2010.
[71] CSIRO. Lake Argyle [Internet]. 2000. Available from: http://www.eoc.csiro.au/hswww/Argyle.htm
[72] Kazempour SJ, Moghaddam MP, Haghifam MR, Yousefi GR. Electric energy storage systems in a market-based economy: Comparison of emerging and traditional technologies. Renewable Energy [Internet]. 2009 Dec [cited 2011 Nov 28];34(12):2630–9. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0960148109001906
[73] Jonah G . Levine. Pumped Hydroelectric Energy Storage and Spatial Diversity of Wind Resources as Methods of Improving Utilization of Renewable Energy Sources. Michigan Technological University; 2003.
[74] Poonpun P, Jewell WT. Analysis of the Cost per Kilowatt Hour to Store Electricity. Energy. 2008;23(2):529–34.
[75] Howes J. Energy storage: Renewable energy's missing link. Power Engineering international [Internet]. 2010 [cited 2012 Feb 22];18(2). Available from: http://cat.inist.fr/?aModele=afficheN&cpsidt=22469406
[76] Ekman CK, Jensen SH. Prospects for large scale electricity storage in Denmark. Energy Conversion and Management [Internet]. 2010 Jun [cited 2011 Jul 30];51(6):1140–7. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0196890409005299

Author biographies

Professor Andrew Blakers is the Director of the Centre for Sustainable Energy Systems at the Australian National University. He was a Humboldt Fellow and has held Australian Research Council QEII and Senior Research Fellowships. His research interests are in the areas of photovoltaic and solar concentrator systems.

Professor Joachim Luther is the former Director of the Fraunhofer Institute for Solar Energy Systems and was the founding head of the Solar Energy Research Institute of Singapore. He has made distinguished contributions to solar science, engineering and public policy. His main research interest is in the areas of photovoltaic, solar and energy efficient buildings and sustainable energy systems.



Ms Anna Nadolny is currently studying a BEng/BSc at UNSW. She is completing her honours year, studying hybrid photovoltaic devices. Her research interests include organic and hybrid device physics, and large scale renewable energy.