The Future of Renewables Linked by a Transnational Asian Grid

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ABSTRACT | In this paper, we argue that Asia’s unique geography, abundant low-emission energy resources, rapid economic growth, and rising energy demands merit consideration of a Pan-Asian Energy Infrastructure. In our study, we focus on development of wind and solar resources in Australia, China, Mongolia, and Vietnam as the potential foundation for an electricity grid stretching from China to Australia. Hourly climate data for a full year are used to estimate renewable energy generation, electricity demand, generation capacity are projected forward to the year 2025, and economic dispatch in an international market is simulated to demonstrate cost benefits. Intermittency, connectivity, future dispatch orders, storage, line losses, and engineering and financial issues are all addressed.

KEYWORDS | Asia; high-voltage direct current (HVDC) transmission; solar power; wind power

I. INTRODUCTION

This paper investigates large-scale international connectivity as a potential alternative to storage.

The scale we examine is Asia, defined as China, Japan, South Korea, the ten Association of Southeast Asian Nation (ASEAN) states, and Australia.

We argue that renewable resources are easier to manage at a high level of aggregation. That, in turn, argues in favor of considering connectivity over a large scale. With large-scale connectivity, averaging effects come into play and uncorrelated regional intermittencies can partially cancel each other out. It also enables discussion of large-scale engineering scenarios.

In considering how the concept might be applied in Asia, the European DESERTEC Industrial Initiative (DII) offers a potential template.

The DII envisages that, by 2050, concentrating solar power plants in the Middle East and North Africa (MENA) can satisfy 70% of MENA’s electricity needs and 17% of the electricity needs of the European Union and some neighboring countries [1]. The solar energy would be transmitted via high-voltage direct current (HVDC) power lines across North Africa and connected to Europe across the Mediterranean Sea.

The DII also envisages North Sea wind and Icelandic geothermal energy feeding into the European grid via HVDC cables.

The objective of the DII is to develop Europe and North Africa’s regional renewable energy resources of sun, wind, hydro, and biomass to replace coal as an electricity source.

Coincident to the DII are European projects such as NorNed [2]. NorNed is a 580-km subsea HVDC transmission link between Norway and The Netherlands.

Since 2008, NorNed has enabled Norwegian hydro electricity exports to satisfy Dutch daytime peak electricity needs, and nighttime Dutch gas and coal-fired electricity to

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be exported to Norway when base load demand in both countries is low. Such bilateral coordination of generation resources enhances electricity market efficiency in both countries. We pose the question: Can some of the European initiatives above be adapted and applied to Asia on a bigger scale and across a larger area? For its part, Asia has solar, wind, and geothermal resources. Asia also has load balancing resources such as pumped storage, hydro, and natural gas.

More importantly, Asia’s electricity consumption is growing more quickly than in Europe due to higher Asian economic growth rates. Reducing global greenhouse gas emissions will be more difficult if Asia’s rising electricity demands are satisfied by fossil fuels. We argue Asia’s renewable energy resources can be linked together by a Pan-Asian Energy Infrastructure composed of bundled HVDC power lines, natural gas pipelines, and fiber optic cables. These could stretch from Australia to China, and possibly beyond into Central Asia and the Russian Far East.

Anticipating that portions of such an infrastructure can be in place as early as 2025. Section II projects electricity supply and demand in Asia forward to that time, and estimates the output of major solar and wind generation regions using global climate data for 2010. Section III summarizes Asian national energy systems. It describes precedents for international connectivity and proposes an HVDC regional network topology for the purpose of examining benefits. Some enabling influences are discussed. By consolidating national grids into aggregated supply/demand nodes, Section IV analyzes transmission flows, electricity prices, and trans-hemispheric seasonal effects in a regional electricity market with sufficient international connectivity.

Section V analyzes practicalities such as costs and needed regulatory reforms. We conclude that first-order analysis of the costs and benefits of a Pan-Asian Energy Infrastructure make the idea worthy of further study.

II. ASIAN ENERGY SUPPLY AND DEMAND

A. Growth

Asia now emits roughly one-third of global greenhouse gases. Assuming continued rapid regional economic growth, Asia’s proportion of global greenhouse gases is certain to expand by 2050 without mitigation efforts. Minimizing disruptive global climate change, therefore, may hinge largely upon Asia’s future energy choices. Between 1980 and 2008, Asia’s electricity consumption rose at a rate of 6% annually, twice the world rate. Over the same period, Asia’s share of global energy-related greenhouse gas emissions doubled, to 34% from 17% [3].

Raising Asia’s living standards while lowering the region’s greenhouse gas emissions will require trillions of dollars of investment in new energy generation and transmission capacity. Our analysis suggests a continuous, noninterruptible regional energy supply sufficient to meet a sizeable amount of Asia’s future energy needs is possible if the regional renewable resource is widely captured and is shared across borders via regional interconnection.

B. Asia’s Renewable Energy Assets

Wind energy is abundant in China and Mongolia. Solar energy is abundant in Australia’s interior. Together, they represent Asia’s most plentiful renewable energy resources for which capture technology currently exists. Under the economic theory of comparative advantage, China and Australia each should focus their renewable energy development efforts primarily on producing the renewable energy resource each is most efficient at producing. For China, that is wind. For Australia, that is sun.

We start by applying comparative advantage in a two-country China–Australia analysis. Together, China and Australia account for 60% of Asia’s electricity consumption (56% for China, 4% for Australia) [3].

We then add secondary energy sources (for instance, solar in China and wind in Australia) as well as renewable energy resources available in Japan, South Korea, and the ASEAN states. We then consider how a Pan-Asian Energy Infrastructure can distribute this energy and the technical and management challenges it presents.

C. Developing Asia’s Renewables

We start by examining large-scale limiting cases to see if renewable energy can satisfy all or most of Asia’s energy needs. We start by examining the world’s three largest renewable energy resources (solar, wind, and ocean energy). These have been identified in a previous energy analysis [4].

1) Ocean Energy: Wave resources exist off southern Australia. Tidal resources exist off northwestern Australia [5] and Indonesia. Deep-ocean troughs exist off Indonesia, the Philippines, and Japan. All appear promising for ocean thermal energy conversion [6].

In this study, we conclude no ocean energy technology is sufficiently developed to include in our analysis. Therefore, we ignore this form of energy.

Solar photovoltaic (PV) technology converts both direct and diffuse radiation directly into electricity. Solar thermal [also known as concentrating solar power (CSP)] technology requires direct normal radiation to create electricity by concentrating sunlight to create heat to feed a thermal cycle and a turbine.

Conversion efficiencies are broadly similar between PV and CSP and both are intermittent energy sources. However, both can store electricity (PV in traditional batteries, CSP in thermal media). This enables solar energy to be adapted (within limits) to meeting grid needs.

Given that world class direct normal radiation exists in Australia and, to a lesser extent, northern China, these two regions are attractive for CSP development.

Researchers at Australia’s Cooperative Research Centre for Coal in Sustainable Development estimate CSP plants in interior Australia can generate roughly 180 GWh of electricity per year per square kilometer [6].

We use this as a rough guide to quantify the exploitable resource. By extrapolating the estimate above, a CSP plant with a mirror field 35 km on a side could have satisfied Australia’s 2008 electricity demand. A mirror field 130 km on a side could have satisfied China’s 2008 electricity demand and a mirror field roughly 173 km on a side could have satisfied Asia’s 2008 electricity demand.

3) Wind Energy: Chinese and U.S. researchers estimate China’s wind resources at more than ten times China’s electricity consumption [7].

Wind’s intermittency, however, presents a hurdle to large-scale exploitation. Nonetheless, wind now satisfies a growing proportion of electricity demand in Denmark, Germany, and South Australia.

Furthermore, new approaches are being developed to handle higher penetrations of this resource to future grids [8], [9].

4) Wind and Solar Energy Intermittency: We propose that interconnectivity can provide steady energy supplies from Asia’s intermittent resources. To quantify this, we take 2010 as a typical year and develop time series for international wind and solar electricity generation from the seven major production regions shown in Fig. 1. We have divided Asia into seven regions: Eastern Australia Solar (EAS), South Coast Australia Wind (SCAW), Western China Solar (WCS), North China and Mongolia Wind (NCW), Coastal China Wind (CCW), and Vietnam Wind (VW).

In doing so, we assume regional intermittency is dealt with by low-loss HVDC transmission infrastructure and adequate numbers of generation plants for load-balancing. This assumption offers fertile ground for additional study at a more local level.

To develop our time series we use the NCEP Final Operational Model Global Troposphere Analyses [10], which covers the time period from July 1999 to the present. These data are then downscaled using the conformal cubic atmospheric model (C-CAM) [11], [12].

The Final Operational Global Analysis data are presented on a 1° square grid presented 6-hourly using the same model used in the Global Forecast System (GFS), which is a synoptic scale medium-range model. Observational data are assimilated in the process. These data were originally obtained from the Computational and Information Systems Laboratory (CISL) at the National Center for Atmospheric Research (NCAR). NCAR is sponsored by the National Science Foundation (NSF). The original data are available in data set number ds083.2. Data on a 2.5° grid are available for the Global Data Assimilation System (GDAS) going back to the mid-1970s.

The data include a number of standard meteorological quantities (such as components of wind velocity, pressure, temperature, and relative humidity) and model derived quantities. Since December 15, 2009, a number of radiation-based variables have also been stored within the data files.

C-CAM is a variable resolution global atmospheric model so does not require lateral boundary conditions. Rather than existing on a regular latitude/longitude or easting/northing grid, C-CAM has a stretchable grid that allows for a finer grid resolution over a particular area. The finer resolution is over Australia which is where the verification of the data has been performed. The C-CAM
output used here is part of a large-scale study of atmospheric processes affecting renewable energy production, so the finest grid spacing occurs over central Australia at longitude 144°, latitude −34.5°. The stretching is defined via the inverse Schmidt factor of 0.15. There are 144 grid points across the six panels of the cube with 18 vertical levels between 40 and 35 km. The spatial resolution over northern Australia is therefore approximately 0.2° and over the area in Asia discussed here the grid stretches to approximately 1°. All of the data are interpolated onto a regular 1° grid to simplify the energy analysis.

The initial values on the C-CAM grid are interpolated from the analyses. In later time steps, the level of detail in the C-CAM fields increases as the finer scales of atmospheric processes develop. To facilitate the approximations in the model and the initial conditions the simulated fields are nudged towards those of the analyses at regular intervals using the method of Thatcher and McGregor [13] whereby a scale-selective filter is applied to preserve the finer scale data being produced.

C-CAM version 10.06 is used for this study. The prognostic cloud scheme, land surface scheme, and schemes for short-wave and long-wave radiation are described in [14]. The model time step is 200 s though the radiation scheme is only interrogated hourly. Data are produced hourly for 10-m wind speeds, percentage cloud cover, and net solar radiation at the ground. The data for 2010 have been extracted from a simulation that covers the entire period for which the 1° NCEP Final Analysis data exist; there should be no spin-up issues associated with the period of interest here. The standard C-CAM implementation is a hydrostatic model which should not present a problem for the broader energy analysis performed in this paper.

Wind speed data at 10 m above the ground are approximately scaled to a height of 80 m and then converted to an estimate of wind generation output using a generic power output curve for large wind turbines. The wind generation regions are large, which averages weather variations, nevertheless large swings in aggregated output can occur as can be seen in Fig. 2. Direct normal solar radiation is estimated from the global insolation and cloud cover provided in the NCEP data. Solar PV output relative to installed capacity is approximated by the direct normal radiation (assuming large-scale arrays are steerable) with a contribution from the diffuse radiation. All solar generation is assumed to be PV to present a worst case of intermittency. Due to the very large generation regions, however, Fig. 3 shows the aggregated output to be smooth, and contrasts interestingly with the wind output. In reality, a mixture of PV and CSP plants can be anticipated in 2025 and the latter, even without thermal storage, have some thermal inertia and usually have a “solar multiple” greater than unity which operators use to minimize ramp rates due to passing cloud cover. These effects are more noticeable in national and regional analyses in which the areas of aggregation are smaller.

As a succinct summary of the seven estimated time series, their correlation coefficients are presented in Table 1. Solar output from different regions is highly correlated due to the underlying diurnal variation. Correlation between solar and wind energy indicates a diurnal pattern of wind, as is the case between western China solar and northern China and Mongolia wind. The high correlation between coastal Chinese and Vietnamese wind is reasonable. There is no correlation between weather effects in different hemispheres.

For single-site renewable energy studies a “typical meteorological year” (TMY) is sometimes constructed to represent the full extent of inter-annual variability. However, the process of constructing a TMY involves processing measured data to emphasize a desired subset of climate parameters, and such methodologies are not appropriate for a multisite study in which the statistics of correlations between the sites are highly important.
Until a true multisite TMY can be relied upon to preserve the variability that drives transmission flows, it is better to use direct data, and to accept that the result will be illustrative rather than comprehensive.

III. A PAN-ASIAN ENERGY INFRASTRUCTURE

Australia’s solar energy resources can, hypothetically, meet Asia’s entire electricity demand using current technology. China’s wind resources can, hypothetically, satisfy China’s electricity needs many times over. Given this, the question becomes logistical: How can these electricity resources, once captured, be delivered to market?

A. A Future Networked Scenario

Asia’s geography offers two logical transit routes for a Pan-Asian Energy Infrastructure. One crosses Asia mostly by land, the other largely by sea. Both are illustrated in Fig. 4. In both cases, Australia is connected to the Indonesian island of Alor via East Timor. The infrastructure then traverses Indonesia’s island chain westward to Java.

From Java, a land-based infrastructure can traverse Indonesian Sumatra, Malaysia, Thailand, and Laos before reaching China’s Yunnan province.

From there, China’s domestic grid can provide carriage from Yunnan to Shanghai for interconnection with Japan and South Korea across the East China Sea.

A sea-based infrastructure can turn northward from Java into the shallow Java Sea and onward into the South China Sea. It can then turn northeast a short distance south of China’s Hainan Island. It can then pass through the Taiwan Strait en route to an East China Sea interconnection linking Japan, South Korea, and central coastal China through the port of Shanghai.

B. Precedents for International Connectivity

1) The DESERTEC Industrial Initiative (DII): Current design plans for the DII, introduced in Section I, call for laying 20 HVDC links, each of 5000-MW capacity, along five routes across the shallow, 200–500-km-wide Mediterranean Sea. These will then interconnect with Europe’s electricity networks.

A Pan-Asian Energy Infrastructure presents a tougher engineering task. It requires crossing two stretches of deep water to the north and south of East Timor before traversing Indonesia’s lengthy eastern archipelago. This is then followed by additional stretches of land or shallow water.

To offer some relative scale, southern Algeria and southern Spain lie roughly 1600 km apart. Southern Australia and southern China lie roughly 6000 km apart.

2) The Gulf Cooperation Council Interconnection Authority (GCCIA): Six Arabian Gulf nations (Kuwait, Bahrain, Qatar, Saudi Arabia, United Arab Emirates, and Oman) have interconnected their electricity grids. The aim is to reduce collective electricity costs through increased cross-border electricity trade and to reduce the aggregate spinning reserve required by the six by sharing the capacity between them [15].

In interconnecting their grids, the GCCIA benefits from being composed of small markets close together easily linked across unchallenging terrain. A Pan-Asian Energy Infrastructure involves greater distances and more challenging terrain.
3) The Trans-ASEAN Electricity Grid: The ASEAN states are planning to deepen interconnections between their national electricity and natural gas distribution systems [16]. To achieve this, ASEAN has drawn up two interconnection projects: the ASEAN Power Grid for electricity and the Trans-ASEAN Gas Pipeline for natural gas.

The aim of both is to reduce consumer costs and increase supply efficiency through increased cross-border energy market competition. Another aim is to enhance energy security through improved supply redundancy.

Like the GCCIA, ASEAN nations benefit from close proximity. The ASEAN states also benefit from having an accepted multilateral bureaucracy in place authorized to develop proposed topologies. In the case of a Pan-Asian Energy Infrastructure, such a bureaucracy either must be created or an existing bureaucracy found to serve as an agreed forum for development of the idea.

C. Asian National Energy Systems

1) China: China’s rapid economic growth is resulting in growing energy needs and worsening environmental pollution due to reliance on coal-fired power.

By 2015, China aims to reduce energy intensity per unit of GDP by 17.5% from 2010, after cutting it by 20% between 2005 and 2010.

As part of this drive, China is building out HVDC power lines across the country to bring online and distribute new electricity supplies. Construction of more than 30 domestic HVDC links is planned between now and 2020.¹

2) Australia: Australia gets more than 90% of its electricity from coal and natural gas [3]. This makes Australia one of the highest per capita greenhouse gas emitters in the world.

Australia’s current coal fired power plant fleet is aging. It requires progressive replacement in coming decades. Replacing this capacity and upgrading Australia’s similarly aging transmission capacity is expected to cost Australia at least $100 billion or about 10% of 2010 GDP.²

3) Northeast Asia: Prior to the March 11, 2011 earthquake, Japan relied upon nuclear energy for roughly one-quarter of its electricity needs.

However, the earthquake and resulting tsunami knocked out a significant amount of that nuclear capacity. Replacing that capacity will take months, if not years. This will create a significant drag on Japan’s economic recovery.

Had a Pan-Asian Energy Infrastructure been in place, Japan could have replaced some (or potentially all) of that lost domestic nuclear generation capacity through imports of electricity from spare capacity elsewhere.

In addition to contingency redundancy, deepened interconnections also can enable cross-border transfers of spare capacity to meet the varying seasonal electricity demand peaks in different domestic markets.

For instance, in Russia’s Far East peak electricity demand occurs in winter due to heating needs. In Japan, South Korea, and parts of China, peak electricity needs occur in summer due to air conditioning loads [16].

4) ASEAN States: The ASEAN states have natural gas, hydropower, wind and, in Indonesia, geothermal. Apart from hydropower, ASEAN’s renewable energy supplies have not been aggressively developed.

D. Benefits of a Pan-Asian Grid

Expanded cross-border connectivity coupled with progressive introduction of carbon pricing may eventually shift Asia away from reliance upon coal, natural gas, and hydro for base load power.

As this occurs, renewables may satisfy a larger percentage of regional base load power needs and uncorrelated intermittencies in different geographic areas can partially cancel each other out.

Residual aggregate intermittency can then be offset through generation assets such as hydropower and natural gas.

Hydropower and natural gas already commonly play a role in individual grids as spinning reserve, or rapidly deployable excess supply.

As renewables increasingly penetrate grids, hydropower and natural gas capacity can be focused primarily on providing timely marginal supply. An early bilateral example of this is Norway’s hydro power being tapped to serve two markets (Norway and The Netherlands) by virtue of the NorNed HVDC cable.

As this occurs, the use of coal fired power can be expected to fall. This is particularly so if carbon pricing erases coal’s energy market price advantage.

Despite this, coal can still play a useful role in future grids as a reliable source of backup capacity, for three reasons.

First, idled coal fired power supply can be brought online to meet seasonal energy demand needs (such as during Russian winter cold spells or during summer heat waves in China, Japan, and/or South Korea).

Such demand peaks strain existing generation capacity, sometimes driving marginal electricity supply prices to extremes. In the worst cases, it can require load shedding (i.e., brownouts and blackouts).

Having ample marginal supply on call can potentially help reduce price extremes and load shedding risk. Using

already depreciated capacity for this role can offer a cost-effective means of doing so.

Second, having spare capacity available for multilateral contingency use can help offset supply shocks such as the one suffered by Japan after the March 11, 2011 earthquake and tsunami.

Third, building electricity generation capacity is time consuming. Forecasting future demand is fraught with uncertainty. Therefore, having depreciated spare capacity available to meet medium-term supply gaps offers a cushion against the unknown.

Taken together, maintaining legacy coal-fired power capacity in future grids dominated by renewables looks sensible.

1) Offsetting Residual Intermittency: Aggregating largely uncorrelated regional intermittencies may reduce the overall problem of intermittency in a Pan-Asian Energy Infrastructure. But it will not completely solve the problem.

Residual load balancing is still required. This is now managed by each national grid individually. For instance, China has two 1800-MW pumped hydro storage facilities, one at Tianhuangping and one at Jixi, and more are planned.

Several other storage technologies appear workable. Compressed air storage uses surplus energy to compress air for release later to generate electricity. Research has concluded it is technically feasible and economically competitive [18]. A variety of battery technologies are being scaled up for grid application [19]. These have the flexibility to provide support services for customers and distribution grids as well as balancing or frequency regulation services. They may be attractive investments despite their initial high cost due to multiple revenue streams becoming available as the storage services industry matures [20].

International HVDC transmission links can also be used to provide balancing services. This may be helpful in reducing generation or storage capacities reserved for rare intermittency events. Some caution should be exercised to prevent this application from displacing their primary function of energy transport.

2) Seasonal and Diurnal Asynchronies: Northern China’s peak electricity demand occurs in winter because of heating needs. Australia’s Outback solar energy resources are strongest in the southern summer, or the northern winter. Therefore, Australia’s potential peak solar energy output is suited to meeting China’s winter heating peaks.

Sydney is two hours ahead of Hong Kong, Shanghai, and Beijing while Perth shares the same time zone.

3) The Potential for Integrating Natural Gas: Massive investments are currently planned in Asia in liquid natural gas (LNG) shipping capacity in order to carry natural gas from export markets like Australia and Southeast Asia import markets like China, Japan, and South Korea.

An HVDC-based Pan-Asian Energy Infrastructure might warrant reexamination of LNG as a natural gas delivery means. That is because an HVDC system would connect to many of the same markets LNG tankers would serve.

If a natural gas pipeline system were laid alongside HVDC cables as part of a Pan-Asian Energy Infrastructure, significant investment savings can accrue through such things as shared labor costs.

Other benefits can include increased network flexibility and expanded fuel-switching opportunities.

IV. PRICE IMPACTS OF INTERCONNECTED ASIAN MARKETS

Some mooted benefits of a Pan-Asian Energy Infrastructure can be difficult to quantify. One that can be estimated using standard techniques is the impact on electricity prices of an international electricity market that we assume will be established and expanded along with physical international connections. We use a software model for market behavior to estimate the dispatch of conventional and renewable generation plant every hour for a full year of operation. Future generation capacity and demand are projected using assumed growth rates, and renewable generation output is determined by the time series developed above using global climate data for 2010, taking this to be a representative climate year.

A. Modeling Approach: Nodes, Supply, and Demand

In this first analysis, we consider the electricity producing and consuming regions of Australia, China, Indonesia, and other ASEAN nations, interconnected by the network envisioned in Fig. 4.

We leave Korea and Japan for inclusion in a future analysis because their contribution is small compared to geographically close East China. Each region contains some diversity in supply capacity, demand intensity, and time zone, so to achieve acceptable modeling accuracy they are subdivided to create network nodes for analysis. The nodes we use are listed by region in Table 2 with installed conventional and renewable generation capacity projected to the modeling year 2025.

Generation capacities are projected forward from the present assuming an average growth rate of 3% per year [3]. Some simple assumptions are used to allocate capacity between multiple nodes within China, Australia, and Indonesia. Above-average growth rates are used for economies that are rapidly developing at present, and growth rates are also varied according to known intentions to develop renewable generation. Typical daily demand profiles are developed for each region, accounting for latitude and longitude differences, and during the modeled...
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Table 2 Network Nodes for Market Analysis Including Generation Capacities and Peak Demands in 2025

<table>
<thead>
<tr>
<th>Node (Region)</th>
<th>Conventional capacity (GW)</th>
<th>Renewable capacity (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>East</td>
<td>64.0</td>
<td>6.2</td>
</tr>
<tr>
<td>West</td>
<td>5.5</td>
<td>4.7</td>
</tr>
<tr>
<td>South</td>
<td>29.6</td>
<td>20.3</td>
</tr>
<tr>
<td>Indonesia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flores</td>
<td>9.6</td>
<td>12.9</td>
</tr>
<tr>
<td>Java</td>
<td>9.4</td>
<td>8.6</td>
</tr>
<tr>
<td>Sumatra</td>
<td>9.4</td>
<td>0</td>
</tr>
<tr>
<td>ASEN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Malaysia</td>
<td>23.4</td>
<td>9.4</td>
</tr>
<tr>
<td>Thailand</td>
<td>31.2</td>
<td>14.0</td>
</tr>
<tr>
<td>Vietnam</td>
<td>9.4</td>
<td>23.1</td>
</tr>
<tr>
<td>China</td>
<td></td>
<td></td>
</tr>
<tr>
<td>East</td>
<td>343</td>
<td>250</td>
</tr>
<tr>
<td>North</td>
<td>406</td>
<td>203</td>
</tr>
<tr>
<td>South</td>
<td>354</td>
<td>94</td>
</tr>
<tr>
<td>West</td>
<td>406</td>
<td>175</td>
</tr>
</tbody>
</table>

year the maximum demand is scaled according to the season.

Chinese capacities dwarf others by an order of magnitude and it can be expected that the impact of international trading on a future Chinese market will be correspondingly small. China, and also Australia, will nevertheless benefit in proportion to the transmission capacity from an international market hungry for its energy resources.

B. Electricity Market Simulation

An international wholesale energy market is simulated using the PLEXOS software [21]. The electricity industry is widely considered to be an oligopoly, which features a limited number of producers, homogeneous products, barriers to entry, and strategic interdependence among companies. The market outcomes are computed using the Cournot equilibrium, which is a flexible and tractable approach based on the concept of Nash equilibrium [22]. It assumes energy companies compete on quantity. This is consistent with the existing Australian National Energy Market (NEM), a mature market operating in the Asian region, in which the rebidding process permits only quantity commitments to be varied between constant price bands [23].

Rather than modeling individual generation companies within countries, which may operate a variety of plant types, we have aggregated generation plant by type (coal, gas, hydro, wind, solar, nuclear) and each aggregation as if it were a participant in the international market. This is a poor representation of individual national markets but it allows us to treat the international market in an intuitive way and observe directly the market position of each type of generation. Generator dispatch is computed on a one-hour cycle accounting for generation capacity of each type, ramp rates, and transmission network constraints. Carbon prices of $15/ton and $50/ton of CO2 equivalent are included and are allocated by multiplying the generation output by a suitable average emission factor. This can change the merit order of dispatch of generation in favor of low-emitting plants. The output of the computation is a set of regional reference prices for each hour and the transmission flows over the network.

C. Results

A full year’s transmission flows and market behavior is modeled using the full, two-route network shown in Fig. 4, and the analysis is repeated for several values of transmission capacity as a sensitivity study. A reference case with no international connectivity is included to show market behavior when the regions are connected internally but not interconnected. Table 3 shows the average regional wholesale electricity prices for the modeled year, and Table 4 shows the consequent total wholesale cost of providing electricity to the Pan-Asian networked region, including the cost of greenhouse gas emissions priced at $15/ton. The variation with capacity is also shown in Fig. 5.

As the interregional transmission capacity grows, the overall cost, of electricity and emissions, will first decrease as cheaper electricity is exported from Australia to other countries. The cost is close to lowest over the sensitivity studies when capacity is 30 GW and represents a reduction of $6.55 billion per year compared to the isolated case. As capacity increases further the transmission congestion between Australia and Indonesia is relieved, resulting in a higher regional price in Australia that is sufficient to cause

Table 3 Impact of Different Interconnection Capacities on Regional Prices (/MWh)

<table>
<thead>
<tr>
<th>Region</th>
<th>Isolated</th>
<th>10 GW</th>
<th>20 GW</th>
<th>30 GW</th>
<th>40 GW</th>
<th>50 GW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austral.</td>
<td>9.50</td>
<td>9.50</td>
<td>9.50</td>
<td>9.50</td>
<td>13.71</td>
<td>20.74</td>
</tr>
<tr>
<td>China</td>
<td>20.90</td>
<td>20.90</td>
<td>20.90</td>
<td>20.90</td>
<td>20.90</td>
<td>20.89</td>
</tr>
<tr>
<td>Indones.</td>
<td>21.26</td>
<td>20.72</td>
<td>20.72</td>
<td>20.72</td>
<td>20.72</td>
<td>20.78</td>
</tr>
<tr>
<td>Malays.</td>
<td>31.88</td>
<td>20.72</td>
<td>20.72</td>
<td>20.72</td>
<td>20.72</td>
<td>20.78</td>
</tr>
<tr>
<td>Philipp.</td>
<td>25.52</td>
<td>20.72</td>
<td>20.72</td>
<td>20.72</td>
<td>20.72</td>
<td>20.78</td>
</tr>
<tr>
<td>Thail.</td>
<td>19.71</td>
<td>20.72</td>
<td>20.72</td>
<td>20.72</td>
<td>20.72</td>
<td>20.78</td>
</tr>
</tbody>
</table>

Table 4 Total Annual Cost of Electricity ($ Billion) in the Pan-Asian Connected Network

<table>
<thead>
<tr>
<th>Cost</th>
<th>Isolated</th>
<th>10 GW</th>
<th>20 GW</th>
<th>30 GW</th>
<th>40 GW</th>
<th>50 GW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electr.</td>
<td>63.68</td>
<td>61.45</td>
<td>60.44</td>
<td>59.45</td>
<td>60.60</td>
<td>64.14</td>
</tr>
<tr>
<td>Emiss.</td>
<td>51.43</td>
<td>51.24</td>
<td>49.30</td>
<td>49.12</td>
<td>48.96</td>
<td>48.96</td>
</tr>
<tr>
<td>Total</td>
<td>115.11</td>
<td>112.69</td>
<td>109.74</td>
<td>108.56</td>
<td>109.56</td>
<td>113.09</td>
</tr>
</tbody>
</table>
an overall cost rise. Therefore, it seems there is an optimum capacity for the network with respect to this measure.

The reduction in the region’s total emission costs suggests that conventional thermal generation is decreased due to more efficient sharing of renewable energy among the participating countries.

Consistent with our other assumptions, we assume that each country achieves a suitable internal transmission network and renewable generation portfolio through internal policy and funding mechanisms, so our analysis is contained to the impacts of international connectivity. Wholesale prices forecast by this model exclude not include costs of generation plant or transmission network as a component of price forecasts. Such infrastructure investments are funded in a variety of ways, and influence the price of energy seen by end users according to the tariff mechanisms employed.

V. PRACTICALITIES

A. Some Obstacles

1) Deep, Earthquake-Prone Oceanic Troughs: These present a major engineering challenge for connecting Australia to a Pan-Asian Energy Infrastructure.

For instance a 32-km stretch of earthquake-prone subsea terrain more than 2000 m deep lies south of East Timor.

The seismicity issue clearly requires more study. In terms of depth, natural gas pipelines have been proposed for similar depths elsewhere in the world. Examples are the proposed 2100-m-deep Medgaz pipeline between Algeria and Spain and the proposed 3100-m-deep SAGE pipeline between Oman and India across the Arabian Sea.

The deepest HVDC cables laid to date have been in waters 1650 m deep between Sardinia and mainland Italy. No technical impediments exist to laying HVDC in deeper water. It just has not yet been done.

2) Line Losses and Transduction: In wind and solar, losses naturally occur between the generation and consumption point. For instance, conversion from available wind energy to electricity by a turbine occurs at about 35% efficiency at an ideal wind speed. Conversion from incident solar energy occurs at about 20% efficiency for PV technology and 30%–40% efficiency for CSP. These are first-order losses.

Second-order losses occur in transmission from remote sites where they might be generated. Present industry estimates are that line losses amount to roughly 3% per 1000 km [24]. By contrast, the local AC loop loses anywhere from 5% to 15%. However, such losses should be seen in the larger context of efficiency gains needed across the entire electricity transmission and distribution chain instead of as a singular disadvantage of HVDC.

3) Regulatory Reforms Around a Common Carrier: In the European Union, the 27-nation bloc is working to integrate its electricity market. Reforms are proceeding in the ASEAN states. In the United States, important lessons were learned in California due to poorly constructed reforms which led to blackouts and bankruptcies. The U.S. Northeastern blackouts of 2003 indicated a strong need to reconsider that region’s network topology, management, and supply buffers.

Ideally, this might open the way for unbundling upstream energy production and wholesale carriage to market. At present, energy plant developers generally must shoulder the risk of insufficient carriage infrastructure. This hinders investment.

A number of common carrier templates exist. In the transport industry, these include toll roads and freeways. Meanwhile, Australia’s proposed National Broadband Network represents the most adventurous application of the model in telecommunications.

There, the government plans to spend roughly US$40 billion, or about 4% of one year’s Australian Gross Domestic Product building a national 100-Mb/s communications system. The Australian government will then manage the system, offering service providers nondiscriminatory wholesale access to the network.

4) Dependence Upon a Single Filament: A Pan-Asian Energy Infrastructure might dangerously centralize failure risk on a single piece of infrastructure. Such risks include earthquakes, fishing boat bottom trawling, equipment failure, and human error. It will be wise to incorporate some diversity when designing routes for the multiple cables
that will comprise the total transmission capacity. Proper design practices are well established to allow for multiple simultaneous failures of transmission lines and generation plants while continuing to serve the peak load [25].

Considering broader responses to contingencies, strategic reserves can be created along the route. Drawing down from such reserves can offset short-term supply disruptions caused by disasters and technical failures.

The best known example of a strategic reserve is the United States’ Strategic Petroleum Reserve. It holds 726 million barrels of oil, equivalent to 75 days of U.S. oil imports. China also is building strategic reserve facilities for both oil and natural gas.

In China’s case, such reserves will offer a supply buffer against shipping disruptions through the narrow Straits of Malacca, the major route to Asian markets for Middle Eastern oil and LNG supplies. As a further buffer against Straits of Malacca closures, China also is building a natural gas pipeline through Burma to the Indian Ocean to gain separate access to Middle Eastern oil and gas supplies before they transit the Straits of Malacca.

A Pan-Asian Energy Infrastructure therefore represents an additional delivery conduit for Asia. It adds to existing delivery infrastructure by expanding options for natural gas to get to market while opening up long distance transmission options for electricity across the region for the first time.

B. Costing Based Upon Comparables

Using publicly available information on existing projects, and then adjusting for capacity and distance, rough, first-order cost estimates of a Pan-Asian Energy Infrastructure can be derived. Additional adjustment factors can then be considered.

For land-based HVDC projects, we assume an investment cost of US$308 per megawatt of rated power per kilometer ($/MW/km). This figure is derived from 2007 industry price estimates of 4000-MW, 500-kV, two-bipole systems [24].

For sea-based HVDC projects, we use published prices for NorNed, a US$700 million, 560-km, 700-MW HVDC link between Norway and The Netherlands completed in 2008. NorNed cost roughly $1747 per megawatt capacity per kilometer (US$/MW/km) [2].

In 2050, we assume 17% of Asia’s electricity needs are met through cross-border HVDC electricity transfers. That is the same percentage of 2050 European demand proposed to be met by North African solar energy imports under the DESERTEC Industrial Initiative [1].

Assuming Asian electricity demand growth of 3% between 2008 and 2050, satisfying 17% of Asia’s 19 858 TWh of 2050 electricity demand, this implies a requirement for 589 393 MW of transfer capacity between Australia and China. This assumes 85% utilization of the HVDC system and 30% line losses over 10 000 km.

To provide perspective, the capacity outlined above is nearly six times the capacity foreseen for North Africa and Europe under the DII.

In both the land-based and sea-based cases, we assume a Pan-Asian Energy Infrastructure crosses the Timor Sea from Darwin, Australia to East Timor and onward to Alor Island in Indonesia.

From there, the infrastructure traverses Southeast Asia either by land across Indonesia and through the Mekong States to China and onward to East China Sea connections to Japan and South Korea.

If by sea, the infrastructure traverses Indonesia’s eastern islands and turns northward from Java into the South China Sea. It then passes Indonesia’s Natuna island before turning northeast just south of China’s Hainan island and then through the Taiwan Strait to an East China Sea interconnection with Japan, South Korea, and central coastal China through the port of Shanghai.

Based upon the comparables above, a land-based system would cost about $2.6 trillion. A sea-based system would cost several times more, or about $8.7 trillion.

Built out over 40 years, annual outlays would amount to $66 billion per year for a land-based system and $217 billion per year for a sea-based system, or 0.6% and 2%, respectively, of Asia’s 2010 GDP.

In 2006, the United Kingdom Treasury’s Stern Review [26] estimated the world needed to start budgeting spending of 1%–2% of global GDP per year on climate change mitigation and adaptation.

In 2009, Asia emitted 11.4 billion tons of carbon from the consumption of energy [3]. As such, the outlays above amount to $6–19 per ton of Asia’s energy related carbon emissions.

It must be noted, however, that the estimates above reflect only transmission infrastructure costs. They do not include electricity generating infrastructure costs. Those are separate.

The DESERTEC Industrial Initiative estimates the costs of the HVDC infrastructure needed to transport solar energy around North Africa and Europe at 11% of the overall project’s investment cost. The costs of the CSP infrastructure account for the rest [1].

Projecting future cost trends of CSP, wind, and other renewables is beyond the scope of this paper. Much hinges upon the future price paths of CSP and other renewable energy technologies in addition to price trends in HVDC. None of that is taken into account here.

However, it is important to stress that the costs of the necessary generation infrastructure dramatically expands the overall cost of a Pan-Asian Energy Infrastructure.

On the other hand, infrastructure projects in HVDC and natural gas pipelines are already underway that look potentially attractive for later interconnection. This offers the potential for the organic growth of a Pan-Asian Energy Infrastructure to emerge out of existing infrastructure projects.
Such existing projects include China’s efforts to lay HVDC across its terrain to expand and interconnect its provincial electricity grids. The aim is to create a unified, interconnected, national grid by 2020. China also is developing higher capacity, leading-edge transmission technology known as ultrahigh voltage direct current (UHVDC).

In the ASEAN states, detailed and specific multilateral energy interconnection projects such the Trans-ASEAN Gas Pipeline Project [27] and the Trans-ASEAN Electricity Grid [16] have been developed. These now await implementation.

We argue that the above analysis presents a defensible case for deeper examination of the costs and benefits of a Pan-Asian Energy Infrastructure.

VI. CONCLUSION

Asia faces a big challenge in building the energy infrastructure needed to sustain rapid economic growth while reducing carbon emissions. Given that most of this will be new, and not replacement infrastructure, Asia has an opportunity to engage in tabula rasa thinking. A Pan-Asian Energy Infrastructure represents an example of this.

We have examined a potential infrastructure design based on international high-capacity electricity transmission between Asian countries and comprehensive harvesting of the region’s best renewable energy resources. Two north–south transmission routes between China and Australia were considered, one island-hopping with short undersea segments and one entirely under the sea. Wind and solar resources in China, Mongolia, Vietnam, and Australia were characterized by hourly climate data for the full year 2010, and national generation capacities were projected forward to the year 2025 by which we anticipate that much of this infrastructure might realistically be funded and constructed. By simulating economic dispatch of generation in an envisioned international market we demonstrated cost benefits with a modest carbon price that justify further detailed examination. Immense strategic, political, and societal benefits may also be anticipated. History offers positive examples of tabula rasa thinking creating long-term benefits. One of these occurred after World War II in Europe.

In the early 1950s, France and Germany founded the European Coal and Steel community. One aim of the community was to intertwine France and Germany’s economies in order to avoid future wars. A half-century, 25 new members, and several name changes later, the European Coal and Steel Community has become the European Union.

Binding Asia’s 14 economies more deeply together through enhanced international energy trade may similarly yield positive long-term economic, environmental, and political outcomes.

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Taggart et al.: The Future of Renewables Linked by a Transnational Asian Grid


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