Enhancing the Integration of Renewables by Trans-Border Electricity Trade in ASEAN

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***Abstract*—To cover its rapidly increasing power demand is one of the biggest challenges of the ASEAN (Association of Southeast Asian Nations) region. But even though ASEAN offers abundant untapped renewable energy sources, its current power generation is strongly based on fossil fuels, mainly due to economic reasons. Trans-border electricity trade could increase economic viability of exploiting renewable energy sources as they are unevenly distributed among the ASEAN countries. In order to analyze the economic benefits of international electricity trade combined with increased renewable generation, a linear optimization model of ASEAN's power supply is presented in this paper which minimizes total cost of generation, transmission and storage. The results show that international electricity trade can lower additional power supply cost from 20.9 % to 14.9 % when CO_2 emissions are reduced by 40 %. Herein, most of the cost saving potential can be realized by trading electricity generated by hydro within the Greater Mekong Subregion.**

***Index Terms*—Asia, Power Generation, Power system planning, Power transmission**

I. INTRODUCTION

For the past decades, the ASEAN (Association of Southeast Asian Nations) community experienced an impressive economic development which resulted in an average annual increase of total real GDP by 5.1 % from the year 1990 until 2010 [1]. Connected to the economic growth of the region is an even stronger increase of its total electricity consumption. In 2010, ASEAN's total consumption of electricity amounted to 633 TWh and grew by an average annual rate of 7.9 % from its power demand in 1990 [1]. Although nowadays, the main share of electricity in ASEAN is generated by fossil fuels (33.2 % by coal, 44.1 % by gas and 10.3 % by oil in the year 2011 [2], the region offers abundant untapped renewable potentials for power generation. That offers the opportunity to mitigate the current rapid increase of greenhouse gas emissions related to power generation. Therefore, increasing power generation from renewable energy sources also became part of ASEAN's political agenda and was mandated as one of the main strategic goals in the ASEAN Plan of Action for Energy in 2007 [3].

As renewable energy potentials in ASEAN are unevenly distributed among its member states, trans-border electricity trade offers the opportunity to reduce total exploitation costs and therefore to enhance future renewable integration. Furthermore, international electricity trade could increase generation capacity utilization due to variations in regional load profiles and therefore reduce the total required generation capacity. But although it was mandated by the ASEAN member states already in 1997 to establish an ASEAN Power Grid (APG) under the ASEAN Vision 2020 [4], and a Memorandum of Understanding on the APG was signed in 2007 [5], only a few trans-border transmission line projects were realized so far, mostly based on bilateral agreements. Besides institutional barriers, the main reasons for the APG to lag behind its realization plan are concerns about the economic viability of the project.

Cost optimization models for expansion planning of generation, transmission and storage capacity are widely used to support decisions about the future design of power supply infrastructure. To analyze the economic viability of trans-border electricity trade in ASEAN combined with increased renewable generation, the usage of power supply optimization models is a promising approach.

In [6], a cost optimization model was developed to estimate possible economic benefits by electricity trade between ASEAN countries. But this work focuses more on multi-year development of power supply infrastructure and does not consider load profiles and intermittent generation from renewables in high temporal (e.g., hourly) resolution. Moreover, in [6] as well as in [7] and [8] the focus is mainly on estimating the economic benefits of trans-border electricity trade in ASEAN without considering higher penetration rates of renewable power generation or reduction of greenhouse gas emissions. Furthermore, many existing studies on trans-border electricity trade in ASEAN like [8] or [9] focus only on a few member countries and do not cover the entire ASEAN region.

In contrast, this paper presents a linear optimization model of ASEAN's power system that considers both trans-border electricity trade and increased power generation from renewables. The aim is to analyze potential power supply cost reduction by a possible APG with different penetration levels of renewable generation. To increase the share of renewables in the model, restrictions on CO_2 emissions of power generation are applied. The model minimizes total cost of generation, transmission and storage with a high spatial (89 model regions) and temporal (hourly) resolution for the year 2035.

In the following, an overview of the applied model structure and of the model input is given first. After that, the analyzed scenarios and the model results are presented, followed by a short conclusion of the paper and an outlook for future work.

II. MODEL STRUCTURE

In this paper, a techno-economic dispatch optimization model is used which is based on the model generator URBS [10]. It minimizes total cost of generation, transmission and storage to supply hourly load profiles of various model regions. The model regions are represented by load centers (nodes) and can be connected via transmission lines (edges). To cover the exogenously given load profile, new generation, storage and transmission capacity can be constructed. The objective function of the model is shown in (1) and describes the total system cost z, consisting of annualized investment costs z^{inv} and fixed operation and maintenance (O&M) costs z^{fix} of the considered generation (g) and storage (s) technologies within the model region r as well as of the transmission lines tl. Investment and fixed cost of generation, transmission and storage depend linearly on their respective capacities c.

Moreover, the investment and fixed costs of transmission lines depend linearly on the respective distance l between the connected model regions and are calculated assuming specific costs per unit length for overhead lines and sea cables. Furthermore, variable costs z^{var} of generation and storage are considered in each time step t and include variable O&M as well as fuel cost. The variable costs depend on the generated electricity and consider the efficiency of the respective generation technology.

$$\begin{aligned} z = \Bigg\{ & \sum_{g,r} \left\{ z^{inv}_{g,r}(c) + z^{fix}_{g,r}(c) \right\} + \sum_{g,r,t} z^{var}_{g,r,t}(gen) \\ & + \sum_{s,r} \left\{ z^{inv}_{s,r}(c) + z^{fix}_{s,r}(c) \right\} \\ & + \sum_{tl} \left\{ z^{inv}_{tl}(c,l) + z^{fix}_{tl}(c,l) \right\} \Bigg\} \end{aligned} \tag{1}$$

The main restriction of the model is shown in (2) and covers the power demand dem of each region in each time step, either by generation gen or energy from storage sto within the respective region or by net imports imp from other model regions. As only the high voltage transmission network is modeled, a loss factor dl is included which takes distribution losses within model regions into account.

$$dem_{r,t} \cdot (1 + dl) \leq \sum_{g} gen_{g,r,t} + \sum_{s} sto_{s,r,t} + imp_{r,t} \tag{2}$$

Transmission losses are considered assuming a loss factor that depends linearly on the length of the respective transmission line.

The model distinguishes between two different generation types: Intermittent and controllable generation. While the specific output per capacity of intermittent generation is determined by an exogenous generation time series, hourly power generation by controllable power generation technologies is determined endogenously by the model.

The maximum share of electricity imports from abroad in order to cover the domestic power demand can be limited for each country. This allows to restrict the maximum extent of trans-border electricity trade.

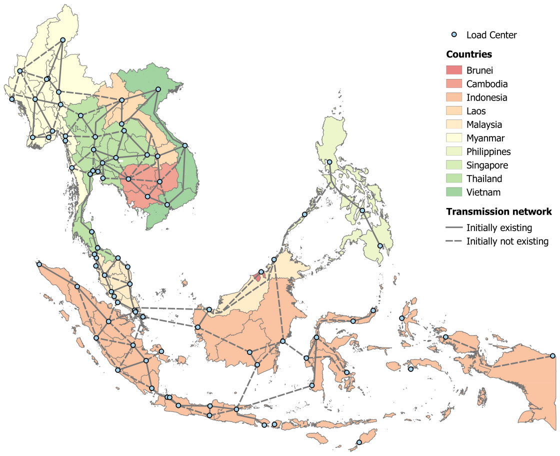

Figure 1. Model regions, load centers and possible transmission network

CO_2 emissions are calculated by fuel-specific emission factors and total fuel consumption. The annual CO_2 emissions of each country can be restricted which in turn increases power generation from renewable energy sources.

III. MODEL INPUT

A. *Model Regions and Transmission Lines*

The model regions with their respective load centers as well as the transmission lines which are taken into consideration are illustrated in Fig. 1. For each model region, the most populated city was chosen as its respective load center.

B. *Generation, Transmission and Storage Technologies*

The considered generation, transmission and storage technologies with their assumed investment, fixed and variable costs as well as efficiencies and depreciation periods are listed in Table I. The variable costs in Table I do not include fuel prices which are based on future projections given in [2]. It is assumed that in Singapore, the expansion of coal-fired generation capacity is not allowed. Power generation from hydro, solar Photovoltaics (solar PV) and wind are modeled as intermittent generation types whereas all other generation technologies are considered as controllable.

C. *Existing Generation and Transmission Infrastructure*

Currently installed generation capacities and transmission lines are taken from [13] and from power supply utilities of the ASEAN countries and are assumed to be initially installed in the model.

D. *Renewable Energy Potentials*

1) Geothermal: The site-specific geothermal generation potential is taken from [14]–[18] and aggregated within the respective model region. Only geothermal potentials which are classified as non-speculative are taken into consideration.

Table I
CONSIDERED GENERATION, TRANSMISSION AND STORAGE TECHNOLOGIES [11] [12]

Generation Technology	**Fuel**	**Investment Cost [USD/MW]**	**Fixed Cost [USD/MW a]**	**Variable Cost [USD/MWh]**	**Efficiency [-]**	**Depreciation Period [a]**
Subcritical	Coal	1 350 000	30 000	4	0.38	40
Supercritical	Coal	1 550 000	30 000	4	0.42	40
Steam Cycle	Biomass	1 880 000	60 000	6	0.25	20
CCGT	Gas / Oil	850 000	15 000	3	0.625	20
Gas Turbine	Gas / Oil	425 000	10 000	2	0.41	20
Hydro Turbine	-	2 080 000	10 000	0		50
Geothermal	-	2 340 000	120 000	0		20
Solar PV	-	1 350 000	10 000	0		25
Wind Turbine	-	1 435 000	20 000	0		25
Transmission Technology		**Investment Cost [USD/MW km]**	**Fixed Cost [USD/MW km a]**	**Variable Cost [USD/MWh]**	**Efficiency [per 1000 km]**	**Depreciation Period [a]**
HV Onshore		500	10	0	0.9	40
HV Offshore		3 500	70	0	0.9	40
Storage Technology		**Investment Cost [USD/MWh]**	**Fixed Cost [USD/MWh a]**	**Variable Cost [USD/MWh]**	**Efficiency [-]**	**Depreciation Period [a]**
Battery Storage		300 000	0	0	0.85	15

2) Biomass: Only residual biomass from agriculture is considered for power generation in this study. Current biomass production data of 305 areas in ASEAN combined with Residue-Production-Ratios and Lower-Heating-Values of the different biomass residues from [19] are used to estimate the biomass potential of each model region. To calculate the available biomass residues, collection efficiencies for field based residues as well as availability factors for both field and process based residues are considered.

3) Hydro: The hydro generation potentials by country are taken from [20]–[27]. As most data on hydro potentials are given for an entire country, they have to be distributed among the model regions. Therefore, raster data on drainage directions, hydrologically conditioned elevation and accumulated number of flow-in raster cells are used from [28]. The hydro potentials are then distributed within a country according to (3). Herein, h is the difference of hydrologically conditioned elevation between cell i and its steepest down-slope neighboring cell, and $NoFIC_i$ the accumulated number of flow-in cells of cell i.

$$HydroPotential \propto \sum_{i \in r} h_i \cdot NoFIC_i \tag{3}$$

The hourly time series of power generation from hydro is determined by applying a 14-day moving average on hourly precipitation taken from [29] and calculated for each model region by geographical intersection. It is assumed that hydro power plants are operating with 3500 full load hours per year.

4) Solar PV: The time series of power generation from solar PV per installed capacity is estimated using data on hourly solar irradiation from [29]. To increase the accuracy of the solar irradiation data, their monthly values are adjusted using a climate-based Angstrom-Prescott correlation [30] [31] between solar irradiation and sunshine hours. In order to determine this correlation empirically, measurements of sunshine hours at 249 stations located all over ASEAN are taken from [32]. The hourly generation of solar PV is then derived assuming technical characteristics of a typical PV module.

5) Wind: The generation time series of wind power is estimated using hourly wind speed data from [29] which are adjusted using high resolution raster data on terrain roughness derived with [33].

E. Power Demand

The annual power consumption by country, respectively by model region are taken from annual reports of ASEAN power supply utilities and projected to the year 2035 using annual growth rates by country given in [34]. As the current power consumption of Peninsular Malaysia is not given for each individual state, the power demand data is distributed among the comprising model regions according to the GDP by state.

Data on current load profiles were collected from the respective power supply utilities of each country. As some load profiles do not cover an entire year but only a typical week or day, these data were extrapolated in order to get annual demand curves. Since for Myanmar no data on load profiles is available, the demand profile from Cambodia is assumed as power consumption per capita, economic development and climate are similar. For model regions where no load profile data are available, the load profile from the model region within the same country and the closest power consumption per capita is applied. Moreover, if load profiles are only available for areas that comprise several model regions, the same load profiles for all included model regions are assumed. Any changes of normalized load profiles over time, e.g., due to economic development were not taken into consideration.

F. Further Model Input

In order to keep the model solvable within reasonable time, 1008 time steps were selected covering six weeks that are equally distributed over a one entire year. The results are then extrapolated to receive annual values.

For the calculation of annuities of investment costs, a depreciation rate of 7 % is assumed. Specific CO_2 emissions by fuel are taken from [35].

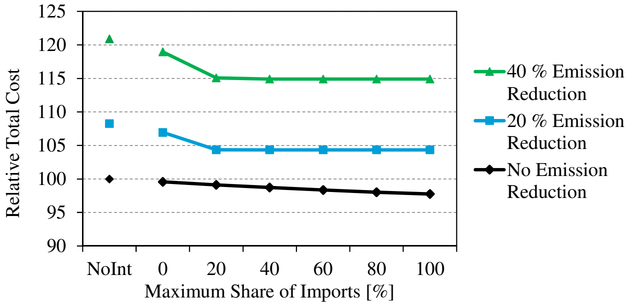

Figure 2. Relative Total Cost of Power Supply

IV. SCENARIOS AND RESULTS

A. Scenario Definition

As a basis for comparison, all countries have to cover their power demand independently without any imports from other countries. These scenarios are indicated with $NoInt$ in the following diagrams. With this reference, reductions of CO_2 emissions of each country by 20 % and 40 % are applied to enhance exploitation of renewable energy sources. Based on these scenarios, the restriction for trans-border electricity trade is more and more weakened by increasing the maximum share of electricity imports to cover the power demand of each country from 0 to 100 %. A maximum import share of 0 % means that even though electricity can be traded between countries, each country has to generate at least the amount of electricity which is sufficient to cover its own power demand, also taking distribution losses into account.

As renewable energy sources in Singapore are not enough to reduce CO_2 emissions by 20 or 40 % without any electricity imports, the total available renewable potential is assumed to be exploited in these scenarios.

B. Results

The total cost of generation, transmission and storage are shown relatively in Fig. 2. Without any trans-border electricity trade, reductions of CO_2 emissions by 20 % would result in additional total cost of 8.3 %, and in an increase of total cost by 20.9 % if CO_2 emissions were reduced by 40 %. By trans-border electricity trade, the increase of total cost due to reductions of CO_2 emissions can be lowered significantly. Like shown in Fig. 2, electricity trade offers the opportunity to reduce the increase of total cost from 8.3 % to 4.3 % with reductions of CO_2 emissions by 20 % and from 20.9 % to 14.3 % when CO_2 emissions are reduced by 40 %. Besides that, Fig. 2 shows that most of the saving potential by international electricity trade can be realized with moderate import shares lower than 40 %, especially when restrictions on CO_2 emissions are applied.

Assuming the input data in Table I, power generation from geothermal and hydro have lower levelized cost of electricity (LCOE) compared to other renewable generation technologies. Most of the geothermal generation potentials are located in Indonesia and the Philippines where the total annual power demand is relatively high compared to other ASEAN countries. Therefore, most of the geothermal potentials are already being utilized domestically, even without applying restrictions on CO_2 emissions. Hence, trans-border electricity trade does not further increase geothermal exploitation significantly. This is shown in Fig. 3 where the final installed generation capacities by fuel are illustrated and the installed geothermal capacity remains almost constant in all scenarios.

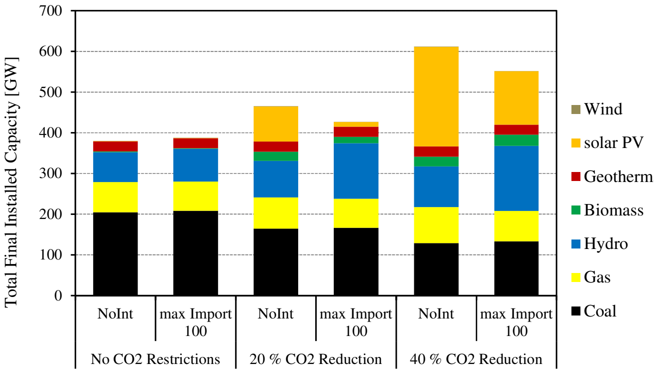

Figure 3. Total Final Installed Generation Capacity by Fuel

In contrast to that, Myanmar, Laos, Cambodia and Borneo offer abundant hydro generation potentials while having a comparatively low annual power demand. This gives the opportunity to export electricity generated by hydro potentials which are not yet exploited for domestic power supply.

Without international electricity trade, power generation from biomass and solar PV is increasing with stronger restrictions on CO_2 emissions. Once the restrictions on electricity imports are weakened, electricity generated by hydro is exported and replaces especially solar PV which in turn reduces total system cost.

Fig. 4 illustrates the annual net electricity import by model region as well as the resulting transmission network for the scenario without restrictions on electricity trade and with reductions of CO_2 emissions by 40 %. The thickness of the transmission lines in Fig. 4 are scaled by their respective transmission capacities. Fig. 4 shows that electricity trade is most intensively on the one hand in the Greater Mekong Subregion where countries with excess hydro potential (Laos, Myanmar and Cambodia) and countries with comparatively high power demand (Thailand and Vietnam) are located close to one another. On the other hand, the abundant renewable potentials of Borneo are used to supply the power demand of Java and Peninsular Malaysia.

V. CONCLUSION AND OUTLOOK

This paper presented an optimization model of ASEAN's power supply to analyze trans-border electricity trade in combination with increased penetration of renewable generation. It was shown that international electricity trade could significantly lower abatement cost of CO_2 emissions related to power generation. Power supply costs could mainly be reduced by increased trade of hydro-generated electricity. This gives countries with excess hydro potentials like Laos, Myanmar and Cambodia the chance to increase revenues by electricity exports. On the other hand, this could give possible importing countries like Thailand and Vietnam access to cost-efficient renewable energy sources.

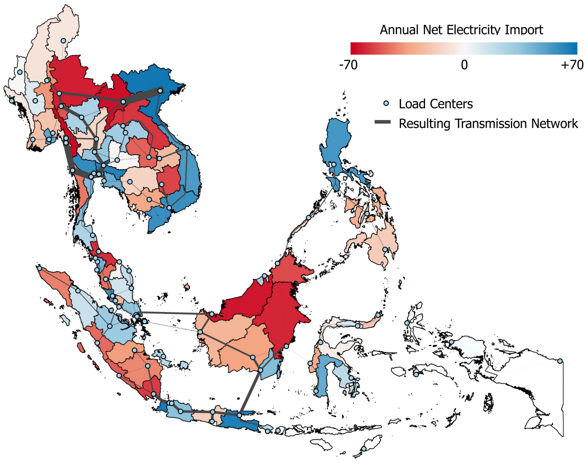

Figure 4. Transmission Network and Net Electricity Imports with 40 % Reduction of CO_2 emissions and without any restrictions on trade

Findings of this paper encourage further research on the modeling of power generation from hydro, especially to analyze the controllability of its power output. Furthermore, environmental and social consequences of hydro potential exploitation have to be taken into consideration. Moreover, the change of demand load profiles caused by structural changes and development of the ASEAN economies offers another interesting field for future work.

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