Optimizing Long-Term Investments for a Sustainable Development of the ASEAN Power System

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Abstract

The electricity consumption in the Association of East Asian Nations (ASEAN) region is one of the fastest growing in the world and will lead to a dramatic increase in greenhouse gas emissions in the next decades. A decarbonization of the region's electricity supply is thus a very important measure when taking action on global climate change. This paper defines cost-optimal pathways towards a sustainable power system in the region by employing linear optimization. The proposed model simultaneously optimizes the required capacities and the hourly operation of generation, transmission, and storage. The obtained results show that all different kinds of renewable sources will have to be utilized, while none of them should have a share of more than one third. The findings give reason for setting up an ASEAN power grid, as it enables the transportation of electricity from the best sites to load centers and leads to a balancing of the fluctuations from wind and solar generation. We suggest fostering a diversified extension of renewables and to elaborate on political and technical solutions that enable to build up an transnational supergrid.

Keywords: Renewable Energies, Wind and Solar Power, ASEAN, Supergrid, Energy System Modeling, Investment Optimization

1. Motivation and Related Work

The economic development of the Association of Southeast Asian Nations (ASEAN) countries has induced a tremendous growth of the energy demand in the last decades. The primary energy demand in the region increased from 223 Mtoe (million tons of oil equivalent) in 1990 to 549 Mtoe in 2011, which is an average growth rate of around 5% per year [1]. This trend is expected to continue at high rates in the next decades [1] and might even be accelerated by global warming might [2]. The increase of wealth will lead to an increased percentage of electricity in energy demand: electricity is expected to account for more than 50% of future growth in energy demand [1]. All those aspects emphasize the importance of an economic viable, environmental friendly, and secure electricity supply.

Currently, the region is relying on four major sources for electricity production: coal, gas, oil, and hydro [1] (see also Fig. 1). Other sources only play a minor role so far, and fossil fuels were responsible for 85 % of the generated electricity [3]. The consequence is a high level of CO_2 emissions which is increasing further at a high pace. The region's energy related CO_2 emissions are expected to grow from 1.2 Gt in 2011 to 2.3 Gt in 2035, resulting in a share of 6.1% of all global emissions [1]. At the same time, the region is highly vulnerable to hazards from climate change, such as increased sea-level, more frequent extreme weather, and agricultural challenges [5]. In order to combat those environmental hazards, a transformation of the ASEAN power system towards higher percentages of low-carbon energy sources is inevitable and should be a constitute of global climate policies.

ASEAN has several economically viable renewable energy resources. However, they are unevenly distributed across the countries and mostly are distant from the load centers in the megacities like Singapore or Bangkok [6, 7]. It is therefore a non-trivial task to find the best locations for the utilization of the renewable resources in a cost-effective and political viable way. However, organizing the transformation into a low-carbon power system at low costs is important for maintaining the prosperous economic growth.

Finding cost-optimal pathways for this transformation towards a low-carbon power system is the main contribution of this article. The optimal configuration of a future power system includes the locations and capacities of the renewable and fossil generation facilities, the placement of storages, and the transmission connections. In this paper, we model the cost-optimal build-up of this infrastructure for different levels of maximally allowed CO_2 emissions.

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Modeling the evolution from a mainly fossil-fuel-based generation mix towards a zero-emission system is essential for policymakers and investment planners. The results give them both a completely emission free target scenario as well as several intermediate steps. We know that our results are not a prediction about the future system and that unforeseen breakthroughs in technology could completely change the picture. The history of energy models and especially of resource optimization models showed that scenarios have to be considered very carefully and often turned out to be wrong in several aspects. To give a prominent example, the scenarios modeled by Nordhaus in the 70's [8] did not foresee the current fracking boom in the US at all. Still, the suggested approach of optimizing the allocation of resources is necessary in order to get an idea of the infrastructure required.

Several energy system models of Southeast Asia were developed in recent years for policy analysis. Following the historical development of these models, the first examples are bottom-up optimization-based models, such as MARKAL (MARKet ALlocation) [9] and bottom-up accounting models, like LEAP (Long-range Energy Alternatives Planning system) [10]. An early example of the application of a LEAP model can be found in [11]. Recently, some new model types that find cost-optimal power generation configurations were published. Major existing models are summed up in Table 1, of which we will discuss the three most relevant ones and compare them to our approach below.

The MARKAL-based model of Watcharejyothin et al. [15] includes five countries of the greater Mekong subregion (GMS) and is built upon their national MARKAL models. The model analyzes the benefits of integrating more local energy sources into the energy system, whereby electricity is one among all energy sectors. The dynamic linear programming model of Chang [18] is the first top-down model for ASEAN with a focus on the integration of RE. Based on macroeconomic data (fuel prices, CAPEX and OPEX of generation, demand growth, among others), the model identifies the priorities for developing new power capacities in order to meet the growing energy demand. The approach, however, does not account for the time-dependent generation and availability of renewable sources such as wind and solar energy.

Another model that analyzes the integration of renewable sources was developed by Yu et al. [13]. It includes the temporal dimension in form of typical days as well as the spatial dimension by considering 21 regions. The main focus ot this model is the evaluation of new hydro resources. Our model is an improvement over that approach by allowing for more details in both dimensions: a higher number of regions and the use of 12 complete weeks with each 168 hourly timesteps in a row instead of a few representative timesteps [13]. We extend the research of Yu et al [13] by analyzing the integration of all relevant renewable energy sources: hydro, wind, solar, geothermal, and biomass. Furthermore, we evaluate storage technology and its competition to transmission extension which could become an important design question for future power systems [19, 20]. We apply the URBS methodology that was developed by Richter [21] and was employed for several studies on renewable integration and optimal grid extension [22, 23]. URBS allows for the simultaneous optimization of operation and the extension of generation, storage, and transmission on high temporal and spatial resolution.

Stich et al. [24] apply the URBS methodology for the first time in the region, but with limited scope to Singapore, Malaysia, and Indonesia. The researchers were mainly looking at short term investments whereas the research in this article goes beyond that by modeling the complete ASEAN region and looking into long time investments.

All existing modeling approaches focus on a time span ranging from the current status to the next 20 years. A precise model of the current infrastructure with complete databases is required in order to achieve validity in such models. The optimal capacity extension of power plants and transmission mainly depends on the current capacity and location of power plants. In our article, a time horizon reaching to the year 2050 is considered. Therefore, the results concerning new infrastructure will not depend on current facilities and data quality anymore but on the generation structure of renewable sources as well as on the development of load in the regions. Our model has three main features that distinguish it from former approaches:

1. the consideration of temporal fluctuations in RE generation as well as demand,
2. the geographical distribution of load and RE resources in 33 subregions,
3. a technological bottom-up approach considering generation, transmission, and storage.

With this model setup, we aim at giving answers to several of the most important questions for policy makers and systems planners: Which resources should be utilized where? What are the most important transmission lines for fostering renewable generation? Should countries cooperate or are self-sufficient solutions equally efficient? And finally, what is the role of storage for the region?

We start with constructing a BAU scenario for CO_2 emissions by assuming an electricity mix for the region as described in [17] and [25]. Based on that, we explore alternative paths to lower emission in 10% steps down to completely emission-free systems. In all scenarios, we optimize the system infrastructure according to costs while keeping CO_2 emissions at a predefined level. The resulting pathways are analyzed and recommendations for policy makers, systems planners, and investors are drawn from the scenario results.

The paper is organized as follows: First we introduce the current situation of the electricity system in the region in section 2. We then explain our modeling approach and the database used in section 3. Next, we develop scenarios which determine the boundaries of the optimization

Table 1: Overview of employed energy models in the ASEAN region

Location	Type	Year & Source
Indonesia, Philippines	MARKAL	1999 [9]
Indonesia, Malaysia, Philippines, Thailand, Brunei, Vietnam, Singapore	LEAP	2002 [11]
ASEAN except Brunei and Singapore	MARKAL	2002-2006 [12]
ASEAN and southest China	min cost	2005 [13]
GMS	MESSAGE	2008 [14]
GMS	MARKAL	2009 [15]
Laos, Thailand	MARKAL	2009 [16]
ASEAN	LEAP	2009-2010 [17]
ASEAN	Dynamic programming	2012 [18]

model in section 4. In section 5 we show, explain, and analyze the results of our scenarios. Finally we conclude our paper with a short resume, some policy suggestions, and an outlook to future research possibilities.

2. Current Electricity Supply and Demand Projections

In this section, the current infrastructure of generation and transmission in the ASEAN region is described. The current demand and its distribution among the countries is displayed, and our projection of growth to the years 2035/2050 is explained.

2.1. Generation

The current power system in the ASEAN region relies on four major sources: coal, gas, oil, and hydro power as depicted in Fig. 1 for all ASEAN countries. In addition, new renewable energies (NRE = all renewable sources except hydro) are utilized in several countries. Amongst them, geothermal energy and biomass already play a very important role in Indonesia [26]. The high share of electricity generated from fossil fuels shows the challenge that lies ahead in a system transformation.

2.2. Transmission

The power transmission system is underdeveloped in several of the analyzed countries. As shown in Table 2, the share of population without access to the national electricity grid is heterogeneous in the ASEAN countries. Singapore, Brunei, Malaysia, Thailand, and Vietnam are almost fully electrified whereas Cambodia and Myanmar have extremely low rates with more than 50% of population being without access to electricity. Table 2 shows that countries that are geographically widespread (including many small islands) as well as less developed countries tend to have lower electrification rates. These countries are assumed to have the highest growth rates of electricity consumption in the next decades as described in the following.

2.3. Current Demand and Projections

The demand for electricity differs from country to country as does the status of economic development. The current total electricity demand in ASEAN plus Papua New Guinea (PNG) was 595.7 TWh in 2010 according to several sources for the region and individual countries [25, 27–29]. Electricity per capita ranges from 0.12 MWh/capita in Myanmar to 8.14 MWh/capita in Brunei as depicted in Table 3. In order to estimate the demand in 2050, we assume a significant growth in the next 20 years until 2035 according to the growth rates given in Table 3 including

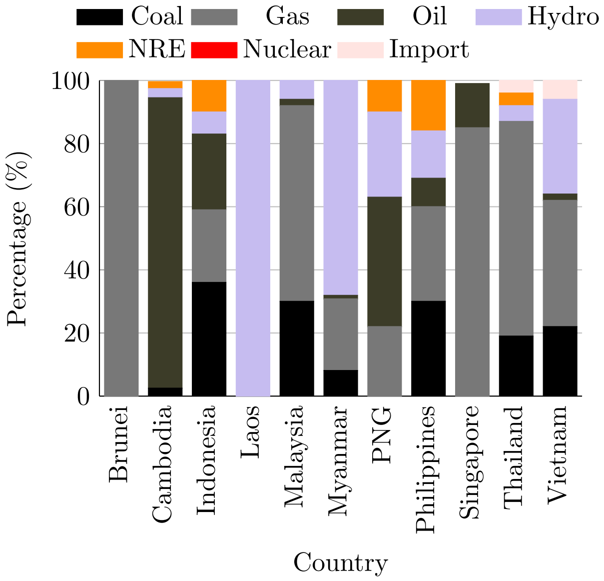

Figure 1: Current generation mix in the ASEAN countries [25] (NRE=new renewable energies).

Table 2: Electrification rates of ASEAN countries. Data from [25] was used except for Cambodia [27], Lao PDR[28], and Myanmar[29]. Data about the share of population without electricity come from [1].

Country	% of Population without Electricity	% of Households with Electricity
Brunei	0	n/a
Cambodia	66	n/a
Indonesia	27	67.2
Laos	22	n/a
Malaysia	1	n/a
Myanmar	51	n/a
Philippines	28	73.7
Singapore	0	100
Thailand	1	86.8
Vietnam	4	98.5

the respective references. From 2035 to 2050, we assume the electricity consumption to remain constant. An argument for this assumption is that electricity consumption and economic growth have been shown to decouple at a certain stage of development in many countries as evidenced e.g. by [30–34].

3. Model and Data base

We apply the model URBS for our analysis and scenario calculations. The model co-optimizes capacity as well as hourly dispatch of generation, transmission, and storage. We name the model "URBS-ASEAN" in the following which includes the model equations as well as the dataset described below. Fig. 2 shows the major inputs and outputs of the model.

3.1. System Cost Minimization

URBS-ASEAN finds a minimum-cost system configuration to meet a predetermined electricity demand from a social planner perspective while having a constraint budget of CO_2 emissions. It is a combined optimization of both dispatch and investment decisions. The costs can be divided into costs for investment and annual fix costs for maintenance of generation "InvG", storage "InvS", and transmission "invT", as well as variable production costs "varG" to:

$$\min c = \min(\mathrm{invG} + \mathrm{invS} + \mathrm{invT} + \mathrm{varG}) \tag{1}$$

Annual Investment costs inv={invG,invS,invT} are thereby calculated as annuity from the installed capacity and specific investment costs KI of each technology:

$$\mathrm{inv} = \mathrm{KI} \cdot \mathrm{capacity} \cdot \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \tag{2}$$

where i is the interest rate and n the lifetime of the facility. We assume an interest rate of 7% [23] and lifetimes according to Table 5 and the descriptions in Section 4.1.2.

The main restriction is that electricity load D_v^t has to be provided in every time-step t and region v by generation $p_{v,g}^t$, storage $p_{v,s}^t$, and electricity imports f_{v,n_v}^t from neighboring regions n_v:

$$\sum_g p_{v,g}^t + \sum_s p_{v,s}^t + \sum_{n_v} f_{v,n_v}^t \geq D_v^t \qquad \forall t \in \mathcal{T}, v \in \mathcal{V} \tag{3}$$

Power generation is modeled as an input-output process. Input commodities are gas, coal, biomass as well as the intermittent hydro, wind, and solar resources or a constant supply by geothermal heat. If fossil fuels are burned, electricity is produced with efficiency η according to Table 5, and in addition, CO_2 is released according to the carbon content of the fuel. The CO_2 emissions are restricted to $\mathrm{E}^{\max}$ by:

$$\sum_{t,v,g} p_{v,g}^t E_{v,g} \leq \mathrm{E}^{\max}. \tag{4}$$

The complete mathematical description of the model including equations for storage, transmission, and capacity extension can be found in the Appendix 7.1 (including a nomenclature in Table 9).

3.2. Time and space:

The model works on a time resolution of 1 h and a spatial resolution of 33 subregions. The time span covered consists of 12 weeks equal to 2016 time steps. Each week represents one month of the year. Modeled subregions are the complete ASEAN region + PNG. The subregions are based on the countries as depicted in Fig. 3 and are further described in Table 10. The criteria for the region arrangement are load centers and resource availability.

3.3. Time Dependent Input Data

Hourly Load. Hourly load curves for the entire year are required for each of the 33 subregions. Facing the impossibility of obtaining real data for each subregion, a generic load model was employed. Load curves are generated based on three characteristics: the hourly curve $L_{t,v}^h$ representing daily fluctuations, the weekly curve $L_{t,v}^w$ to account for different consumption on workdays vs Saturdays and Sundays, and the monthly curve $L_{t,v}^m$ to consider seasonal variations. A normalized load curve $L_{t,v}$ for a whole year in one region results from the following equation:

$$L_{t,v} = L_{t,v}^m \cdot L_{t,v}^w \cdot L_{t,v}^h, \qquad \forall t \in \mathcal{T}, v \in \mathcal{V}. \tag{5}$$

A typical characteristic for each of the parameters is illustrated in Fig. 4. The different parts of the load curve are constituted as follows:

- Hourly curve ($L_{t,v}^h$): The average hourly load data of Singapore of 2008 [35] was employed for all the regions as we assume a converging economic development until 2050 in all ASEAN countries. We expect a growth of air conditioning, services, and commercial sectors leading to a characteristic comparable to Singapore nowadays. We distinguished between three types of days: work days, Saturdays, and Sundays.
- Weekly curve ($L_{t,v}^w$): The average value for each day of the week of Singapore's load [35] was utilized.
- Monthly curve ($L_{t,v}^m$): The monthly values are normalized values of the average high temperatures of representative cities. The underlying assumption is a strong correlation between temperature and electricity consumption driven by cooling requirements as evidenced e.g. in [36].

This characteristic is scaled to the annual demand in each country [37] with demand projections for all countries according to section 2. The demand projections for countries have then to be split down to the subregions according to the following data: transformer capacity repartition [38], generation distribution with data from [39] and [40] (assuming that thermal power plants are built close to load centers [41]), and demand distribution [42].

Table 3: Development of electricity consumption in the ASEAN countries

Country	Growth rate (% per year)	Consumption 2010 (TWh)	Consumption 2010 (MWh/capita)	Consumption 2035/2050 (TWh)	Source
Brunei	0.50	3.26	8.14	3.69	[25]
Cambodia	13.20	2.01	0.14	44.56	[27]
Indonesia	5.50	145.10	0.60	554.31	[25]
Laos	8.10	2.35	0.37	16.51	[28]
Malaysia	3.00	109.82	3.88	230.17	[25]
Myanmar	7.40	6.09	0.12	35.92	[29]
PNG	5.00	3.12	0.45	10.55	[25]
Philippines	4.40	56.84	0.61	166.79	[25]
Singapore	1.20	40.62	8.00	54.74	[25]
Thailand	3.60	140.84	2.12	340.98	[25]
Vietnam	6.40	85.68	0.99	403.93	[25]

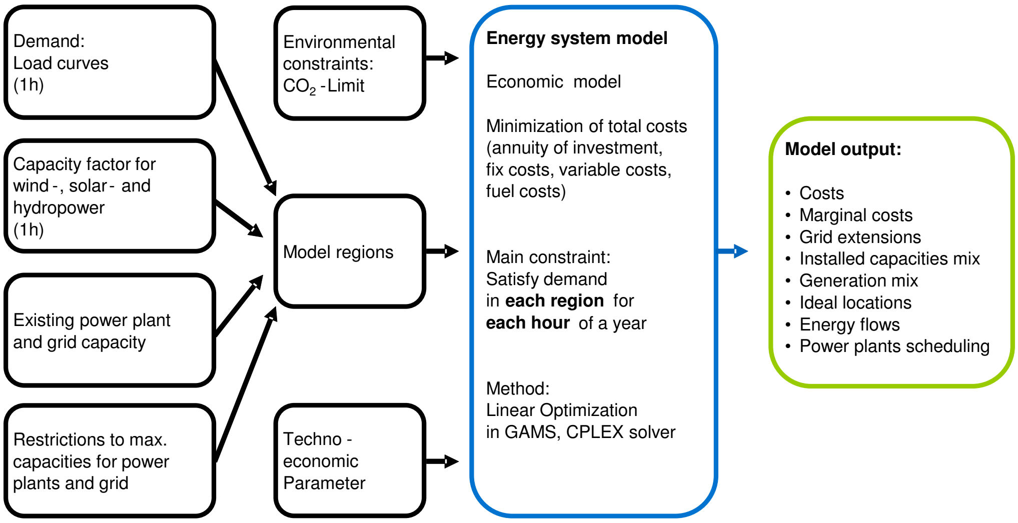

Figure 2: Major inputs and outputs of the URBS methodology

Must-run power plants. Power generation from must-run power plants is predetermined by hour-by-hour weather conditions in the modeled year. The capacity factors (CF) for the must-run technologies were mainly calculated from weather data:

- Wind: Hourly mean wind speed was transformed to electric output power by applying a typical characteristic curve of a wind turbine.
- PV: Photovoltaic power output was derived linearly from hourly global horizontal irradiation.
- Hydro run of river: The hydropower time series were based on monthly rainfall averages from selected locations within each region (see Table 10). Thereby, a time delay of two months between rainfall and actual power generation was assumed. Hourly generation profiles for the modeled year were interpolated from this monthly data.
- Geothermal: Geothermal power was assumed to run at constant value during the whole year.

The weather data employed is originally from NASA [43] and was processed by Janker [44]. Measurement points in the 0.5 grid of NASA are aggregated to our subregions. The aggregation method was validated and showed a fitting of full load hours and hourly generation [44] as well as gradients [45] very well. We use the year 2007 as a typical year for the hourly weather situation.

3.4. Controllable generation, transmission, and storage

Controllable power plants. Controllable power plants include all fossil, biomass, or nuclear fired power plants that are employed. In each hour, the model can decide how much electricity should be produced. Restrictions are the limit for CO_2 emissions in the ASEAN region and a maximum potential for biomass production per region.

Transmission. Electricity transmission in the ASEAN region is modeled using a region-to-region transport model [22], including losses according to the distance between two country's geographical center points. In the transport model, energy can be allocated and transported like a physical good. Distribution losses of 7.5% are accounted

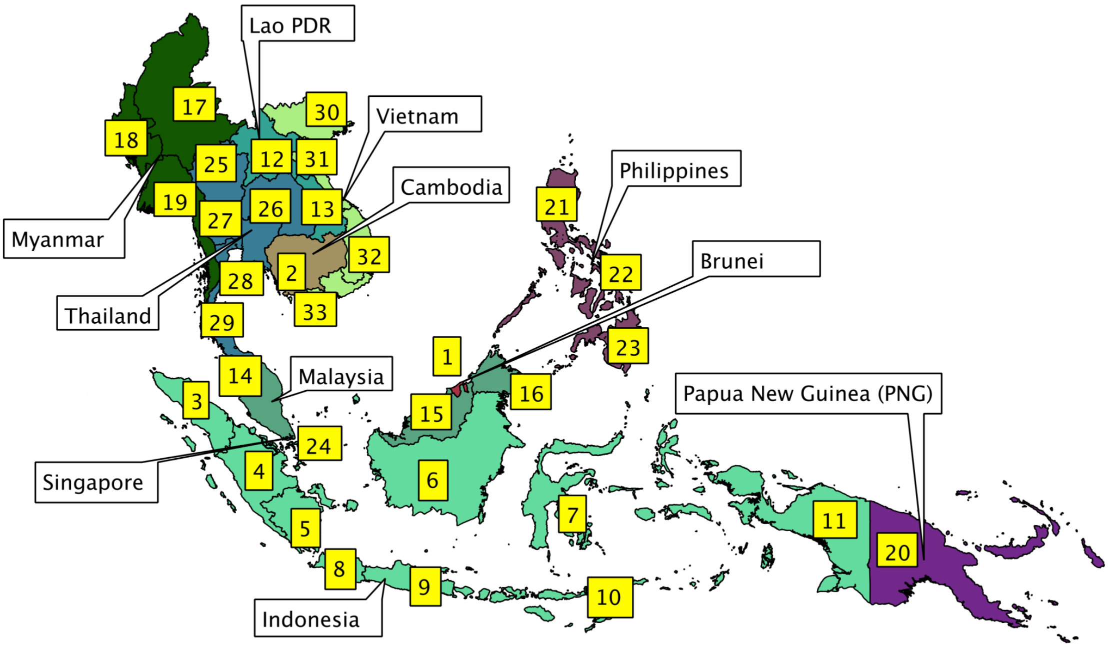

Figure 3: Overview of the modeled regions

for in each region by increasing the respective final demand. Investment costs for the distribution network are not included in this model which has to be reminded when analyzing the scenario results.

Storage. The model includes pumped hydro as well as battery storage. Both processes have a specific efficiency as well as a maximum capacity assigned. In addition, the maximum energy content of the reservoir is limited. In the model, the reservoir level is half filled at the beginning of the optimization period and has to be half filled at the end again. The storage equations can be found in the Appendix.

4. Scenario development

In this section we give an overview and explain the scenarios that we are evaluating. In all our scenarios we consider a greenfield approach. This allows us to find the optimal configuration of infrastructure in a case where the infrastructure is built from scratch. Since in the very long term all of the current infrastructure has to be replaced anyhow, our approach allows for a long-term planning and policy. It gives the planners a vision for how the power systems should be developed in order to achieve certain CO_2 reductions at minimum cost. Accordingly, we consider electricity load forecasts for the year 2050.

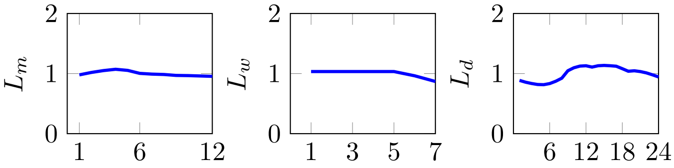

Figure 4: Illustration of the load model formulation, left: Month of the year, middle: Day of the week, right: Hour of the day

4.1. Main scenario

We start our overview with the scenario that is called "main scenario" in the following. This scenario is considered to be the most realistic, and our alternative scenarios are derived from it. The major input parameters for the scenarios are the potentials for renewables and the costs for each technology. Feed-in characteristic of renewable generation is the same for all scenarios as described in section 3.

4.1.1. Potentials for renewables

Potentials for renewables in the ASEAN region are discussed in several articles and reports as shown in Table 11. However, the numbers for the respective potentials differ greatly. Just to give one example, wind potentials in [3] vs. [6] differ by a factor of 23 for Thailand. In order to come up with traceable numbers we did a calculation for the potentials on our own, considering the complete technical potential. The potentials are mainly based on the available land area per region, population, and factors depending on the quality of the resource. The procedure for this estimation is described briefly in the following according to the different technology types. The result of this approach is also depicted in the appendix in Table 12. The resulting numbers seem to be much higher than previously published potentials. However, most other sources only consider sites with full-load hours above certain levels; when comparing only those potentials, our results fit those previous studies quite well.

Wind Onshore. For each region, a time series for the generation in each timestep as well as potentials are to be defined. The time series for the hourly generation from fluctuating sources are called capacity factors (CFs). Those are based on historical weather data [43] that were processed by [44]. The dataset consists of three CFs for onshore wind power (highest/middle/lowest annual full-load hours) for each of the 294 districts in the whole ASEAN, summing up to 792 characteristic time series in total. For each of our modeled subregions (see Table 10), we consider the relevant districts thereof and group the time series according to the annual full-load hours as summarized in Table 4.

Table 4: Classification of FLH (full load hours) groups for wind power generation sites

Group #	FLH-range Onshore	FLH-range Offshore
1	≥ 2000	≥ 2000
2	$\geq 1500, <2000$	$\geq 1500, <2000$
3	$\geq 1000, <1500$	-
4	<1000	-

Averaging the characteristics for each group in each subregion leads to 4x33 characteristic time series for wind generation. The potential "Pot" for each subregion and category can be calculated by the area of the region "Area_v", the percentage of the area that can be used for wind turbines "Ratio_wind", and the potential factor "F_wind" :

$$\text{Pot}_{\text{wind-on},v} = \text{Area}_v \cdot \text{Ratio}_\text{wind-on} \cdot \text{F}_\text{wind-on} \tag{6}$$

with $\text{F}_\text{wind-on} = 7\ \text{MW/km}^2$ and $\text{Ratio}_\text{wind-on} = 0.025$ (meaning that 2.5% of the area can be used for wind power plants).

Wind Offshore. The methodology for deriving CFs for offshore wind is similar to onshore but only 2 groups (see Table 4) and thus 2x33 CFs were computed from 92 CFs in the database. The potential is calculated according to:

$$\text{Pot}_{\text{wind-off},v} = \text{Area}_v \cdot \text{Ratio}_\text{wind-off} \cdot \text{F}_\text{wind-off} \tag{7}$$

with $\text{F}_\text{wind-off} = 15\ \text{MW/km}^2$ and $\text{Ratio}_\text{wind-off} = 1$.

Solar PV. We consider two types of solar PV installations and therefore also two types of potential, the so called "rooftop" PV which is installed on buildings, and the "utility-scale" PV that is built on open fields.

- Rooftop: The potentials are derived from two main factors: the population and the area of the region. Depending on the population density ρ, we assign three different values based on [46] for the PV area per Capita γ: $\gamma_1 = 45m^2/\text{Capita}$ for $\rho \in [0; 100]$; $\gamma_2 = 20m^2/\text{Capita}$ for $\rho \in [100; 500]$; $\gamma_3 = 15m^2/\text{capita}$ for $\rho \in [500; \infty]$. The potentials can then be calculated by:

  $$\text{Pot}_{\text{rooftop},v} = \text{Capita}_v \cdot \gamma_v \cdot \text{F}_\text{PVroof} \tag{8}$$

  with a potential factor of $\text{F}_\text{PVroof} = 125\ \text{MW/km}^2$, as suggested by [47].

- Utility-scale: The potential was estimated similar to the wind potentials:

  $$\text{Pot}_{\text{utility-scale},v} = \text{Area}_v \cdot \text{Ratio}_\text{PVutil} \cdot \text{F}_\text{PVutil} \tag{9}$$

  with a ratio factor $\text{Ratio}_\text{PVutil} = 0.02$ and a potential factor of $\text{F}_\text{PVutil} = 65\ \text{MW/km}^2$ as given by [47] for ground based plants.

Other potentials:. Additional potentials that have to be obtained consider hydropower, geothermal, and biomass. The potentials and respective sources are given in Table 11 on a per country base. We distributed those value to the subregions proportional to the electricity demand. The resulting potentials for each subregion are displayed in Table 12.

4.1.2. Costs and Efficiencies

In this subsection, all costs and efficiencies that were assumed in the scenario calculations are described.

Generation. Investment costs of power generation facilities are an important parameter in all models concerning investment decisions. In our model, we follow the cost predictions of the IEA WEO 2013 [48] for 2035, all assumption are in $\$_{2012}$. As there is no explicit ASEAN region in the EWO, we assume the costs to be the average of the costs given for China and India. The resulting costs and the efficiencies are shown in Table 5. The respective fuel prices were estimated in accordance with data from the IEA [1] and are set to: 15 $\$/\text{MWh}_\text{th}$ for coal, 45 $\$/\text{MWh}_\text{th}$ for natural gas, and 62 $\$/\text{MWh}_\text{th}$ for biomass/biogas.

Table 5: Assumptions for investment costs and efficiencies according to [48]. Efficiencies of must-run plants are not considered explicitly but incorporated in the hourly capacity factors (CF). All cost assumptions are expressed in $\$_{2012}$.

Type	Invest. [\$/kW]	O&M [\$/kW]	Efficiency [%]	Lifetime [years]
Coal	1250	50	48	40
Gas OC	375	19	40	30
Gas CC	625	22	59	30
Wind Onshore	1340	20	-	25
Wind Offshore	2050	70	-	20
PV Rooftop	1225	20	-	25
PV Open Area	990	17	-	25
Biomass	1750	62	35	
Hydropower	2390	55	-	50
Geothermal	1875	38	-	30

Transmission. Concerning the transmission grids, the costs are 500 \$/MWkm for overland lines and 2500 \$/MWkm for sub-sea cables with a lifetime of 40 years. If a connection between two areas requires sub-sea as well as overhead lines, a weighted average is built (see [22] and references therein).

Storage. The model allows for the installation of electricity storage. This includes battery storage technology and, to some limited extend, also pumped hydro. Installing the latter is possible in several countries (e.g. in Vietnam [49]) but there is no study available including the potentials for the whole ASEAN. As a rough estimation, 1 GW power and 12 GWh of storage capacity are allowed at costs of 500 \$/kW and 100 \$/kWh in each subregion. The costs for the battery are 500\$/kWh in the base scenario and potentials for batteries are unlimited. Lifetime of the batteries is 20 years in all scenarios, which is an optimistic case compared to today's measurements.

4.1.3. Maximal CO_2 emissions

The maximal allowed CO_2 emissions are reduced from a base level of 250 g/kWh in 10 steps down to a zero emission scenario. The base level is derived from the total emissions of the power sector in 2012 [1], divided by the electricity consumption assumed for 2050. In other words, total emissions in the base case are assumed to stay constant at the 2012 level while electricity consumption is increased. The level of 250 g/kWh could be reached with a power system of mainly gas and the cheap hydro resources while more expensive renewable technology like geothermal, biomass, wind, and solar are not necessarily required. Scenarios with less CO_2 emissions show the pathway to a very low carbon or even emission free electricity supply in the ASEAN region.

4.2. Alternative scenarios: "Autonomy" and "Tech"

From our base scenario, we develop two alternatives. The first alternative scenario "Autonomy" assumes that countries are not willing to cooperate and will not allow a cross-border electricity exchange. We restrict the electricity transport to the interchange between regions within countries. This scenario also allows for the evaluation of the value that a cooperation in this region could have for the integration of renewable energy sources. Our second alternative, the "Tech" scenario, assumes tremendous technological progress in the development of PV cells and batteries. Organic PV cells will bring a breakthrough in production costs leading to the cutting of investment costs in half. Additionally, batteries will be produced on industrial scale and also face tremendous cost reductions down to 250 \$/kWh. The cost development in the "Tech" scenario is depicted in Table 6.

Table 6: Change of investment costs in the "Tech" scenario

Technology	Base/Autonomy	Tech
PV Rooftop	1225 \$/kW	612.5 \$/kW
PV Open-area	990 \$/kW	495 \$/kW
Battery	500 \$/kWh	250 \$/kWh

5. Analysis of results

This section gives an overview of the model results. We start with the analysis of results from the main scenario focusing on the optimal generation mix. Then, we compare the development of costs and the importance of grid and storage in all scenarios.

5.1. Main results

The main results consider our base scenario according to 4. This scenario is considered to be the most realistic one and thus analyzed in more detail here.

5.1.1. Optimal generation mix

First we analyze the optimal generation mix that should be utilized in order to achieve the respective carbon limitations at minimum costs which is depicted in Fig. 5. This illustration allows us to derive several conclusions. First we see that coal power, being the cheapest option for the power supply in the region, supplies around one third of the electricity at 250 g/kWh. This trend towards coal is already described in the forecasts of the IEA [1] and APEC [25]. However, at this level of CO_2 emissions, renewable energy sources are already used heavily to counterbalance the high emissions caused by coal which emits around 700 g/kWh. The alternative to this coal/renewables mix would be a system with mainly gas-powered plants. However, the latter proved to be a more expensive solution than the coal/renewables mix solution. A fuel shift from coal to gas is only observed when the maximal emissions are reduced drastically to less than 100 g/kWh.

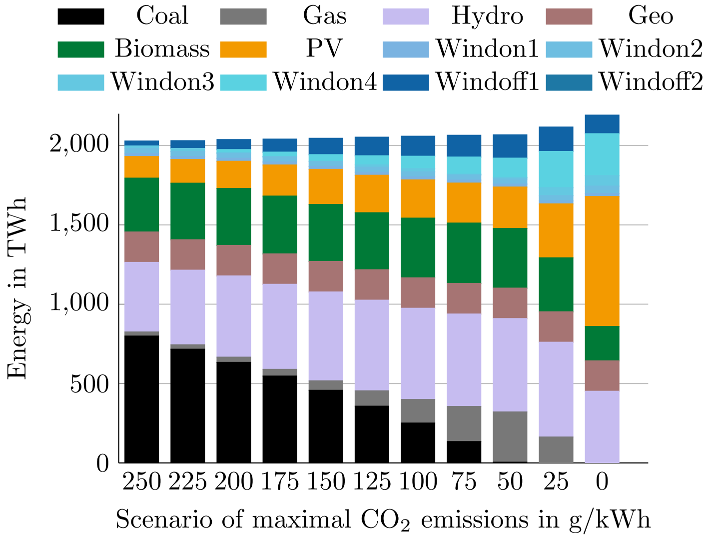

Figure 5: Development of generation mix in the main scenario according to maximal CO_2 emissions allowed.

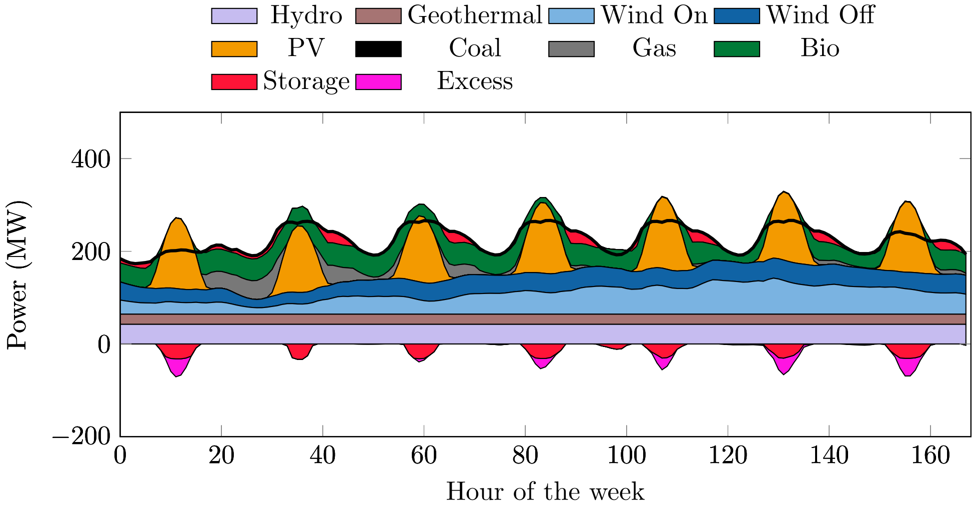

Figure 6: Production in a typical week summed up for all analyzed regions in the scenario of 25 g/kWh of CO_2 in the generation mix.

The geographic distribution of generation is depicted on the right side of Fig. 10, which together with Fig. 5 gives more insights to the optimal resources allocation. We see that employed renewables should be diverse in all scenarios: The regions' hydro power potential is the most important source, providing 438 TWh - 600 TWh in the scenarios. The geothermal potential of 192 TWh is exploited in all considered scenarios as it is a cost-effective technology without emissions that is available and close to the load centers of Indonesia. Biomass is a source that is used to balance the fluctuations and thus is also applied in all scenarios and all regions. Concerning wind power onshore and offshore, we see their contributions are only small in the scenario with 250 g/kWh. The capacity is concentrated on the very good sites that can be found in Vietnam and the Philippines. When further reducing the maximally allowed emissions, wind power becomes more and more important. Especially in southern Vietnam, wind power onshore and offshore should heavily be exploited. Additional sites explored include Myanmar's coast as well as the Indonesian islands that have reasonable wind sources. Regarding PV, we can see a steady growth when emissions go down. Especially in the scenario where no emissions are allowed at all, PV becomes a major source of electricity accompanied by heavy employment of batteries that allow to balance these fluctuations.

The hourly generation profile for the complete ASEAN region in a typical week for the scenario with 25 g/kWh of CO_2 is depicted in Fig. 6, which is also showing the role of different sources in scenarios with mainly renewable energies: hydropower and geothermal provide a non-controllable baseload. Wind and PV fluctuate on a daily and weekly basis and have to be balanced by either biomass and natural gas, or by storage. Fig. 6 also illustrates that not all of the generation can be integrated economically but will partly be wasted in form of excess electricity. The peaks of PV generation are not integrated completely in an economically optimized system.

5.1.2. Grid connections

Grid connections play an important role in a power system with high shares of intermittent renewables as they allow to balance fluctuations across space. The importance of this balancing was assessed for the European system several times (e.g. in publications by [22],[23],[50], among others). In this article, we analyze the effects for the ASEAN region which has a complete different supply structure: While Europe mainly relies on wind and solar power in scenarios with high shares of renewables [51], hydropower and geothermal power sources are predominant in the ASEAN power systems [1]. As those sources are less or, not even at all, variable, balancing seems less relevant. Nevertheless, they are often far away from the load centers and therefore also require large transmission capacities.

Fig. 10 illustrates the development of transmission lines and the regions' net export (colors of polygons: red is exporting, blue is importing) when aiming at a low carbon power supply and clearly shows that the exploitation of renewable sources is a driver of transmission extensions in the ASEAN power system. At 250 g/kWh, the largest lines should be built between Sumatra and Malaysia/Singapore in order to transport electricity generated from biomass and geothermal sources. Other lines are used to transport hydro generation, e.g. from Cambodia and Laos to Vietnam and from western Myanmar to the center and south of the country. When moving forward to 125 g/kWh, the hydro sources in western Myanmar are utilized further, and the electricity is now transported down to the Bangkok area. The lines from Cambodia and Laos to Vietnam as well as from Kalimantan are extended significantly. Finally, at CO_2 emission restrictions as low as 25 g/kWh, those lines are extended even further. The transmission line between southern Vietnam and Cambodia gains special attention as it is used to transport offshore wind power from the coast to the center of the ASEAN region now. Southern Vietnam will become a net exporter as soon as those wind sources are exploited. In order to help policy makers, especially the APEC planning for new interconnections, Table 7 shows the most important connections that were identified.

5.2. Robustness of results - comparisons to alternative scenarios

As many input parameters are uncertain, we conducted two alternative scenarios. In the first scenario, we assume that countries will not cooperate, but try to develop their electricity systems on their own. For this case, transmission between countries is not allowed in the optimization. This scenario allows for the quantification of benefits from a cooperation in the region and can thus give arguments for ongoing political discussions about intensive energy cooperation (see e.g. [52–54], among others). The scenario is called "Autonomy" in the following.

The second alternative scenario simulates a breakthrough in the renewable technology that is available decentralized, i.e. photovoltaics and battery technology. Therefore, investment costs for those technologies are decreased according to Table 6. The scenario is called "Tech" in the following.

Effects on Cost-Optimal Mix. In order to see the change in generation mix, we compare the three scenarios for CO_2 levels of 250 g/kWh, 125 g/kWh, and 25 g/kWh (see Fig. 7). We observe that lower costs for PV lead to an increased usage in all scenarios. The electricity generation from PV is at least doubled through the cost reductions. The "autonomy" scenarios lead to less employment of wind and hydro power, which has to be replaced. This reflects the fact that wind and hydro power are easier to integrate if balancing across larger areas is possible. In the scenario of 125 g/kWh, wind can be replaced by gas while still following the emission targets. In the scenario with only 25 g/kWh of CO_2, very large amounts of PV combined with batteries have to be used to replace generation from wind. Fig. 7 shows that large amounts of overproduction will be the consequence of insufficient grid extensions and from prohibiting international electricity exchange.

Effects on costs. In order to evaluate the effects of those scenarios, we analyze the changes in costs of electricity supply. Costs are expressed as the sum of investment and operation costs for generation, transmission, and storage divided by the electricity demand. Fig. 8 shows the evolution of the costs according to scenario and allows us to draw several observations and conclusions:

- Costs increase with lower CO_2 allowances. This increase is moderate until maximal emissions of around 100 g/kWh, but develops dramatically with even stricter emission constraints.

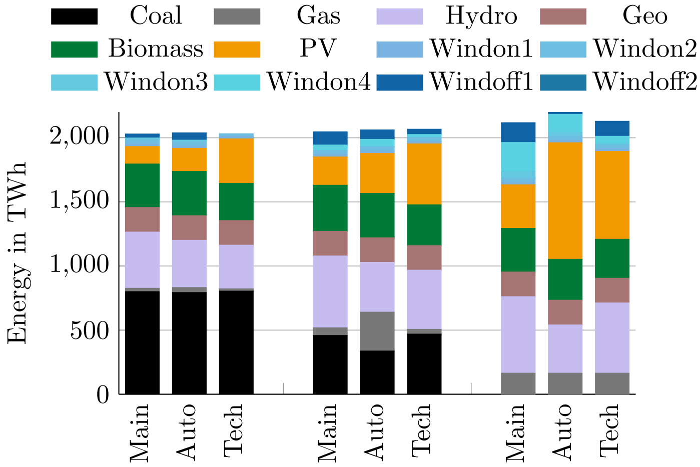

Figure 7: Generation mix in three scenarios with different maximal CO_2 emissions: left 250 g/kWh, middle: 125 g/kWh, right: 25 g/kWh

- Costs are lower in "Tech" scenarios as PV costs are less. Especially when emissions constraints are strict, cheap PV and batteries are helpful.
- Autonomy of countries leads to higher costs. This gap becomes greater with lower emission allowances. At 250 g/kWh the costs are 5% higher and for 25 g/kWh, costs are 40% higher for autonomous countries. These costs can be seen as the benefits for cooperation and already include the expenditures for necessary grid extensions.
- A fully CO_2-free power supply seems not to be feasible without cross-border electricity exchange in the ASEAN region as potentials for renewable generation are too low in some of the countries.

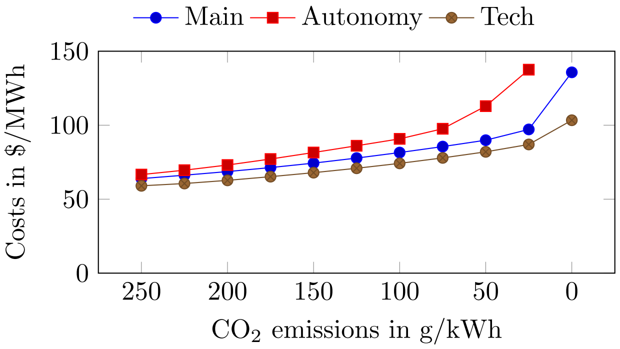

Figure 8: Evolution of costs for electricity supply in the three different scenarios. The zero emission scenario proved to be infeasible for the "Autonomy" case.

The role of battery storage. Another technology question that we want to answer concerns the possible role of battery storage in this future power system. As stated in section 3, we allow the installation of battery storage in the

Table 7: Extension of the most important transmission lines in the main scenario.

Connection	250 g/kWh	125 g/kWh	25 g/kWh
Myanmar West - Myanmar South	4 GW	26 GW	29 GW
Vietnam HoChiMinh - Cambodia	5 GW	11 GW	24 GW
Jakarta - Sumatra South	13 GW	15 GW	22 GW
Myanmar South - Bangkok	1.5 GW	15 GW	20 GW
Sumatra Central - Malaysia	5 GW	6 GW	18 GW
Cambodia - Thailand Central	0.7 GW	6 GW	16 GW
Malaysia - Thailand	2 GW	14 GW	18 GW
Laos - Vietnam Hanoi	0.7 GW	2.5 GW	13 GW

system optimization. Fig. 9 depicts the installed storage capacity for the three scenarios and the variations of allowed CO_2 emissions. In the main scenarios, batteries are only employed at zero CO_2-emission. In the case of lower battery costs, they are already applied at higher emissions allowances and can play a larger role. In the case of “autonomy”, batteries are crucial if emissions should be as low as 50 g/kWh. However, we see that batteries only play an important role in scenarios with very strict emission constraints even if costs are reduced to 250 $/kWh.

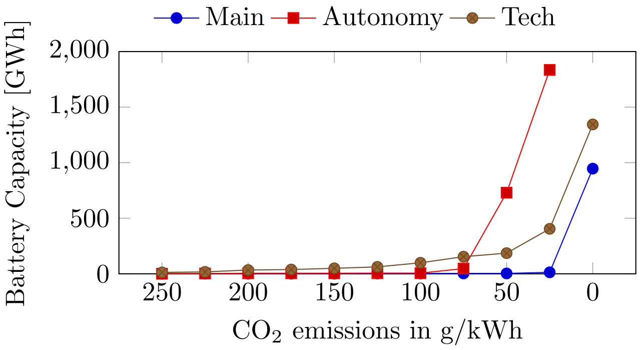

Figure 9: Cost optimal battery capacities for the three different scenarios under varying CO_2 emissions

Effects on Cost-Optimal Grid Extensions. Finally, we analyze the change in cost-optimal grid extensions with the development of cheap decentralized technology in the “Tech” scenario. Therefore, we compare the optimal capacities of the major lines that were identified above (see Table 7) for the main scenario to the capacities of the same lines in the “Tech” scenario. Table 8 shows the optimal capacities in the “Tech” scenario as well as the change against the main scenario. We see that the optimal transmission extension is lowered significantly. Less hydro power is used which leads to a reduction of the transmission from Myanmar to the load centers. Also, fewer wind power plants are installed as PV is the cheapest option now. Therefore, transmission from Vietnam’s shore to Cambodia and the Bangkok area is reduced. All in all, we see that cost reductions of decentralized technology indeed lead to lower transmission capacity. But we also see that transmission capacities remain still high between the subregions and the cooperation between the countries should be strengthened in any case.

6. Conclusion and Policy Recommendations

This article investigates cost-optimal electricity infrastructure extensions for the ASEAN region including generation, transmission, and storage. The results showed that the region will have to explore all different technologies that are available, i.e. wind, solar, geothermal, hydro, and biomass generation, in order to be able to construct a power system with low carbon emissions. Generation from hydro, biomass, and geothermal sources should be prioritized as those are the cheapest options for the region. The lower that emissions are restricted to be, the more additional wind and PV there are that have to be applied. In all scenarios, a mix of all those technologies is the best option; none of them should have a share of more than one third of generation in any scenario. Battery storage is only significantly applied in scenarios with emissions below 100 g/kWh, even if the costs would drop dramatically.

We observe that cooperation between countries becomes important if the region aims to achieve a system with less than 200 g/kWh of CO_2 emissions. The differences of costs, which are the advantages of cooperation, are up to 40% if wind power is employed to a large extent. We were able to identify four major connection lines in the area: a connection from western Myanmar to the center and south of the country and down to the metropolitan area of Bangkok to transport hydro generated electricity; a connection from Cambodia to the Ho-Chi-Minh region in Vietnam for transporting hydro power from Cambodia and wind power from Vietnam; a connection from Sumatra to the Malay Peninsula and Singapore for transporting biomass and geothermal generated electricity; and a connection from Laos to the region of Hanoi to transport hydro electricity. Those four major connection lines were also important in cases with heavily reduced costs of PV and storage. We, therefore, can suggest to elaborate on political and technical issues that enable the construction of these beneficial transmission corridors. It will be crucial to follow cost-optimal pathways when restructuring power systems, as higher costs are a major barrier for large-scale renewable integration. Only by aiming for low-cost systems, it will be possible to maintain the economic growth and prosperity of the region while successfully taking action to slow down climate change.

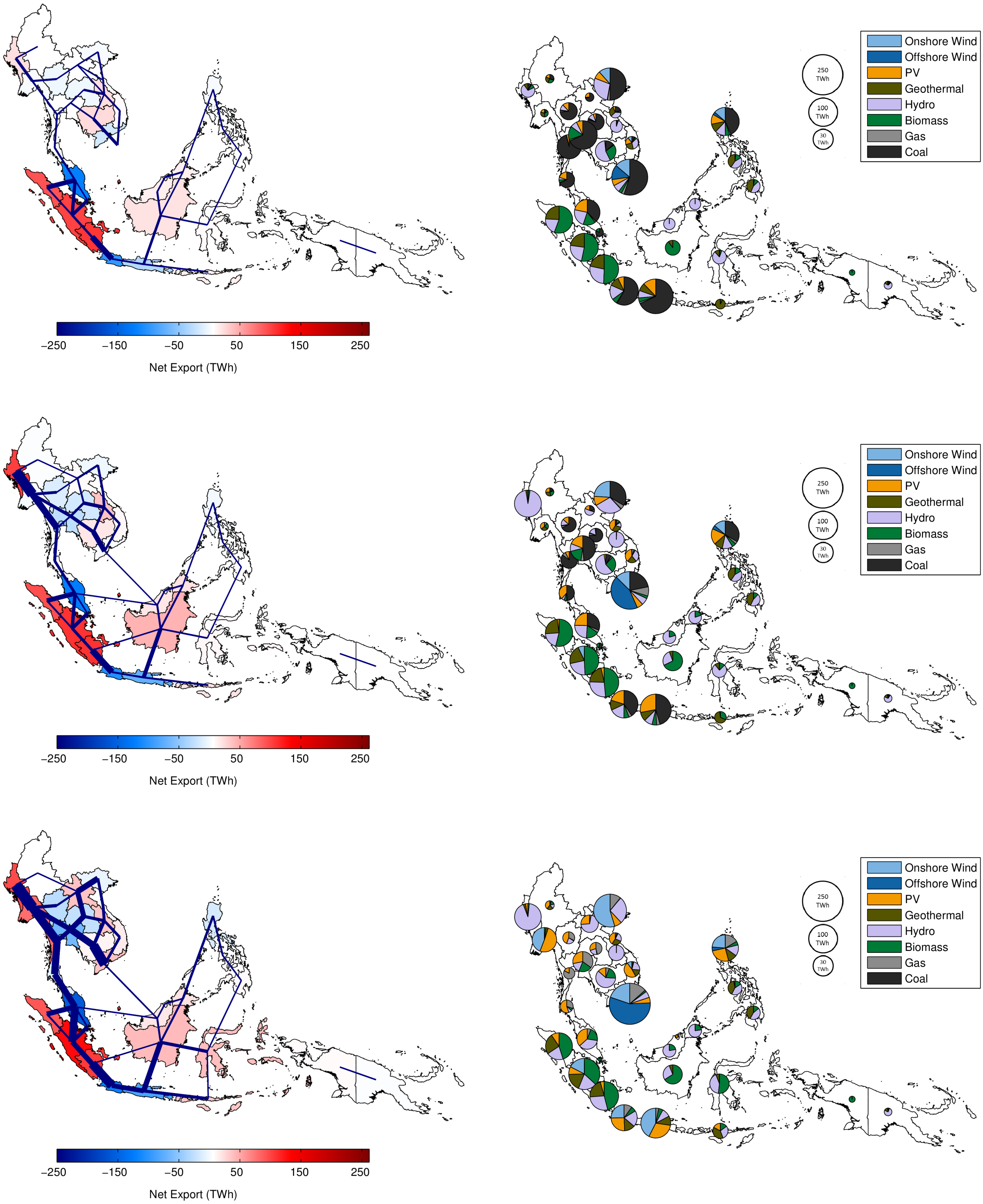

Figure 10: Generation and Transmission in the Base Scenarios with varying CO_2 restrictions. In the upper figure, 250 g/kWh are allowed, in the middle 125 g/kWh and on the bottom only 25 g/kWh are allowed.

Table 8: Extension of the most important transmission lines in the Tech scenario and the percentage of change compared to the main scenario.

Connection	250 g/kWh	125 g/kWh	25 g/kWh
Myanmar West - Myanmar South	0.02 GW (-99.5%)	13 GW (-50%)	24 GW (-17.2%)
Vietnam HoChiMinh - Cambodia	6.8 GW (+36%)	6.7 GW (-39.1%)	15 GW (-37.5%)
Jakarta - Sumatra South	13 GW (-0%)	14 GW (-6.6%)	17 GW (-22.7%)
Myanmar South - Bangkok	0.3 GW (-80%)	13 GW (-13.3%)	17 GW (-15%)
Sumatra Central - Malaysia	5.8 GW (+16%)	7.2 GW (+20%)	11 GW (-38.9%)
Cambodia - Thailand Central	0.7 GW (-0%)	1.7 GW (-71.7%)	8.6 GW (-46.3%)
Malaysia - Thailand	1.6 GW (-20%)	3.1 GW (-77.9%)	8.9 GW (-50.5%)
Laos - Vietnam Hanoi	1.9 GW (+171%)	4.4 GW (+76%)	8.9 GW (-31.5%)

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7. Appendix

7.1. Complete Model Formulation

The model is based on URBS that was originally developed by [55]. Regarding the region analyzed, we call the model URBS-ASEAN. A nomenclature of the model can be found in Table 9. The model is a linear optimization model that minimizes the costs consisting of investment and operating costs of generation, storage, and transmission:

$$\min c = \min(\text{invG} + \text{invS} + \text{invT} + \text{varG}) \tag{10}$$

where each part can be described by the following equations:

$$\text{invG} = \sum_{v,g} p^{\text{cap}}_{v,g} \cdot \text{KI}_g \cdot \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \tag{11}$$

$$\text{invS} = \sum_{v,s} p^{\text{cap}}_{v,s} \cdot \text{KI}_s \cdot \frac{(1+i)^n \cdot i}{(1+i)^n - 1} + \sum_{v,s} r^{\text{cap}}_{v,s} \cdot \text{KIR}_s \cdot \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \tag{12}$$

$$\text{invT} = \sum_{v,n_v} f^{\text{cap}}_{v,n_v} \cdot \text{KI}_{v,n_v} \cdot \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \tag{13}$$

$$\text{varG} = \sum_{v,g,t} p^t_{v,g} \cdot \text{KV}_g. \tag{14}$$

The system operation is limited by supplying the demand

$$\sum_g p^t_{v,g} + \sum_s p^t_{v,s} + \sum_{n_v} f^t_{v,n_v} \geq D_v(t) \qquad \forall t \in \mathcal{T}, v \in \mathcal{V} \tag{15}$$

and the maximal CO_2 emissions allowed in the scenario:

$$\sum_{t,v,g} p^t_{v,g} \text{E}_{v,g} \leq \text{E}^{\max}. \tag{16}$$

All controllable generators have to be operated within their limits:

$$p^t_{v,g} \leq p^{\text{cap}}_{v,g}(t), \qquad \forall t \in \mathcal{T}, v \in \mathcal{V}, g \in \mathcal{G}_{\text{control}} \tag{17}$$

and the renewable generators have to follow a predefined characteristic:

$$p^t_{v,g} = p^{\text{cap}}_{v,g}(t) \cdot \text{CF}_{v,g}(t), \qquad \forall t \in \mathcal{T}, v \in \mathcal{V}, g \in \mathcal{G}_{\text{ren}}. \tag{18}$$

Transmission between regions is limited by the transmission capacity f^{cap}_{v,n_v}:

$$f^t_{v,n_v} \leq f^{\text{cap}}_{v,n_v} \qquad \forall t \in \mathcal{T}, v \in \mathcal{V}. \tag{19}$$

The operation of storage is constraint by the input-output capacity $p^{\text{cap}}_{v,s}(t)$:

$$-p^{\text{cap}}_{v,s} \leq p^t_{v,s} \leq p^{\text{cap}}_{v,s} \qquad \forall t \in \mathcal{T}, v \in \mathcal{V}, s \in \mathcal{S} \tag{20}$$

and by the reservoir level $r_{v,s}$ and respective limit $r^{\text{cap}}_{v,s}$:

$$r^t_{v,s} = r^{t-1}_{v,s} - p^t_{v,s} \qquad \forall t \in [2...T], v \in \mathcal{V}, s \in \mathcal{S} \tag{21}$$

$$0 \leq r^t_{v,s} \leq r^{\text{cap}}_{v,s} \qquad \forall t \in \mathcal{T}, v \in \mathcal{V}, s \in \mathcal{S} \tag{22}$$

$$r^t_{v,s} = 0.5 r^{\text{cap}}_{v,s} \qquad \forall t \in 0; \text{t}_{\text{last}}, v \in \mathcal{V}, s \in \mathcal{S}. \tag{23}$$

The models allows the capacity of generation, storage, and transmission to be extended within the following boundaries:

$$0 \leq p^{\text{cap}}_{v,g} \leq \text{POTp}_{v,g} \qquad \forall v \in \mathcal{V}, g \in \mathcal{G} \tag{24}$$

$$0 \leq p^{\text{cap}}_{v,s} \leq \text{POTp}_{v,s} \qquad \forall v \in \mathcal{V}, s \in \mathcal{S} \tag{25}$$

$$0 \leq r^{\text{cap}}_{v,s} \leq \text{POTr}_{v,s} \qquad \forall v \in \mathcal{V}, s \in \mathcal{S} \tag{26}$$

$$0 \leq f^{\text{cap}}_{v,n_v} \leq \text{POTf}_{v,n_v} \qquad \forall v \in \mathcal{V}, n_v \in \mathcal{N}_v. \tag{27}$$

The extension of infrastructure leads to additional costs depending on the specific investment costs KI as described in equations (11) - (13),

7.2. Overview of the modeled regions

Table 10 provides all modeled regions including the country they are belonging and the annual electricity consumption. Table 11 gives an overview of renewable potentials as estimated by current literature. Finally, Table 12 provides information of the reneable potentials that were used as model input.

Table 9: Nomenclature of model description

Symbols	Explanation
Sets	
$t \in \mathcal{T}$	Timesteps
$v \in \mathcal{V}$	Regions
$n_v \in \mathcal{N}_v$	Neighboring regions of region v
$g \in \mathcal{G}$	Generator types
$\mathcal{G}_{ren} \subseteq \mathcal{G}$	Renewable generators
$\mathcal{G}_{control} \subseteq \mathcal{G}$	Controllable generators
$s \in \mathcal{S}$	Storage pumps and turbines
Variables	
invG	Investment costs of generators g
invS	Investment costs of storage s (power and reservoir capacity)
invT	Investment costs of transmission lines from n to n_v
varG	Variable costs of generators g
c	Overall System Costs
$p_{g,v}^{\text{cap}}$	Maximal output of generator g in region v
$p_{s,v}^{\text{cap}}$	Maximal power output of storage s in region v
$r_{s,v}^{\text{cap}}$	Storage reservoir capacity of storage s in region v
f_{v,n_v}^{cap}	Maximal flow over transmission line from region v to n_v
$p_{g,v}^t$	Power output of generator g in region v at timestep t
$p_{s,v}^t$	Power output of storage s in region v at timestep t
f_{n,n_v}^t	Power flow from n to n_v at timestep t
$r_{s,v}^t$	State of charge of storage s in region v at timestep t
Parameters	
$\text{D}_v(t)$	Demand in each region v and timestep t
KI_g	Specific investment costs of generators
KI_s	Specific investment costs of storage power
KIR_s	Specific investment costs of storage reservoir capacity
KI_{n,n_v}	Specific investment costs of transmission
KV_g	Specific variable costs of generators
$\text{CF}_{v,g}^t$	Capacity factor for renewable generation
$\text{POTp}_{v,g}$	Potential of generation capacity in region v
$\text{POTp}_{v,s}$	Potential of storage power capacity in region v
$\text{POTr}_{v,s}$	Potential of storage reservoir capacity in region v
POTf_{v,n_v}	Potential of transmission capacitiy between region v and n_v
$\text{E}_{v,g}$	Specific emissions of generator g in region v.
E^{max}	Maximal CO_2 emissions in scenario

Table 10: Overview of modeled regions and their projected demand in TWh

n°	Acronym	Region	Country	Load/Hydro location	Demand [TWh]
1	Brunei	Brunei	Brunei	Brunei	3.26
2	Camb	Cambodia	Cambodia	Cambodia	2.01
3	ISumN	North Sumatra	Indonesia	Medan	7.00
4	ISumC	Central Sumatra	Indonesia	Padang	7.00
5	ISumS	South Sumatra	Indonesia	Palembang	7.00
6	IKal	Kalimantan	Indonesia	Palangka Raya	4.90
7	ISulM	Sulawesi and Malaka	Indonesia	Palopo	6.32
8	IJaka	Jakarta	Indonesia	Jakarta	55.35
9	IBali	Bali	Indonesia	Bali	55.35
10	INusa	Nusa Tenggara	Indonesia	Kupang	1.34
11	IPapua	West Papua	Indonesia	Nabire	0.83
12	LaosN	North Laos	Lao PDR	Xiangkhoang	1.56
13	LaosS	South Laos	Lao PDR	Salavan	0.80
14	MalP	Peninsular Malaysia	Malaysia	Kuala Lumpur	100.27
15	MalSara	Sarawak	Malaysia	Kuching	5.27
16	MalSab	Sabah	Malaysia	Kota Kinabalu	4.39
17	MyaNE	North East Myanmar	Myanmar	Myitkyina	2.01
18	MyaC	Central Myanmar	Myanmar	Naypyidaw	2.01
19	MyaS	South Myanmar	Myanmar	Mawlamyaing	2.01
20	PNG	PNG	PNG	PNG	3.12
21	PhilLuz	Luzon	Philippines	Luzon	40.13
22	PhilVis	Visaya	Philippines	Cebu	8.55
23	PhilMin	Mindanao	Philippines	Davao	8.16
24	Sing	Singapore	Singapore	Singapore	40.62
25	ThaiNW	North West Thailand	Thailand	Lampang	20.63
26	ThaiNE	North East Thailand	Thailand	Khon Kaen	19.81
27	ThaiC	Central Thailand	Thailand	Nakhon Ratchasima	49.63
28	ThaiBang	Bangkok	Thailand	Bangkok	36.33
29	ThaiP	Peninsular Thailand	Thailand	Surat Thani	14.45
30	VHanoi	Hanoi	Vietnam	Hanoi	33.16
31	VNCoast	North Coast	Vietnam	Dong Ha	4.18
32	VSCoast	South Coast	Vietnam	Nha Trang	4.18
33	VHoChi	Ho Chi Minh City	Vietnam	Ho Chi Minh City	44.13

Table 11: Overview of estimated potentials in GW for renewable technology in ASEAN according to current literature

Region	Geoth.	Hydro	Biomass
Brunei	0.00	0.07 [56]	0.00 [57]
Cambodia	0.00	9.00 [58]	2.15 [58]
Indonesia	15.20 [59]	35.01 [60] [3]	55.00 [39]
Laos	0.00	26.00 [61]	0.06
Malaysia	0.00	35.01 [60] [3]	3.67 [3]
Myanmar	0.99 [62]	100 [62]	0.99 [62]
PNG	0.17	1.00 [63]	0.06
Philippines	4.14 [3]	6.99 [3]	2.16 [3]
Singapore	0.00 [3]	0.00 [3]	0.20 [3]
Thailand	0.00 [3]	6.42 [60] [3]	2.62 [60] [3] [64]
Vietnam	1.40 [49] [65]	22.00 [60] [3]	1.00 [60] [49]
assumed FLH	7000	4000	7000

Table 12: Potentials in GW as calculated by our approach desribed in Section 4.1.1

Region	Hydro	Geo	Bio	Wind On-1	Wind On-2	Wind On-3	Wind On-4	Wind Off-1	Wind Off-2	PV Open	PV Roof
Brunei	0.07	0.00	0.00	0.00	0.00	0.00	3.20	0.00	0.00	0.92	1.60
Camb	9.00	0.00	2.15	0.00	0.00	2.06	96.90	0.00	0.00	28.60	47.70
ISumN	5.00	3.20	7.50	0.00	0.00	0.00	72.60	0.00	0.00	21.00	56.80
ISumC	5.00	3.20	7.50	0.00	0.00	1.52	102.00	0.00	0.00	30.00	63.80
ISumS	5.00	3.20	7.50	0.00	0.00	3.04	87.10	0.00	0.00	26.00	76.20
IKal	4.50	0.40	5.00	0.00	0.00	0.00	341.00	0.00	4.69	98.50	79.80
ISulM	4.50	0.40	5.00	0.00	8.67	2.56	137.00	0.00	0.00	42.80	78.70
IJaka	3.67	1.60	0.83	0.00	0.00	8.32	17.00	0.00	0.00	7.30	105.00
IBali	3.67	1.60	0.83	0.00	0.00	16.40	37.70	0.00	0.00	15.60	128.00
INusa	3.67	1.60	0.83	0.00	0.00	12.40	24.90	0.00	0.00	10.80	37.00
IPapua	0.00	0.00	20.0	0.00	0.00	0.00	231.00	1269	684.00	66.60	19.90
LaosN	13.00	0.00	0.03	0.00	0.00	0.00	179.00	0.00	0.00	51.60	25.70
LaosS	13.00	0.00	0.03	0.00	0.00	0.00	45.70	0.00	0.00	13.20	12.30
MalP	4.00	0.00	1.85	0.00	0.00	0.00	73.50	0.00	0.00	21.20	59.10
MalSara	4.50	0.00	0.91	0.00	0.00	0.00	69.00	0.00	0.00	19.90	13.40
MalSab	4.50	0.00	0.91	0.00	0.00	0.00	40.80	0.00	0.00	11.80	17.30
MyaNE	33.30	0.33	0.33	0.00	0.00	0.00	165.00	0.00	0.00	47.70	72.60
MyaC	33.30	0.33	0.33	0.00	0.00	0.00	65.20	0.00	0.00	18.80	42.60
MyaS	33.30	0.33	0.33	0.00	0.00	6.49	137.00	0.00	0.00	41.50	67.10
PNG	1.00	0.17	0.06	2.59	20.90	12.90	220.00	489.00	255.00	74.00	27.20
PhilLuz	2.33	1.38	0.72	1.99	6.39	23.00	50.50	1.78	55.70	23.60	112.20
PhilVis	2.33	1.38	0.72	0.00	1.05	11.60	21.20	0.00	0.00	9.75	42.60
PhilMin	2.33	1.38	0.72	0.00	0.00	1.28	62.90	0.00	0.00	18.50	57.60
Sing	0.00	0.00	0.20	0.00	0.00	0.00	0.39	0.00	0.00	0.11	8.80
ThaiNW	1.50	0.00	0.05	0.00	0.00	0.00	78.00	0.00	0.00	22.50	46.60
ThaiNE	1.50	0.00	0.05	0.00	0.00	0.00	81.10	0.00	0.00	23.40	54.80
ThaiC	3.00	0.00	2.26	0.00	0.00	0.00	69.30	0.00	0.00	20.00	45.10
ThaiBang	0.00	0.00	0.00	0.00	0.00	0.00	11.00	0.00	0.00	3.14	23.00
ThaiP	0.47	0.00	0.26	0.00	0.00	2.10	40.60	0.00	0.00	12.30	31.70
VHanoi	12.0	0.00	0.08	0.00	2.73	12.0	48.80	0.00	258.00	18.35	62.80
VNCoast	3.00	0.70	0.13	0.00	0.00	9.50	19.00	0.00	379.00	8.23	25.10
VSCoast	3.00	0.70	0.13	0.00	0.00	8.19	46.60	282.00	0.00	15.80	45.10
VHoChi	4.00	0.00	0.67	4.35	7.34	7.34	16.00	756.00	409.50	10.10	67.20