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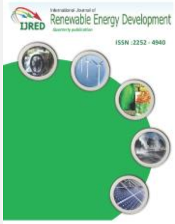

A 100% Renewable Electricity Scenario for the Java-Bali Grid

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ABSTRACT. Currently, many countries try to satisfy their energy needs with an increasing usage of renewable resources. The general motivations, with varying weighting in the different countries, are ecological reasons, concerns about energy security, and economical considerations. A question that is for now rather theoretical, although interesting for opening a long-term perspective, is how an energy supply from exclusively renewable energy resources could look like. This question has to be answered individually for any specific energy supply system. The present paper has the objective to present and evaluate a scenario for an electricity supply only from renewable energy resources for the Java-Bali grid. After designing a load time series for the year 2050 for the Java-Bali grid, a scenario is developed how to cover the load with electricity from renewable energy resources alone. Assumptions about the usable energy sources are made as well as assumptions about the available power plant capacity or energy potential. A specific challenge is the fact that solar energy must be the main source in such a renewable-energy based system, which comes with the need for a large storage capacity to match the power supply at any time with the load. Several possibilities are presented how to bring down the storage capacity: the increment of the installed PV capacity, the usage of bioenergy for seasonal balancing, and the complementation of the proposed short-term storage with an additional long-term storage. The study shows some of the specific challenges that a gradual transformation of the current electricity supply system on Java and Bali into a renewable-energy-based one would face and gives some hints about how to cope with these challenges. Scenarios like the one designed in this study are an important tool for decision-makers who face the task to scrutinize the consequences of choosing between different development paths.

Keywords: energy modeling, energy resources, storage, long-term storage, time series analysis

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1. Introduction

The integration of electricity from renewable energy sources into the electrical grids in Indonesia is economically and ecologically reasonable. A growing share of the needed power can and should be harvested from solar radiation, river runoff, from geothermal sources, and from different types of waste. Indonesia has set the targets of delivering 23% of the needed end energy (over all sectors) and 25% of the electric energy from renewable sources by the year 2025 and 31% of the needed end energy by the year 2030 (Irena, 2017; Ministry of Mineral Resources Indonesia, 2015). An interesting, although still rather academic question is whether it is possible to generate all the needed electricity (or needed energy in general) from renewable resources, and how this could be achieved. This article has the aim to tackle this question for the power grid on Java and Bali (JB grid). A scenario shall be presented and discussed according to which the needed electric energy is generated only from renewable energy sources (100% RE scenario).

Such a scenario is highly counterfactual considering that currently less than 10% of the electricity in Indonesia (and also in the JB grid) is generated from renewable resources (Asean Center for Renewable Energy, 2017). In 2014, 6.4% of the electricity came from hydropower plants, 2.4% from geothermal power plants, and very small shares from other renewable resources (Asian Development Bank, 2014). However, a scenario does not have the objective to depict the current state of affairs. Moreover, it is not even a prediction. The scenario described in this article is not intended to represent the reality in some decades. It is neither a development plan. The objective of the scenario is rather to examine the implications if electricity were to be generated exclusively from renewable energy resources that are

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harvested from the grid area itself. It is intended to give information about how such an electricity supply system would look like. Scenario designs in this sense are an important instrument for decision makers who have the task to scrutinize the consequences of their decisions (Heinecke, 2012). Scenario designs are the scientific brothers of the artistic genres of fantasy and science fiction, with the difference that they are bound to strict consistency requirements and that the realization of the imagined states of affairs, in a defined timeframe, should be at least conceivable.

The JB grid represents a particularly challenging case for a 100% RE scenario. It is not only by far the largest grid in Indonesia, covering 76% of the national electricity consumption, but it also covers a very densely populated area with nearly 1000 people per square kilometer. The latter is a special challenge for a renewable-resource based system given that the usage of some of these resources requires the occupancy of more or less large areas.

The scenario will define the electricity supply shares delivered by the different energy sources. It will present three different electricity supply system logics reducing gradually the need for storage capacities. The large needed storage capacity is the main challenge in the transformation of the electricity supply system into a renewable-energy based one and requires careful consideration.

2. Method

The study is based on time series modeling. Time series are generated for one year for the load and for the electricity generation in the JB grid. The time series have an hourly resolution.

The model refers to the year 2050. Even if a scenario is neither a prediction nor a development plan, a time reference is needed. The reference to the future is necessary because the electricity consumption in the JB grid is still growing, and the scenario should be done for the consumption that can reasonably be assumed for some defined year in the future. The future consumption is derived from assumptions about the demographic and economic development. The load curve itself is designed as a scale-up of the current load curve in the JB grid.

The electricity generation time series is designed such that it matches the load at any hour. Four renewable energy sources are considered: solar radiation, geothermal energy, biomass, and river runoff. Installed power plant capacities are assumed for geothermal power and hydropower. For bioenergy an annual energy potential is assumed. Installed PV and storage capacities are open parameters. Solar energy covers the demand that is not covered by the other energy sources. The PV power generation is modeled according to meteorological data (radiation and temperature) acquired from a commercial weather database that covers the JB grid area (Meteonorm, www.meteonorm.com). PV power plants are distributed over 17 locations all over the grid area. The calculation is done with horizontally oriented panels without shading losses. Storages are used to shift a part of the harvested solar energy from hours with excess power to hours with power deficit.

The modeling renders the needed PV and storage capacities. Different system logics and configurations, which are explained below, come along with different PV and storage capacities. Sets of PV and storage capacities that deliver the energy that is not delivered by the other sources are the primary outcome of the calculations.

3. Results

3.1. Consumption scenario

The electricity consumption scenario for 2050 is derived from assumptions about the population development, the per-capita productivity development, and the electricity consumption elasticity with respect to economic growth in Indonesia and in the JB grid area in particular.

Concerning the population development, decreasing birth rates are assumed (from currently 2.35 children per woman (World Bank, 2015; Index Mundi, 2016) to 1.9 in 2050) and decreasing age-specific mortalities for all age groups. All these and some more assumptions are made with reference to more advanced countries that are taken as models Indonesia would come closer to in the next decades. The population model renders 325 million people in Indonesia in the year 2050. 170 to 180 million people are assumed to live in the JB grid area, which corresponds to a population density of more than 1,200 inhabitants per km^2.

A steady positive development of the productivity per capita is assumed, although with decreasing growth rates. Combining this assumption with the fact of the still growing population, a steady positive, although decreasing economic growth is assumed.

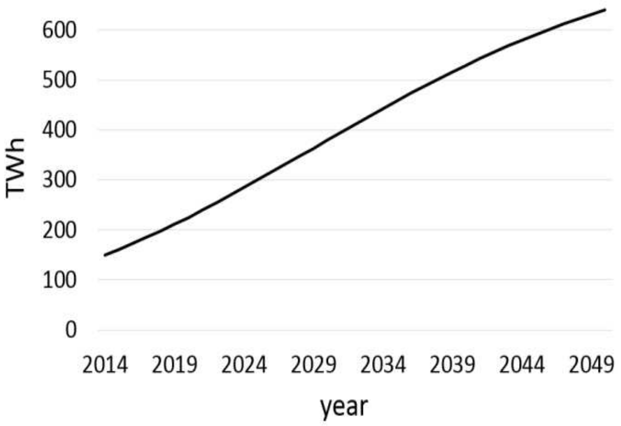

Fig. 1 Electricity consumption in the JB grid from 2014 to 2050 according to the modeling

Currently, the electricity elasticity with respect to economic growth is still larger than 1, which means that the electricity consumption in Indonesia grows faster than the economy (in terms of GDP) (Aviliani, 2014). Increasing energy efficiency measures are assumed so that the electricity elasticity decreases in the future. Without going further into the quantification details of the different modeling steps, the resulting electricity consumption development in the JB grid in the considered time span from 2014 to 2050 is shown in Fig. 1

The model renders an annual consumption of 640 TWh in the JB grid for the year 2050 (compared to 149 TWh in 2014 (International Energy Agency, 2014; PLN, 2017)). This is equivalent to about 3,800 kWh per capita, while it amounted to about 1,000 kWh per capita in 2014. The resulting per-capita consumption for 2050 corresponds to the current one in Malaysia and is considerably lower than, for example, the current consumptions in Germany (6,700 kWh/cap) or South Korea (9,300 kWh/cap) (Index Mundi, 2017).

The projected consumption we assume is considerably lower than the one that is accepted as the National Energy Policy target for 2050. The latter is located at 7000 kWh per capita per year (Anindhita et al. 2015).

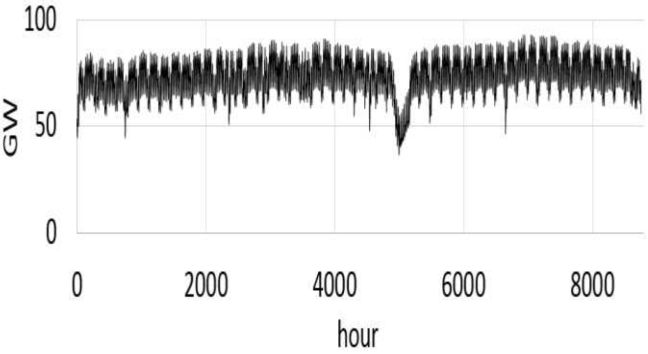

Fig. 2 Assumed load curve for 2050

The load curve for 2050 is designed as a scale-up of the load curve of 2014 (data courtesy of PT PLN) such that the annual demand reaches the modeled amount of 640 TWh. It is represented in Fig. 2. (The pronounced consumption decrease between the hours 4,950 and 5,150 is caused by the holidays at the end of Ramadan, which was at the end of July in that year).

3.2 Energy sources

The following renewable energy resources are taken into account:

- solar radiation
- geothermal energy
- hydropower
- biomass.

Wind energy is not taken into consideration because the average wind speeds in the JB grid are generally low (Technical University of Denmark, 2017), and everywhere well below the average speeds that are generally considered to be necessary for commercial wind energy conversion. Ocean energy is not considered either. There are remarkable resources in Indonesia especially concerning tidal currents and ocean thermal energy (Ernst & Young et Associés, 2016), but the costs are still high, and there is no evidence that they will come down during the next decades. Even if there are considerable cost reduction potentials (Magagna et al., 2015), these cost reductions can be only realized if the markets are developed. We do not want to exclude that ocean energy may play an important role in the future in Indonesia, but we do not want to count on it in our scenario design given its unclear economic perspective in the timeframe we consider.

3.3 Power mix

The installed capacities and/or annual electricity supply contributions of the different power sources are determined as follows:

- For *hydropower* and *geothermal power* the existing and planned power plants, according to the Electricity Supply Business Plans of PLN until 2025 (PLN, 2017), are taken as reference. As the scenario refers to the year 2050 (and not to 2025 as the Business Plans do) some further capacities beyond the installed and planned capacities are added. For geothermal power plants 30% of the combined existing and planned capacity are added so that an installed capacity of about 5,500 MW is reached. For hydropower plants 20% of the combined existing and planned capacity are added so that an installed capacity of about 5,800 MW is reached (we consider that the remaining untapped hydropower potential is smaller than the remaining untapped geothermal potential). For geothermal power plants, an availability of 85% is assumed (Mines et al., 2015). This renders an annual electricity generation of 41 TWh. For hydropower, a capacity factor of 0.35 is assumed, which is that low because of the seasonal fluctuations in the river runoff. The annual hydropower generation is 18 TWh.
- For *bioenergy*, assumptions about the annual energy potential, but not about the installed power plant capacity are made. The assumptions are based on a study made by GIZ that quantifies the electricity that could be generated on a national scale from agricultural waste, in particular from waste from palm oil production, rice cultivation, and sugar cane growing (GIZ, 2014). Applying the calculation to the JB grid area (according to the existing agricultural activities in that area (Badan Pusat Statistik, 2014)) and reducing the result slightly due to the assumption that not all the agricultural waste will be used, the resulting annual potential is about 7 TWh. We consider that waste is the only reasonable biomass source in the considered grid area, given that special

bioenergy plantations are no option on the densely populated islands (Popp, 2014).

- The supplied electricity from PV is the difference of the annual electricity demand of 640 TWh and the electricity supplied from geothermal power plants, hydropower plants and bioenergy plants, i.e. about 574 TWh. The PV power plant capacity is an open parameter and depends on the system design, in particular on the capacity of the applied storage systems. The PV capacity is distributed over 17 locations all over the grid area, which helps to take advantage of balancing effects due to possibly different weather conditions at the different locations.

Table 1
Power plant mix and annual energy supply

	Installed capacity (MW)	Annual energy supply (TWh)	
Geothermal power	5,500	41	(6%)
Hydropower	5,800	18	(3%)
Bioenergy	not determined	7	(1%)
PV	open parameter	574	(90%)

3.4. Temporal generation patterns, storage

Some of the considered energy sources are available as permanent power flows (geothermal energy), others as more or less regularly fluctuating power flows (solar radiation, river runoff), others rather as stored energy (bioenergy). These differences come along with different temporal generation patterns and different possible systemic roles of the different generation technologies:

- Geothermal energy is based on the permanent heat flow from the hot interior of the Earth to the surface. Geothermal power plants are preferably operated as permanently running baseload power plants.
- Hydropower is subject to seasonal fluctuations. As an indicator of the fluctuations we take the annual runoff curve of the Citarum river in West Java (data courtesy of PT. PLN). The curve has an approximately sinusoidal shape with the maximum in March and the minimum in September. How strictly the hydropower generation is related to the river runoff depends on the capacity of the water reservoirs. We take their capacity to be sufficient to allow power generation shifts on a daily and monthly time scale, but not sufficient to allow seasonal shifts. The seasonal fluctuations in the river runoff are reflected, hence, in seasonal fluctuations in the monthly electricity generation. In the modeling, specific energy amounts are assigned to the different months in accordance with the climatic conditions, and respecting the annual capacity factor of 0.35.
- Bioenergy is based on chemically stored energy, which makes its usage highly flexible. The biomass itself can be stored with limited energy loss for a certain time. Additionally, the secondary bioenergy carrier, like biogas, can also be stored for long periods. In the timeframe of one year we consider therefore an unlimited flexibility of the bioenergy supply.
- Solar energy is given as an energy flow that fluctuates in different time horizons: There is a strong regular daily variance, a certain seasonal variance, and a rather random variance according to changing weather conditions. Using PV, solar power generation is fluctuating in strict dependence on the given solar radiation.

As nearly 90% of the supplied electricity is based on solar energy the generation profile of which depends on the fluctuating radiation conditions, large storage capacities are required that allow matching the power supply with the given load curve. The capacity of the other power plant types, which can deliver power on demand, is much too low to balance the fluctuating solar energy generation.

Currently a pumped storage plant is under construction in West Java (Upper Cisokan, storage capacity about 5.2 GWh, charging and discharging power capacity about 1 GW) (World Bank, 2017). Three further pumped storage plants are included in the PLN business plans (PLN, 2017). Altogether these pumped storage plants have a storage capacity of about 20 GWh and a charging and discharging power capacity of about 4 GW. At an average daily electricity consumption of 1,753 GWh (for the assumed annual consumption of 640 TWh), only 180 GWh of which – on average – are covered by non-solar sources (see Table 1), these planned storages are far from being sufficient to cover the load that is not covered by the non-solar sources when no sufficient solar radiation is available, for instance during the night hours. Therefore the second important open parameter, besides the installed PV capacity, is the additionally necessary storage capacity. In the following we will use the expression “pumped storage” if referring to the 20 GWh pumped storages that are built or planned by PLN, and we will use the expression “storage” if referring to the additional storage capacity.

Subsequently, the needed installed PV and storage capacities will be calculated. The capacities depend on the system logic, i.e. how the different system components, the different generation and storage systems are applied, and on the used storage type. We distinguish between the following three systems:

- System I: Hydropower, pumped storages, and bioenergy are applied such that the remaining maximum load, which has to be covered by the storage if the PV power is not sufficient, is minimized. That means, these system components are used for load peak shaving (on a daily time scale for pumped storages, on a monthly time scale for hydropower, and on an annual time scale for bioenergy). The storage is conceived of as a combination of additional pumped storages and electrochemical storages (batteries).

- System II: The difference of system II from system I is that bioenergy is used, in system II, for seasonal balancing.
- System III: The system components are applied as in system II. Additionally, to the mentioned storage system, consisting of pumped storages and batteries, a second storage system based on synthetic methane is used.

3.5. System I: reduction of storage discharging power

System I follows the logic of reducing as much as possible the maximum load that has to be covered by the storage. That means, all generators the operation of which is limited by the respective energy source and that can deliver power on demand (all besides geothermal and PV power plants) are used for load peak shaving. The reasoning behind this approach is that the maximum power covered by the storage should be kept as small as possible because higher discharging powers come along with higher costs for the storage system.

3.6. Operational logic

The operational logic of system I is as follows:

- The geothermal power plants run permanently at a constant power of 0.85 times the installed capacity.
- PV covers the remaining load, i.e. the load minus the supplied geothermal power, whenever PV power is available. Excess PV electricity is stored (first in the pumped storage and then, if the pumped storage is full or if the excess power is higher than the available pump power, in the additional storage).
- The monthly allocated amounts of hydropower are used to cover the peaks of the remaining load (after supplying geothermal and PV electricity) within the respective months.
- The pumped storage plants are operated on a daily basis using the daily stored energy to cover the peaks of the remaining load (after supplying geothermal power, PV power and hydropower) in the evening and night hours of the respective day.
- Bioenergy is used for further load peak shaving on an annual time scale.
- The storage is used to store excess PV energy and to cover the remaining load after supplying power from all the mentioned sources. The storage system, a combination of additional pumped storages and batteries, causes losses of 10% at charging and further 10% at discharging. Self-discharge is considered to be 0.0042% per hour (3% per month). The maximum charging power is taken to be 0.25 kW per kWh storage capacity, and the maximum discharging power is taken to be 0.2 kW per kWh storage capacity. These are reasonable limits for both pumped storages and electrochemical storages (Luo, 2014).

The operational logic is represented in Fig. 3 for a one-week period.

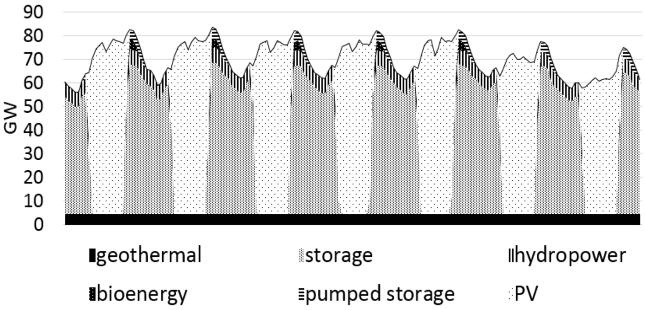

Fig. 3 Energy supply during a one-week period according to system logic I

3.7. System configuration with minimum PV capacity

The two open parameters, i.e. installed PV capacity and needed storage capacity, are complementary: The larger the PV capacity is, the smaller the storage can be, and vice versa. If the PV capacity is large, more electricity is generated on days with lower radiation so that less energy has to be supplied by the storages on those days. The fact that installed PV capacity and needed storage capacity are complementary means that there is a system configuration with minimum PV capacity at the expense of a high storage capacity, and a configuration with minimum storage capacity at the expense of a high PV capacity. We consider first the configuration with minimum PV capacity.

The simulation renders a minimum installed PV capacity of 410 GW that is necessary to cover the demand. This capacity equals a total PV area of about 2,200 km2, which is about 1.6% of the land area covered by the JB grid. It corresponds to an installed capacity of 2.4 kW per inhabitant, or a PV area of 13 m2 per inhabitant.

The storage level run over one year for this configuration is shown in Fig. 4. It is dominated by fluctuations in two time scales: the day/night rhythm and the annual rhythm of rainy and dry season.

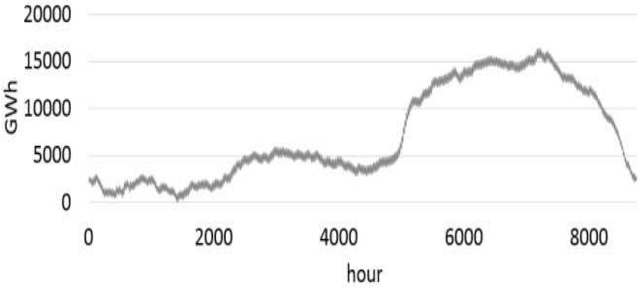

Fig. 4 Storage level over a one-year period for system I for minimum PV capacity (quantified in terms of potential energy stored in the pumped storage or electrochemical energy stored in the charged batteries)

The storage capacity is determined basically by the seasonal fluctuations of the solar radiation, which is more abundant in the dry season and less abundant in the rainy season. The storage gets big because it has the task of shifting solar energy from the dry (and sunnier) season to the rainy (and less sunny) season. The maximum storage level is reached at the end of the dry season at the end of October, and the minimum storage level is reached at the end of the rainy season in March.

Hydropower has an anticyclical behavior and hence the potential to balance the seasonal variation of the solar energy yield. However, the installed hydropower capacity is not sufficient to achieve a complete balancing.

The storage capacity for the configuration with minimum PV capacity is 16,000 GWh (compare this number to the 20 GWh pumped storage capacity contained in the PLN business plans). This is equivalent to an installed capacity of 91 kWh per inhabitant. It is difficult to imagine that such an enormous storage capacity could be installed.

Additionally, for these and all the other calculated capacities it has to be taken into account that they are only lower-limit estimations: no capacity safety margins are taken into account; a meteorological model year is considered that does not necessarily correspond to a real year; generator availability limits are not taken into account (with the exception of geothermal power plants); the modelled year is analysed from a bird's eye view allowing the ideal allocation of the different energy resources, which is not possible in real grid operation; transmission and distribution losses are not considered. Due to these reasons the installed capacities should be larger in reality than the capacities calculated in our scenario.

It becomes clear that the biggest challenge of the considered configuration is not the large PV capacity, but the large storage capacity of 16,000 GWh. The storage capacity must be brought down. The way to achieve this is the reduction of the seasonal balancing function of the storage because it is the fulfilment of this function that requires large storage capacities. One possibility to reduce the seasonal balancing through the storage is the increase of the PV capacity. As mentioned before, PV capacity and storage capacity are complementary, which means that a larger PV capacity allows the reduction of the installed storage capacity.

3.8. Increased PV capacity

A larger PV capacity increases the electricity generation in the rainy season. This allows the reduction of the needed storage capacity because less energy has to be shifted from the dry season to the rainy season. Fig. 5 shows the PV capacity that is necessary to generate the needed power in dependence on the storage size. The right end of the curve represents the configuration discussed in Section 3.7 with a PV capacity of 410 GW and a storage capacity of about 16,000 GWh. The left end of the curve indicates the minimum storage capacity that can be reached by increasing the PV capacity, which is about 960 GWh. This capacity is basically determined by the share of the energy demand during the nights that has to be covered by the storage.

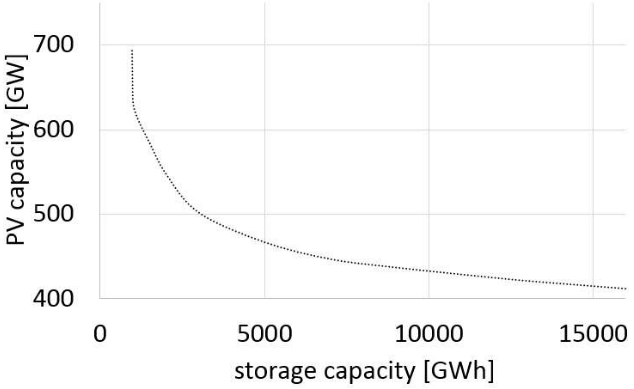

Fig. 5 PV capacity as a function of storage capacity in system I

The curve shows that, under reasonable economic assumptions, the optimum storage size for system I is very far away from the 16,000 GWh belonging to the configuration presented in section 3.7. Where exactly the optimum is located depends on the exact economic parameters, in particular on storage capacity costs and PV capacity costs. However, the problem of economic optimization shall not be tackled here. It deserves an own article based on the scenario developed in the present article.

3.9. System II: bioenergy for seasonal balancing

It would be desirable to shift down the curve in Fig. 5. Shifting downwards the curve means that less storage capacity is needed at any given PV capacity, and less PV capacity is needed at any given storage capacity. Such a shift of the curve can be reached if the system logic is modified in an appropriate way. One possibility is to use bioenergy for seasonal balancing instead of using it for load peak shaving. This is implemented in system II.

The modified application of bioenergy releases the storage system partially from its task of balancing the seasonal solar energy yield fluctuations. So less storage capacity is needed.

As bioenergy is based on chemical energy carriers, it is generally appropriate for long-term balancing. The biomaterial itself may have a limited stability, but the secondary bioenergy carriers, like biogas or liquid biofuels, can be, in principle, stored for a long time and used for long-term balancing (Arasto et al., 2017).

The different utilization of the available bioenergy is implemented in the model in the following way: In system I bioenergy is used for those of the 8760 hours of the year in which the remaining load (load minus power supplied from all generators besides bioenergy plants and storage) is large. This does neither directly nor indirectly imply any major seasonal balancing. In system II bioenergy is allocated to days in which the difference between energy demand and energy supply from all generators besides bioenergy plants and storage is large. Normally these are workdays (which have a higher consumption) with low solar radiation. Days with low solar radiation occur mostly during the rainy season. That means that bioenergy is allocated mostly to days in the rainy season, i.e. it is used basically for seasonal balancing. On the respective days the allocated bioenergy is then used again for intraday load peak shaving.

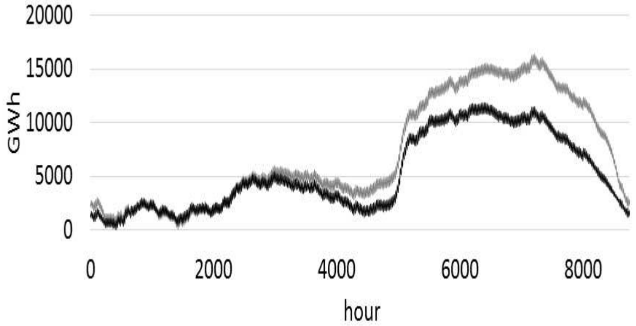

Fig. 6 Storage level over a one-year period for system I (grey) and II (black) for minimum PV capacity

Although the available amount of bioenergy is by far not sufficient to balance completely the seasonal PV fluctuations, Fig 6 shows that there *is* a considerable balancing effect that is reflected in a more equilibrate run of the storage level. The figure represents the configuration with minimum PV capacity (410 GW), and hence with the largest respective needed storage capacity.

The desired effect of the application of bioenergy for seasonal balancing is to be seen in the fact that the needed storage capacity is reduced from 16,000 GWh in system I to 12,000 GWh in system II.

Analogue to system I, the storage capacity in system II can be further reduced by increasing the PV capacity. Fig 7 shows that the application of bioenergy for seasonal balancing reduces the needed storage capacity for any given PV capacity. For instance, at an installed PV capacity of 470 GW the storage capacity drops from 5,000 GWh for system I to just 1,000 GWh for system II. This shows the considerable effect of using the available bioenergy for seasonal balancing.

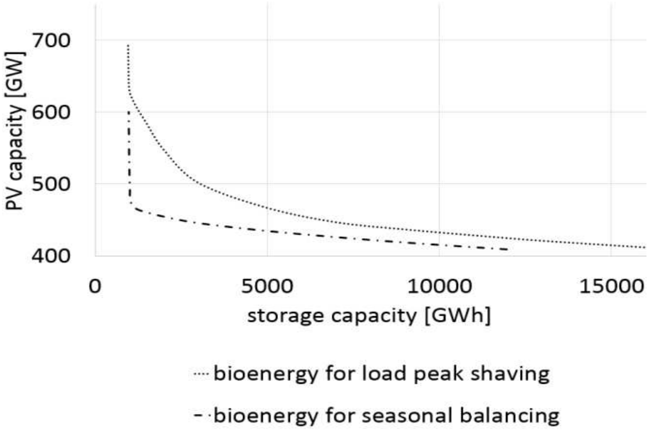

Fig. 7 PV capacity as a function of storage capacity in systems I and II

3.10. System III: Combination of short-term and long-term storage

A possibility to reduce further the needed pumped storage and battery capacity is the combination of these storages with a second, technically different, storage system. According to the different characteristics of different technical storage solutions some of these are more appropriate for specific requirements than others. For instance, some storage types are more appropriate for short-term storing, while others are more appropriate for long-term storing (Kemfert et al., 2016).

Short-term storages are characterized by frequent charging/discharging, i.e. by a high energy throughput per capacity unit over a relevant time lapse. Long-term storages are characterized by a lower charging/discharging frequency and hence by a lower energy throughput per capacity unit over a relevant time lapse. Therefore it is more important for short-term storages to have low charging/discharging costs than for long-term storages, while it is more important for long-term storages to have low storage capacity costs than for short-term storages. Short-term storages tend to have higher power-to-capacity ratios than long-term storages. Additionally, self-discharge is more critical for long-term storages than for short-term storages.

Pumped storages and batteries, the storage types used in systems I and II, are appropriate short-term storages (in the following the storage system in systems I and II is called *storage I*). In system III this storage system is complemented by a second storage system that is appropriate for long-term storing (in the following called *storage II*). We choose a methane storage as long-term storage.

For storing energy in methane, excess electricity is used to produce hydrogen through the electrolysis of water. And the hydrogen, together with carbon dioxide, is used to produce methane. This is realized in the so-called Sabatier process with the exothermic reaction $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$. The methane can then be used to generate electricity in gas engines, gas turbines, or combined cycle power plants. The maximum cycle efficiency of a methane storage is about one third (Sterner et al., 2014).

What qualifies the methane storage as a long-term storage is the low cost of the gas storages and the inexistence of self-discharge. Charging/discharging processes, however, come along with higher costs due to the necessary charging infrastructure, electrolyzers and methanation units, and due to high cycle losses.

In the model the operation of the two different storage systems is implemented in the following way: Storage I has priority in charging and discharging. Only if storage I cannot absorb all the given excess energy (due to limited storage capacity or due to limited charging capacity), storage II is charged, and only if storage I cannot deliver all the energy that is needed to cover a given load (because the storage is empty or because the available discharging power is insufficient), energy is taken from storage II

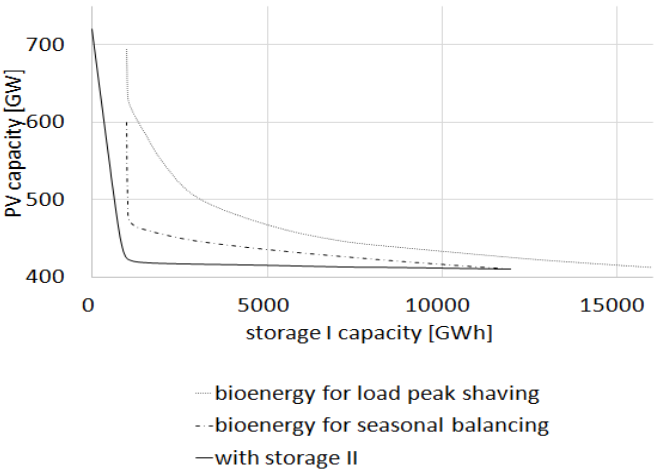

Fig. 8 PV capacity as a function of storage I capacity for systems I, II, and III (system III without charging power limit for storage II)

As to be seen in Fig. , the integration of storage II reduces the needed storage I capacity at any given PV capacity, and the needed PV capacity at any given storage I capacity. For instance, at a PV capacity of 430 GW the storage I capacity is 6,000 GWh for system II, but only 900 GWh for system III.

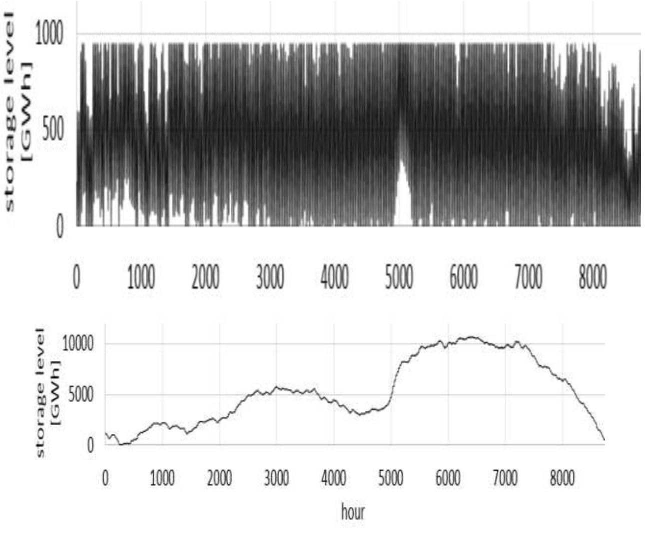

Fig. 9 Storage levels (top: storage I, bottom: storage II) over a one-year period for system III for a storage I capacity of 950 GWh and a PV capacity of 426 GW (storage II level quantified in terms of the lower heating value of the stored gas)

Especially interesting is the storage I capacity range between 900 and 950 GWh, where the curve for system III bends quite abruptly upwards. This is the capacity range in which storage I really acts as a short-term storage while storage II acts as a long-term storage. Storage I covers basically the daily fluctuations, while storage II covers basically the seasonal fluctuations. If the capacity of storage I is larger than 950 GWh, then it takes over an increasing part of the seasonal balancing, and if it is smaller than 900 GWh, then storage II takes over an increasing part of the daily fluctuations. Just in the storage I capacity range of 900 to 950 GWh each of the two storage systems adopts one of the two functions of short-term and long-term storing. Fig. represents the complementary behavior of the two storages for a storage I capacity of 950 GWh.

The needed gas storage capacity for the storage I capacity range of 900 to 950 GWh is about 11 TWh (quantified in terms of the lower heating value of the stored gas). This is not a very large gas storage volume. Many countries have much larger gas storage capacities. Germany, for instance, has a natural gas infrastructure with a storage capacity for more than 200 TWh electrical energy (Fraunhofer Gesellschaft, 2010).

In the calculation represented in Fig 8 the charging power for storage II is not limited. All the energy that cannot be stored in storage I is stored in storage II. The needed maximum charging power for storage II is represented in Fig 10. In the interesting storage I capacity range of 900 to 950 GWh it is around 250 GW (quantified in terms of the electrolyzer input power).

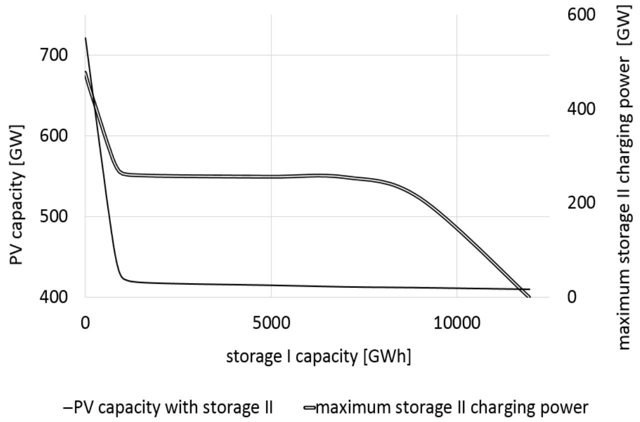

Fig. 10 Maximum charging power of storage II for a system without charging power limitation

While gas storage capacities are economically less critical, the charging power of storage II *is* economically relevant. Investment costs for electrolyzers and methanation units will be considerable also in the medium-term future.[*] It is important therefore to consider configurations in which the storage II charging power is limited. Fig 11 shows the respective curves for electrolysis power limits of 100 GW, 25 GW, and 10 GW.

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[*] In (Albrecht et al., 2013) medium-term electrolyzer costs of 700 Euro/kW_{el} and methanation unit costs of 600 Euro/kW_{CH4} are assumed. As the respective markets are not yet developed, these numbers are still quite vague estimations.

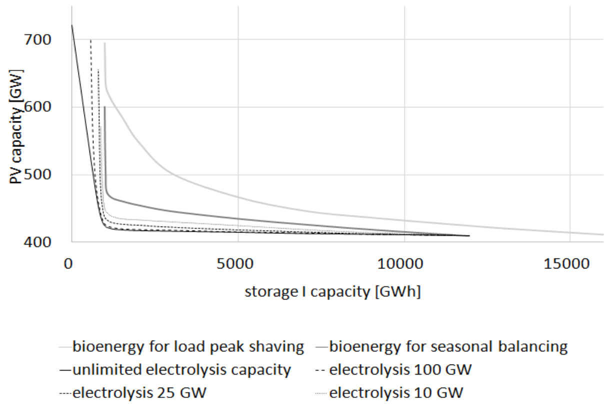

Fig. 11 PV capacity as a function of storage I capacity for systems I and II, and for system III with unlimited charging power and with different charging power limits

Limiting the charging power for storage II increases the needed PV capacity for any given storage I capacity (and the needed storage I capacity for any given PV capacity). However, even with a maximum charging power of only 10 GW the integration of storage II still reduces considerably the needed storage I or PV capacity compared to the capacities needed in system II. For instance, at an installed PV capacity of 440 GW the needed storage I capacity is reduced by nearly 3,000 GWh (from 4,000 GWh in system II to 1,100 GWh in system III), and at an installed storage I capacity of 1,000 GWh the needed PV capacity is reduced by 90 GW (from 540 GW in system II to 450 GW in system III).

4. Conclusions

Renewable-energy-based electricity should be integrated increasingly into the JB grid. This makes sense not only because of environmental concerns, but also because of the fact that the respective technologies have become more and more economically competitive.

To power the JB grid *exclusively* with electricity from renewable sources harvested from the grid area itself is challenging. The future energy demand is high and the population density is very high. Renewable energy sources besides solar energy are quite limited with respect to the expectable energy demand. The dependence on solar energy is therefore high, and consequently – due to the given seasonal fluctuations of solar radiation – the storage need is high. Especially the high storage need is a considerable challenge. This general evaluation leads to the following energy political conclusions:

a) The high dependence on solar energy requires special attention to alternative sources. Geothermal power and hydropower should be promoted in order to reduce the dependence on solar energy as much as possible. In the case of hydropower, sufficiently large water reservoirs are important to increase the flexibility of the power plants. An additional interesting aspect is that hydropower has an anticyclical annual behavior with respect to solar energy.

b) The available biomass should be used for balancing as much as possible the seasonal solar energy fluctuations.

c) Due to the impossibility of balancing completely the seasonal solar power fluctuations with hydropower and bioenergy, the complementation of short-term storage systems (pumped storages and batteries) by a long-term storage system with lower storage capacity costs (gas storages) is necessary. Even at small charging powers a secondary long-term storage system reduces considerably the needed short-term storage capacity.

d) The allocation of the necessary large PV capacity is not an easy task. Besides roof areas and ground-mounted systems, offshore PV systems should be taken into consideration (Trapani et al., 2013). Especially along the northern shore, which is protected from high waves, many appropriate locations can be found.

e) Calculation was done with respect to locally available resources. The import of energy resources from less densely populated islands can be useful. In this context the planned cable connection through the Sunda Strait to Sumatra can play an important role (HVDC Sumatra Java, 2016).

The scenario gives an impression of how challenging a completely renewable powering of the JB grid is. However, it is not impossible. Take Germany as an example: Two decades ago it was considered as practically impossible to deliver a high share of the needed electricity from renewable sources. Now, in 2017, already more than one third of the electricity is generated from wind, sun, biomass, and water (Umweltbundesamt, 2017). And it has even become conceivable to generate in the medium-term future *all* or at least *nearly all* the needed electricity from renewable resources (Henning et al., 2012). The problems have turned out to be solvable. Also for the JB grid the challenges will be overcome step by step if there is a political will to transform the energy supply system gradually into a renewable-energy-based one. This study has the aim to show some important challenges that have to be tackled if such a transformation becomes a political aim.

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