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Global energy storage demand for a 100% renewable electricity supply

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Abstract

This study demonstrates – based on a dynamical simulation of a global, decentralized 100% renewable electricity supply scenario – that a global climate-neutral electricity supply based on the volatile energy sources photovoltaics (PV), wind energy (onshore) and concentrated solar power (CSP) is feasible at decent cost. A central ingredient of this study is a sophisticated model for the hourly electric load demand in >160 countries. To guarantee matching of load demand in each hour, the volatile primary energy sources are complemented by three electricity storage options: batteries, high-temperature thermal energy storage coupled with steam turbine, and renewable power methane (generated via the Power to Gas process) which is reconverted to electricity in gas turbines. The study determines – on a global grid with 1°x1° resolution – the required power plant and storage capacities as well as the hourly dispatch for a 100% renewable electricity supply under the constraint of minimized total system cost (LCOE). Aggregating the results on a national level results in an levelized cost of electricity (LCOE) range of 80-200 EUR/MWh (on a projected cost basis for the year 2020) in this very decentralized approach. As a global average, 142 EUR/MWh are found. Due to the restricted number of technologies considered here, this represents an upper limit for the electricity cost in a fully renewable electricity supply.

Keywords: Renewable electricity supply; storage demand; energy system modeling; global; high-temperature thermal storage

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1. Motivation

Photovoltaics and wind energy will play a major role in a future, carbon-neutral energy supply. [1] In recent years, several studies covered the technical possibility of a fully renewable energy supply [e.g., 2]. None of them, however, determined - on a global scale and in full detail - the storage capacities in the electricity sector which are required to guarantee demand matching for each hour of a year. Thus, the cost of electricity in a fully renewable supply sector is still strongly debated. [3] In several steps, this study leads to results which effectively answer these questions.

In this work we investigate a scenario of global, decentralized 100 % renewable energy sources (RES) based electricity supply on an hourly basis. Details of the approach are described below. The decentralized 100 % renewable limit case investigation will provide an upper limit for the cost of a fully renewable electricity supply.

Questions we address in this work are

- What is the global demand of storage capacity for a fully renewable electricity supply?
- What is the levelized cost of electricity in such a scenario (on a regional and national level as well as a global average)?
- How does the optimal storage mix look like?

This work especially introduces high-temperature thermal energy storage (TES) coupled with steam turbines as a third storage option besides batteries and renewable power methane (RPM).

2. Approach

Based on a model for the hourly resolved electricity demand in > 160 countries for a full year – which has been published in a separate paper - , a 100 % renewable electricity supply for regions of 1° latitude by 1° longitude is simulated, and the cost-optimal system configuration is determined for each region. The used hourly primary energy production data for PV, wind energy and CSP are described below.

The analysis neglects the potential of hydro power, bioenergy and geothermal power, which clearly limits the validity of the results for a number of countries. However, including those unequally distributed potentials simply exceeds the scope of this study.

In view of the decentralized character of the modeled energy systems, energy exchange between adjacent regions is neglected. In the framework of our model, this corresponds to the assumption that electricity distribution networks are fully developed, but not connected to other regions via transmission networks of more than 100 km length.

2.1. Energy System Model

The energy system model applied for each local energy system considers ubiquitous resources with high potential: PV, wind energy (onshore) and CSP[†]. [3], [4] These volatile energy resources are complemented by three energy storage and conversion options. Components and energy flow paths of the model are shown in Fig. 1. Besides batteries, the following two additional pathways are considered in this model:

In the first energy conversion-and-storage path, electrical energy is converted to renewable power methane (RPM) via the Power to Gas process, i.e. electrolysis followed by a methanation step. The produced methane is a renewable substitute natural gas (SNG) which can be fed into existing gas grids avoiding the manifold difficulties of hydrogen injection. [17], [22] In this way, long-term storage of renewable energy becomes possible, as well as utilization in

[†] Only linear concentrating solar power is considered, more specifically parabolic trough collectors

the heating and mobility sector (natural gas vehicles). However, we focus here on the possibility of reconversion of the renewable gas to electricity. In our model system (Fig. 1), there is one direct and one indirect path: The gas can be used in flexible gas power plants, or it can be converted into high-temperature heat and fed into the steam turbine, which originally belongs to the CSP plant.

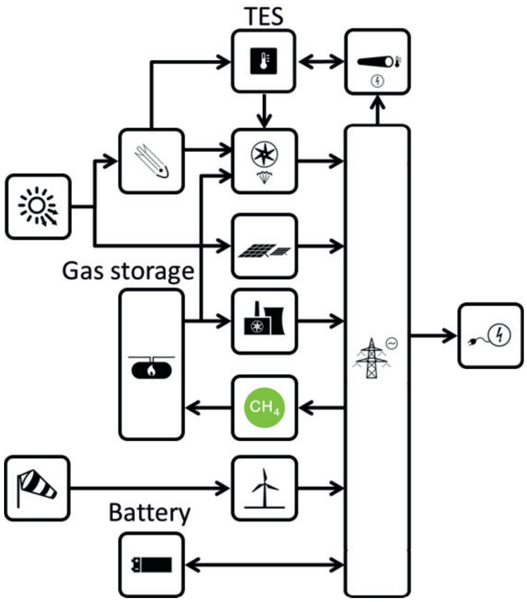

Figure 1. Block diagram of the considered energy system model of a fully renewable electricity supply based on solar and wind energy complemented by three storage options.

The second energy conversion-and-storage path considered here uses excess energy to heat a high-temperature thermal energy storage (TES, e.g. molten salt). The thermal energy comes either from a CSP plant or is generated from electrical energy via a heating rod. In times of high energy demand, the stored thermal energy is converted back to electricity by a steam turbine (ST).

The described energy conversion and storage options are integrated into our energy system model called MRESOM (Multi-Region Energy System Optimization Model) using a linear optimization approach. Analyses of energy systems can be performed with representation of technical interrelationships and economical optimization. It is used to draw decisions on investment and dispatch of power plants and other components of energy systems. Simulations cover a period of one year with a temporal resolution of one hour.

2.2. Data

2.2.1. Resource data

Resource data are based on NASA SSE data (Surface Meteorology and Solar Energy SSE Release 6.0). [23], [24] The original data were converted to hourly resolution by the German Aerospace Center. [3] The spatial resolution is 1 ° latitude x 1 ° longitude. Feed-in time series for fixed, optimally-tilted PV power were obtained by applying a model of Huld et al. [5] Wind power feed-in data were calculated by applying manufacturer supplied wind speed-power curves of currently available wind turbines with 100 m hub height.

2.2.2. Demand data

Electricity demand data with hourly resolution are taken from a model (separately published) based on macroeconomic data and historical electrical demand data of 2010 for > 160 countries. [6] The model uses superposition of temporal sine waves in order to represent – separately for each country - several characteristical periodical features of regional electricity demand. The model was calibrated with real hourly resolved demand data for a number of countries.

2.2.3. Financial and technical parameters

The model determines cost-optimal energy systems on a projected cost basis for 2020. The specific cost estimates for PV and wind power plants are widely used for the year 2020 and accepted in the community. [7]–[9] Capital expenditures (Capex) for gas power plants (OCGT and CCGT) are not assumed to reduce in the coming years. [10], [11]

Parameters for the Power to Gas technology respect the development potential of the technology as well as the fact that in a 100% renewable electricity supply scenario, CO_2 extraction technology (from CO_2 streams or from air) will be required. Specifically, the Capex and efficiency values given for Power to Gas are chosen that such that they effectively include cost and energy expenses required for the CO_2 extraction process. The efficiency given here refers to the lower heating value of methane. Capex for underground natural gas storages is quite low; values in literature range from 0,013 to 0,064 EUR/kWh. [12]

Table 1. Financial assumptions for components of the energy system for the year 2020. Parameters for gas storage, TES and the solar collector field are given per $kW(h)_{th}$. All other parameters are given per $kW(h)_{el}$.

Technology	Capex [EUR/kW]	Opex fix [EUR/kW]	Opex var [EUR/kWh]	Lifetime [a]
PV	900	15	0	25
Wind	1000	30	0	25
Power to Gas	940	24	3	25
CCGT	750	15	1	30
OCGT	380	7.6	1	30
Solar collector field	500	10	0	25
Steam turbine	700	14	0	30
Heating rod	20	0.4	0	30
Hot heat burner	100	2	0	20

Storage technology	Capex [EUR/kWh]	Opex fix [EUR/kWh]	Opex var [EUR/kWh]	Lifetime [a]
Battery	250	5	0	10
Gas Storage	0.05	0.001	0	50
TES	28	0.28	0	20

Concerning battery technology, it is assumed that until 2020 lead-acid batteries will be the cheapest electrochemical energy storage option. Afterwards, we assume sodium-sulfur batteries (NaS) to be lower in cost than lead-acid batteries. Assumptions for battery storage base on lead-acid technology with a depth of discharge (DoD) of 80 % (referred to the nominal capacity) and a round-trip efficiency of 80 %. [13], [14]

The CSP component in this model consists of a linear concentrating parabolic trough collector, a molten salt thermal energy storage, and a steam turbine power block. In 2010, investment cost of CSP plants with 8 hours thermal storage was at about 6000 EUR/kW, and it is assumed that this will reduce to 2000 EUR/kW in 2050.

According to the presented cost development curves, cost CSP plants will decrease to 3600 EUR/kW in 2020. Cost breakdown for components of CSP plants is based on the study *Desert Power 2050* and further in-depth calculations by the *Dii* for CSP projects in the year 2015. [11]

Table 2. Technical assumptions for components of the energy system for the year 2020.

	Efficiency [%]
Battery	80
Gas Storage	100
RPM	50
CCGT	58
OCGT	38
Thermal energy storage	92.5
Steam turbine	42
Heating rod	100
Hot heat burner	95

Table 3. Energy-power ratio of considered storage technologies

Energy/Power	[h]
Battery	6
Gas storage	1
Thermal energy storage	8

Further assumptions are weighted average cost of capital (WACC) of 7 % and an exchange rate of 1.33 USD/EUR.

2.2.4. Aggregation on a national and global level

The global simulation yields cost-optimal energy system configurations for each of the simulated 15,388 independent regions in 163 countries. The raw results are normalized, i.e. they provide the required installed system component capacities relative to a total regional electricity demand.

To provide absolute numbers, we have chosen the approach to use national data for the total electricity consumption in 2010 for scaling, as well as data for the global population density (2000) on a 1° x 1° grid to provide a scaling of the energy consumption within each country. [15]

2.3. Limitations

A study as complex as the one presented here does inevitably necessitate simplifications. The temporal resolution of one hour excludes aspects of grid stability on the time scale of minutes. Storage capacities in this work are purely used for load balancing and seasonal energy storage. Storage applied for power quality tasks is not part of this work, as a consequence of the hourly resolved optimization.

The approach to neglect hydro power, bioenergy and geothermal power, whose potentials are extremely difficult to cover in a global approach, leads to significant overestimation of the electricity cost for several countries; hydro power has a share of 16 % in the current global electricity generation. [16]

The boundaries of the rectangular energy system cells are chosen without any respect to technical borders of existing energy systems. Geographically extended grid infrastructure is not considered, but a local grid within the local energy system is required and is assumed to be sufficient.

In view of the goal of a climate-neutral energy supply in general, a significant limitation of this study is that only the electricity demand is covered. However, demand for heating and transportation would be even more difficult to integrate.

3. Results

Using the approach described above, we identify the following capacities as an economic optimum for a global, 100% renewable electricity supply: 7,300 GWp installed PV power, 6,700 GW onshore wind power and 3,900 GW_{el} CSP. In our model, wind power supplies almost half of the generated electricity (see Figure 2a). PV supplies a third (9,400 TWh) of the generated electricity, whereas CSP generates around 20 % (6,000 TWh).

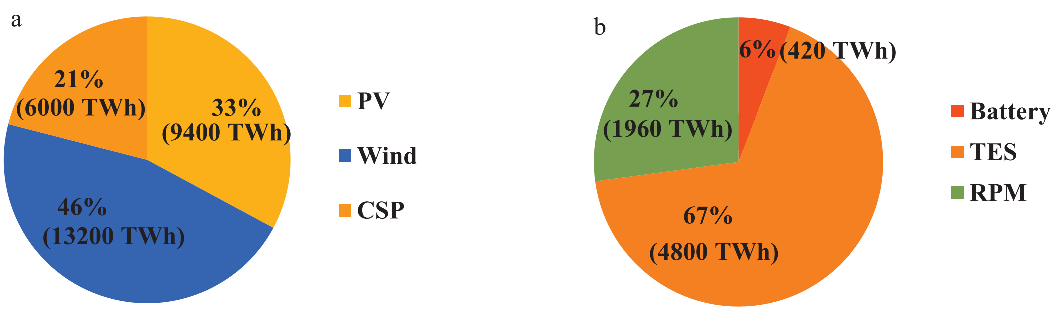

Figure 2. (a) Total annually generated electricity and relative shares of the three primary energy sources; (b) Global sum and relative shares of annual energy output of the three considered storage options

65 % of electricity demand is covered by immediately consumed electricity supplied by PV, wind power and CSP. Respectively, a share of 35 % is not immediately consumed electricity and is supplied by storages: Batteries supply 420 TWh, gas power plants (OCGT and CCGT) supply 1,960 TWh on the basis of RPM and the TES have the largest global share with an energy output of 4,800 TWh (see Figure 2b).

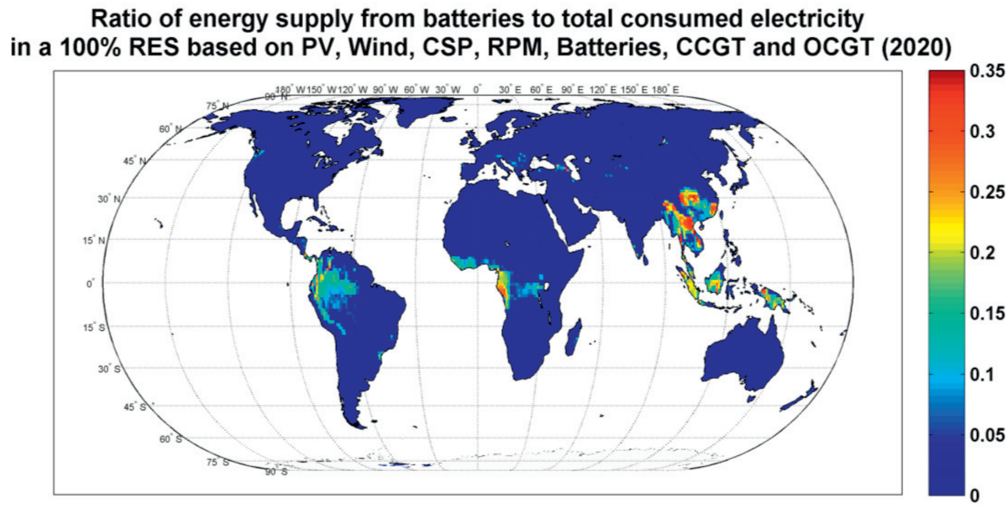

Figure 3. Spatial distribution of the ratio of energy supply by batteries to total consumed electricity

The required global storage capacities are 1.5 TWh for batteries, 1,690 TWh_{th} gas storage, 2,360 GW_{el} RPM input power and 73.6 TWh_{th} TES. Derived market sizes for the three storage technologies are: 375 bn EUR for battery storages, 85 bn EUR for gas storages, 2,210 bn EUR for RPM plants and 2,060 bn EUR for TES.

The regionally optimal amount of stored energy depends on the type of RE source used. In tropical regions batteries are preferred due to poor wind and direct normal irradiation (DNI) conditions (see Figure 3). Major energy source in these regions is PV which is complemented economically best by battery storages.

The TES finds its major application in regions near to the equator. The spatial distribution predominantly goes along with availability of direct irradiation.

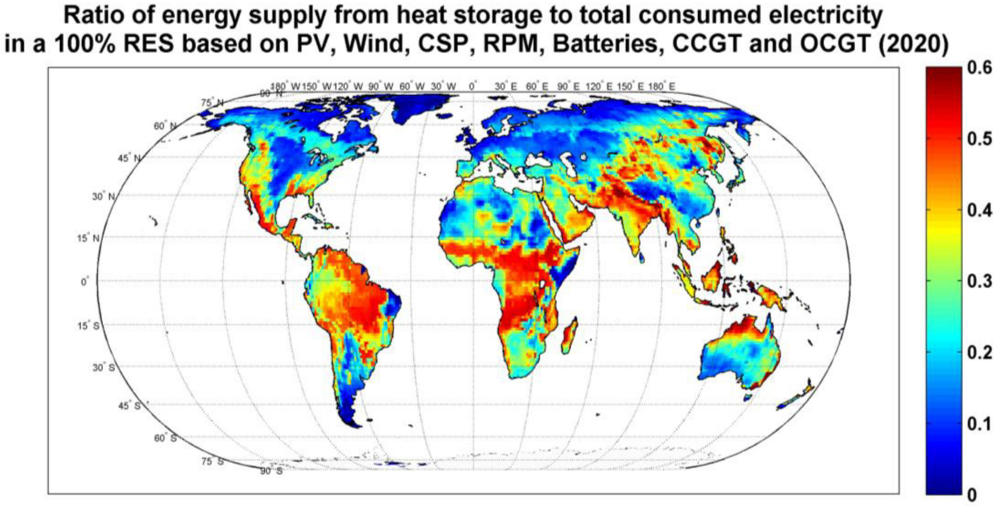

Figure 4. Spatial distribution of the ratio of energy supply by TES to total consumed electricity

Spatial distribution of RPM storage is, compared to batteries and TES, more homogeneous. The supply rate of the RPM is significantly lower than of the thermal energy storage, but the technology is needed at all sites to enable long-term energy storage. Larger capacities of RPM storage can be found at sites with good wind conditions such as, e.g. in southern Argentina, at the shore of the North Sea etc.

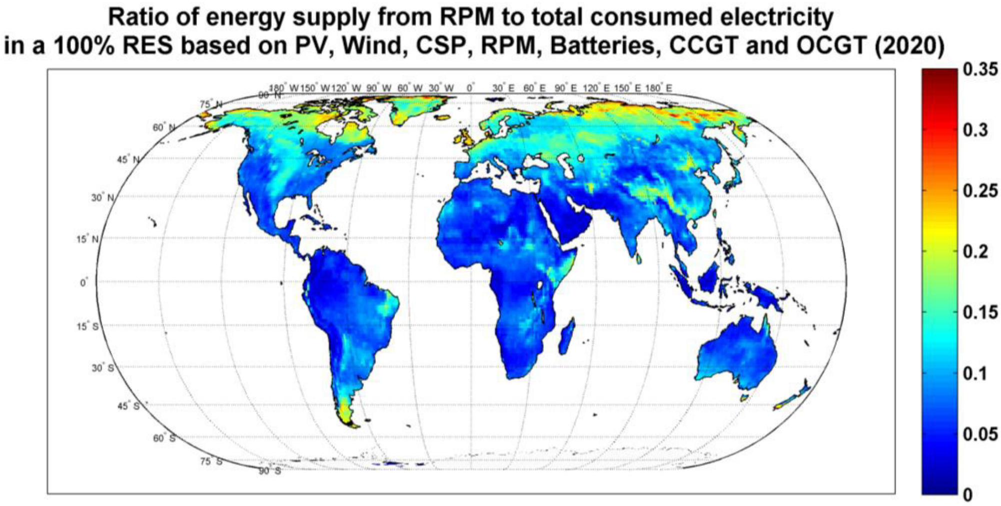

Figure 5. Spatial distribution of the ratio of energy supply by RPM to total consumed electricity

For the average global levelized cost of electricity supply in this decentralized 100% RES scenario for the year 2020, we find a value of 142 EUR/MWh (aggregated on national level). This value varies significantly over the different regions (see Figure 6).

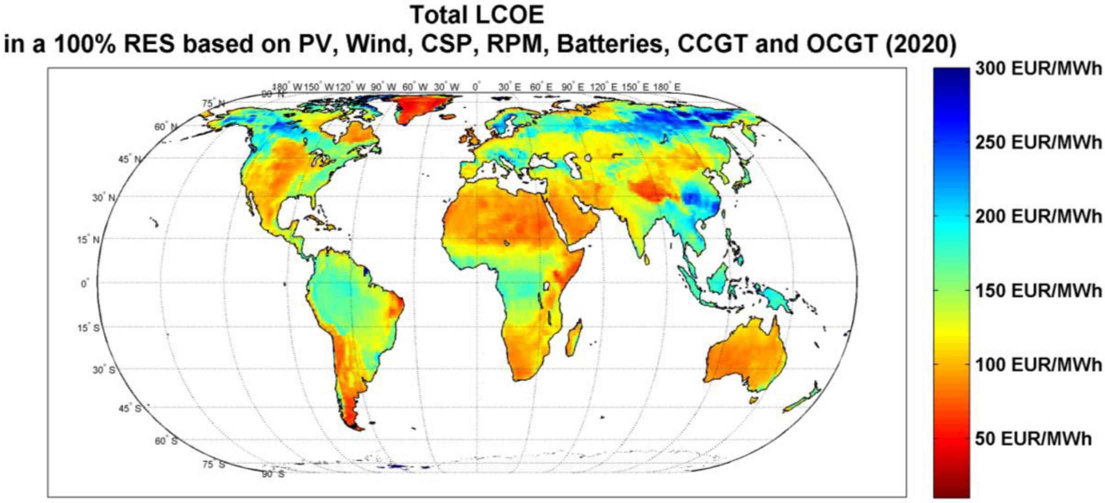

Figure 6. Spatial distribution of total LCOE for the year 2020

On a national level, the minimum LCOE can be found in Somalia with 80 EUR/MWh due to above average availability of solar and wind resources. The maximum LCOE of 203 EUR/MWh is determined for Bosnia-Herzegovina, basically due to a combination of bad wind and solar conditions.

The analysis does not only yield the cost-optimal energy system configurations for each region, but also its optimal operation. Therefore, also conclusions on e.g. the full load hours of each technology component result from our simulation.

To highlight an interesting result, the full load hours for steam turbines are generally rather high: Full load hours (Flh) range from 2,310 h in Denmark to 5,750 h in the Sultanate of Oman. On a global average, steam turbines achieve 3,760 Flh.

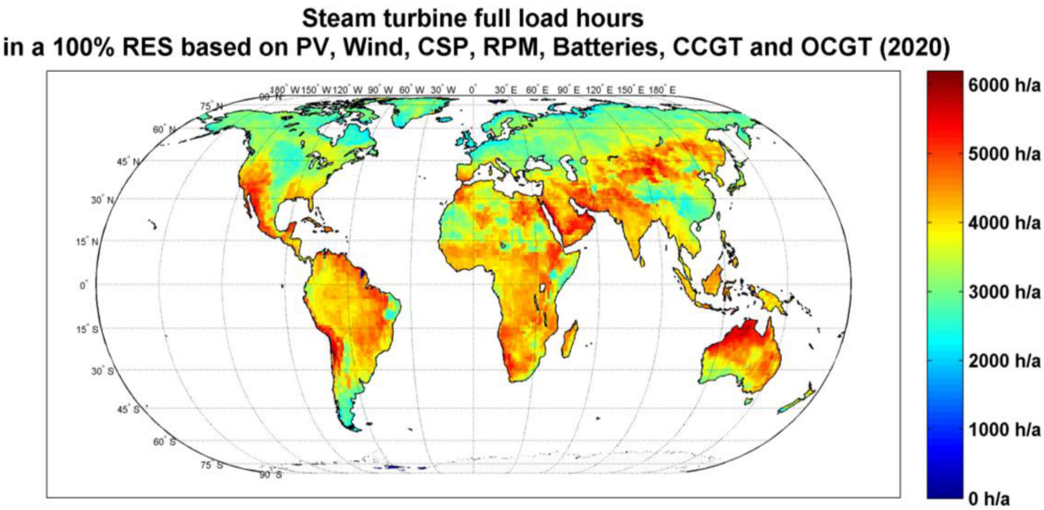

Figure 7. Spatial distribution of full load hours of steam turbines

On the one hand ST act as power block of the CSP plants, on the other hand the ST is the converter of thermal energy stored in the TES to electricity. Moreover, in case that heat is directly available from the solar collector field or from the TES, even RPM can be burnt and re-converted to electricity in STs for covering the load requirements. This triple function of steam turbines has significant impact on their full load hours.

The results discussed here are understood to be a small selection of the full range of results of this global simulation. Rather than extending the presentation of the results, we want to stress that our approach is not limited to the analysis of the "final energy system state" of a 100% renewable electricity supply, but that it can also be used to yield insights about the transition towards higher renewable electricity share.

4. Conclusions

We have investigated a cost-optimal, global, fully renewable electricity supply based on volatile energy sources complemented by three storage options: Batteries, Renewable Power Methane (RPM) via the Power to Gas process, and high-temperature thermal energy storage (TES) in combination with CSP, steam turbine and heating rod. Using a dynamical, spatially and temporally resolved energy system model, and country based demand profiles for 163 countries, allowed a detailed determination of the required storage capacities.

Regarding the considered storage technologies, our study shows that TES is preferred for short-term energy storage; battery storages play a rather minor role. On a global scale, TES provide ten times more electricity (via steam turbines) than batteries. It should be mentioned that total battery capacities could be larger in real power systems taken into account using batteries for grid stability or other tasks.

The extensive use of the TES - two thirds of electricity supplied by storages is provided by this storage options - leads to high Flh of the steam turbines. The triple use as converter of (i) thermal energy from the solar collector field, (ii) thermal energy from the high-temperature thermal energy storage, and (iii) of thermal energy generated by using RPM in a hot heat burner lowers the cost per unit of energy generated by the ST and improves the economical attractiveness of steam turbines. Even if exergy losses on a first look speak against converting electrical energy into thermal energy, the dynamical system approach shows that it is part of the operation of a cost-optimal renewable energy system.

Likewise, the dynamical system approach shows that RPM, in spite of its cost and lower efficiency compared to the other storage options, becomes a central part of the cost-optimal energy system portfolio. Regarding electricity supply only, it is required for a cost-optimal realization of RES penetrations of 80 % and above. It is important to note – even if it is beyond the scope of this study to discuss in detail - that energy conversion and storage via Power to Gas is more versatile than other options, since gas can be easily distributed and used in other energy sectors like heating or transportation.

The restriction to solar and wind resources in our approach tends to overestimate the electricity cost and storage demand especially for regions with high hydro power potential. At the example of Bosnia Herzegovina (BH), where our simulation identifies the overall highest national average LCOE of 203 EUR/MWh for all of the 163 considered countries, this is indeed the case: The hydro power potential of BH is estimated at over 6,000 MW [19]; i.e. a realistic renewable energy system for BH will certainly include a high share of hydro power. In fact, for many of the 60 countries for which our analysis determines LCOE above the world average of 142 EUR/MWh, considerable hydro power resources exist. [20]

This leads to the following hypothesis: The maximum nation-average LCOE in a decentralized 100% renewable supply scenario is on the order of 150 EUR/MWh. The verification of this hypothesis, however, is beyond the scope of this study.

At the low-cost end of the national LCOE order in our analysis, Somalia stands at 80 EUR/MWh. Today, electricity in Somalia is generated almost exclusively in diesel generators and costs on average more than 1,000 EUR/MWh. [21]

Including further system components into future analyses will allow to further reduce costs. It is to be expected that in particular considering hydro power, grid interconnections and coupling with other energy sectors such as heat, mobility and desalination will be important levers.

Last but not least let us mention that a significant global reduction of greenhouse gas emissions will basically require an almost fully renewable electricity sector, since it will be even more difficult to reduce emissions in other sectors, e.g. transport or industry. In our analysis, we have derived for the first time an estimate of the required cost-optimal energy system portfolio for such a scenario.

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