Mathis Buddeke, Frank Merten, Kamil Rodzynko

Impacts of different European renewable expansion strategies

on the future demand for flexibility options like storage and transmission grid

Originally published in:
2017 14th International Conference on the European Energy Market (EEM)
6-9 June 2017, Dresden, Germany
IEEE 2017
DOI: 10.1109/EEM.2017.7982011

Wuppertal
Institut

Mathis Buddeke *
Frank Merten *
Kamil Rodzynko *

Impacts of different European renewable expansion strategies on the future demand for flexibility options like storage and transmission grid

* Wuppertal Institut für Klima, Umwelt, Energie gGmbH
Division Future Energy and Mobility Structures
Döppersberg 19
42103 Wuppertal
Germany

Phone: +49 202 2492-0
Fax: +49 202 2492-108

Impacts of Different European Renewable Expansion Strategies on the Future Demand for Flexibility Options Like Storage and Transmission Grid

Mathis Buddeke
Wuppertal Institut
Wuppertal, Germany 42103
Email: mathis.buddeke@wupperinst.org

Frank Merten
Wuppertal Institut
Wuppertal, Germany 42103
Email: frank.merten@wupperinst.org

Kamil Rodzynko
Wuppertal Institut
Wuppertal, Germany 42103
Email: kamil.rodzynko@wupperinst.org

***Abstract*—In the last years, many energy scenario studies have proofed that a power supply highly based on renewable energies (>90 percent) is feasible. The agreement of the United Nations about very ambitious overall decarbonisation goals once again clarifies the relevance of its realisation. However, existing scenarios reaching this target differ in the compositions of generation technologies. Some scenarios focus on wind energy in the northern part of Europe, others base on a large utilisation of solar technologies in the South. Apart from the generation capacities, the needed technical flexibilisation strategies such as grid extension, demand flexibilisation and energy storage are generally known and considered in many scenarios. Yet, the impact of different renewable generation strategies on these flexibility options and their ability to ensure security of supply within their technical potentials are not fully understood. Therefore, this work focuses on the effects and interdependencies of different scenarios, power grid and energy storage, which have been analysed based upon the BMBF research project RESTORE2050. The results of the project show that the local utilisation of flexibilisation options depends to a great extent on the technology focus of the long term renewable expansion strategy. This applies for the spatial flexibilisation as provided by transnational interconnection capacities between the considered 32 countries, especially the ones connecting regions with a surplus of power generation (e.g. United Kingdom, Norway and Spain). Another impact of the renewable scenario is seen on the required temporal flexibilisation of electricity generation and demand. In addition, the available options (storage, DSM) will compete for high utilisation in a future energy system.**

The differences in the utilisation of these applications, which base on the varying shares of PV and Wind generation, lead to the conclusion that the decision about the long-term RE shares ought to be made very soon in order to avoid inefficient flexibility pathways. Otherwise, if the future RE structure will be kept open, adequate adoption of new flexibility options will be difficult, especially in case of technologies with long lead and realisation time (e.g. new power grids and large scale energy storage devices).

I. INTRODUCTION AND SCIENTIFIC BACKGROUND

Nowadays many studies addressing power system analysis on a European scale are available. However, most of these studies deal with scenarios, pathways and technical options to achieve RE shares of nearly 80%. Only a small number of studies consider and discuss cover rates for renewable energies of more than 90% or almost 100% [1]. Furthermore, most of the conducted studies analyse only one (mostly economically optimised) distribution of the renewable generation capacities. However, the heterogeneous scenarios of existing studies show that the final system configuration is very sensitive to assumptions such as investment costs or performance parameters of the addressed technologies. In addition, policies, consumer or market trends have decisively determined renewable energies expansion in recent years and will most likely have a major impact on the future power system design, too. However these aspects are normally not considered explicitly. As these effects and their impacts are very hard to assess, we use two different scenarios, in order to reflect possible outcomes indirectly. Thus, an understanding of the impact of different European expansion strategies on flexibility options such as storage, transmission grids and demand side management (DSM) has to be achieved. It is therefore necessary to look at a variety of RE compositions and to analyse how different strategic developments affect the requirements for such flexibility options. This can provide information on the question which common European RE development strategy turns out to be sustainable in the long term. As part of the research project RESTORE2050, an energy system model was developed to address such questions by performing simulations based on two given high RE-scenarios; one focusing on wind energy and another one on solar energy. In this paper, the following central research questions are analysed:

- What are the main characteristics of the two existing, different high RE-electricity long-term scenarios for Europe in the year 2050, chosen as baseline for our own analyses?
- What are the impacts of these two scenarios on the use characteristics and the 'need' of transmission grids as well as on energy storage on a regional scale in Europe?
- Which interdependencies may arise between transmission grid and storage due to the different scenarios?

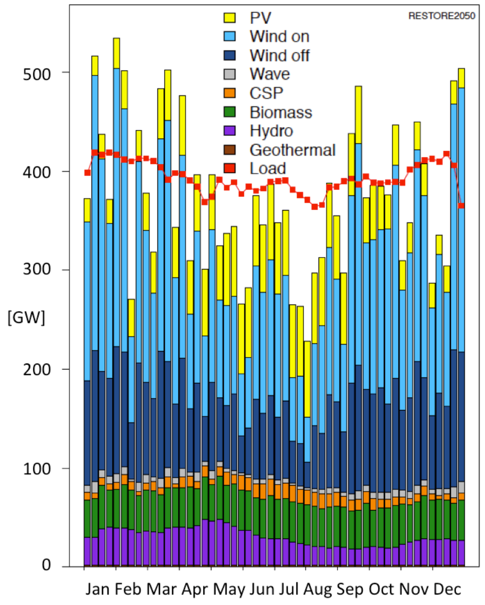

Fig. 1. Weekly mean infeed of renewable generation technologies in the ISI-reference scenario

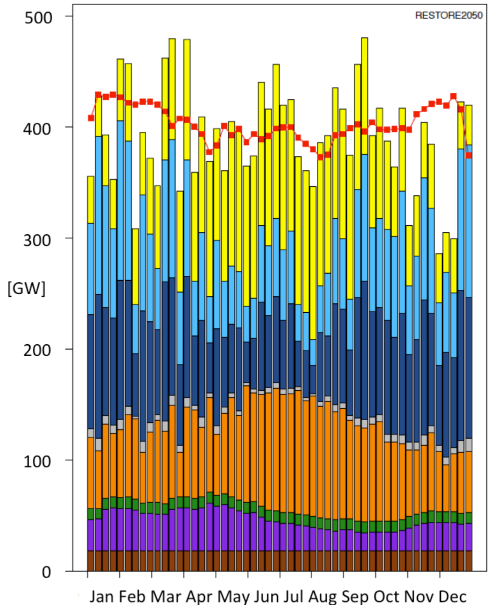

Fig. 2. Weekly mean infeed of renewable generation technologies in the GP/EREC-reference scenario. Legend: see Figure 1

II. MODEL SETTING AND METHODOLOGY

A. *Scenario setting*

Within the RESTORE2050 project, two reference scenarios for the long term development of the European power system were selected from a broad review [1] of existing publications. The main selection criteria were renewable shares in the electricity generation of at least 90% and quantitative information on the distribution and type of generation technology per country. While resulting in a similar energy balance for the addressed energy systems of roughly 100% (annual energy balance) the main difference of the two studies lies in the technology focus of RE-electricity generation. The first scenario [2] is referred to as 'ISI-scenario'. It focuses on wind energy as primary energy source. Therefore, coastal regions, especially adjacent to the North Sea and the Atlantic have large shares of installed capacity. In the second scenario [3] 'GP/EREC', larger shares of electricity are produced with photovoltaics (PV) and concentrating solarthermal power plants (CSP) located in southern Europe. The latter scenario also features electricity import from CSP located in North Africa, which is implemented as an additional 'infeed-only' region. In this scenario specific region no electricity demand is considered. The electricity demand as well as installed capacities of eight renewable power generation technologies such as photovoltaics (PV), wind onshore, wind offshore, biomass, geothermal, runwater, wavepower and concentrating solarthermal power (CSP)) were derived from the reference scenarios for each of the considered countries. As the studies did not cover exactly the same number of countries as in our work, the database was completed and time series for electricity infeed and demand were modeled, using the procedures as described in [4] and [5]. Table I illustrates the RE-capacities as well as the resulting electricity production for the chosen weather year.

TABLE I
INSTALLED RE-CAPACITIES (P), ANNUAL ELECTRICITY PRODUCTION (E) AND ELECTRICITY DEMAND IN THE TWO SCENARIOS [WEATHER YEAR 2004]

Scenario	**ISI**		**GP/EREC**	
	P [GW]	E [GWh]	P [GW]	E [GWh]
PV	340	438	613	791
Wind onshore	607	1315	311	673
Wind offshore	191	768	186	748
CSP	18	88	81	679
Biomass	88	353	12	87
Hydro	190	498	168	488
Geothermal	2	13	23,5	164
Wave	21	56	33	56
Sum	**1457**	**3528**	**1427**	**3685**
electricity demand [GWh]				
Sum	**3452**		**3533**	

B. *Model setting*

The analyses presented here are based on simulations that were carried out in context of the RESTORE2050 project, a BMBF funded research project under lead of NEXT ENERGY, conducted together with the University of Oldenburg and Wuppertal Institut.

Within this project, the RESTORE energy system model, an optimisation based dispatch model for interconnected electricity systems was developed. Details of the model have previously been presented in [6].

The quadratic objective function of the model aims at the minimisation of residual loads (RL) in the overall system by using different flexibility options such as storage units, transmission grid and sectoral demand side management. Given load and generation time series, the model calculates the RL and uses these flexibility options in order to reduce the RL and its temporal peaks. The remaining share of positive RL is assumed to be covered by a fossil backup power plant park that is not implemented in the optimisation.

The database used covers an overall number of 32 countries in Europe. Furthermore North Africa is implmented as an infeed-only region (no electricity demand considered) for solarthermal power plant capacities (only GP/EREC).

For each of the countries an hourly resolved loadcurve as well as infeed time series for all considered renewable generation technologies are implemented. The database covers 10 full weather years of which one (2004) is selected for the simulation. The weather year 2004 has been chosen due to its representative characteristics with regard to the solar irradiation and wind speeds as derived from [4].

A basic grid model features Net Transfer Capacities (NTC) between all countries that allow the model to deploy loss-free energy transmission in order to minimise the RL. The capacities of interconnections represent the already existing NTC connections according to Entso-E [7], assuming all projects of the Ten Year Net Development Plan (TYNDP) 2014 [8] to be realised by 2050.

Storage units, such as pumped hydro (PHS), compressed air energy storage (CAES) and storage hydroelectric plants (HS) are implemented and their dispatch is constrained by charging/ discharging power and efficiencies as well as storage capacities and temporal self-discharge. Table II lists all considered storage units. Many of them, representing the largest share of the overall storage capacity and discharging power, are storage hydroelectric plants marked as 'HS-seasonal'. These are basically large runwater plants with a storage basin that is primarily fed by the natural water inflow during the snow melt season and are not equipped with pumps to actively store energy. In case multiple storage units are assigned to one region these are aggregated. Here, two different categories of storage are distinguished by the ratio of installed charging power and storage capacity (E2P-ratio). All short term storage units (E2P<24h) and all long term storage units (E2P>24h) are modelled as one unit per region.

TABLE II
TYPES, TECHNICAL PARAMETERS AND REGIONAL ALLOCATION OF THE MODELLED STORAGE UNITS

Unit ID	**Type**	**P$_{charge}$ [GW]**	**P$_{discharge}$ [GW]**	**C [GWh]**
24	PHS	1.03	1.03	107
11	HS-seasonal	-	8.4	17008
12	PHS-seasonal	2.74	2.74	1530
4	Mult. tech.	6.31	6.56	45.68
14	PHS	6.99	6.99	184
13	HS-seasonal	-	5.7	9800
17	HS-seasonal	-	4.4	7900
16	Mult. tech.	3.03	3.03	35
9	PHS	6.78	6.78	39
22	Mult. tech.	1.4	1.4	11.2
21	HS-seasonal	-	23.4	84300
27	HS-seasonal	-	10.8	33758
3	Mult. tech.	5.46	5.46	37.14
10	Mult. tech.	1.46	1.46	70
2	Mult. tech.	4.2	5.8	494
1	HS-seasonal	-	3.7	3201
6	HS-seasonal	-	8.1	8800
Sum		**39.4**	**105.75**	**210086**

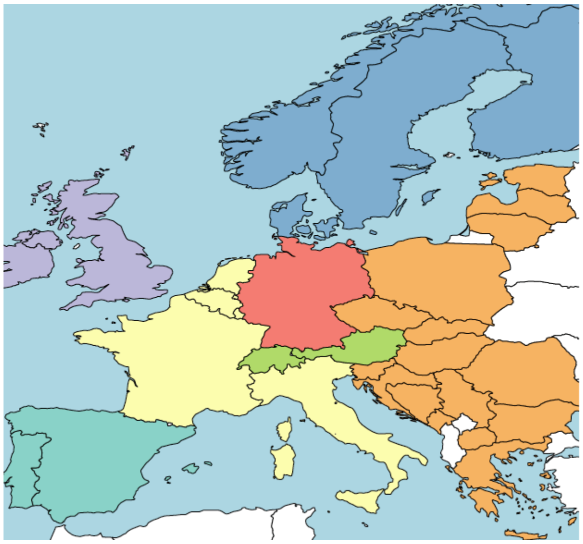

Fig. 3. Area of investigation. Colours indicate the regional aggregation in the performed simulations. In GP/EREC an additional infeed- only region "North Africa" is considered

In order to reduce the problem size for the optimisation, a Rolling Horizons approach was implemented that consecutively optimises overlapping time periods (horizons) of 24-72h of the simulated year. Despite the Rolling Horizons approach, a seasonal storage dispatch is realised as described in detail in [9]. All seasonal storage units are marked with the extension '-seasonal'. Another way to increase calculation speed is the regional aggregation. The simulations performed in this analysis are based on a reduced resolution of 7 regions as shown in figure 3. The considered regions cover the Iberian peninsula (1), Western Europe (2), GB (3), Germany (4), Scandinavia (5), Eastern Europe (6) and the Alpine region (7). Prior comparisons of highly resolved model runs (33 regions/countries) with the aggregated energy system (7 regions) have shown that the most relevant interconnections (bottlenecks) are still incorporated. Still, for the detailed analyses of the impacts on transmission grids, at least one detailed simulation run that covers all countries will be considered.

C. Methodology and structure of analysis

The analyses in this work are mainly based on two simulations of the potential European power system in 2050. Each simulation addresses one of the reference scenarios ISI or GP/EREC as described in II-A. Apart from the differing RE-capacities, the basic system design is identical with regard to the considered interconnection capacities between the regions as well as the installed storage capacities. This includes the minimal expected grid extension up to 2050 (current state of development plus all mentioned projects in TYNDP 2014) and the minimal available storage infrastructure, basically covering storage units that are already available today. In these simulations the dispatch of the flexibility options is modeled. To assess which of the expansion strategies, represented by the reference scenarios, is beneficial for the integration of renewable power generation and the spatial and temporal flexibilisation of energy, the resulting dispatch of distribution and storage infrastructure is compared.

For storage units, the comparison concentrates on the overall amount of stored energy per unit. In order to gain information on the scenario specific dispatch patterns, the number of load changes (from charging to discharging mode) and the energy residence time are analysed. The residence time is defined as the period of time for which energy has been stored. For each discharging process, the hourly energy balance of all recent charging and discharging processes is calculated backwards in time. The residence time is the time span between the actual discharging process and the first occasion when charged and discharged energy is in balance, which is the moment when the storage level lastly falls below the current value.

For transmission lines between the regions, the amount of transferred energy as well as the primary direction of transmission are compared for the two scenarios. In addition, for one of the reference scenarios (ISI) a simulation with full regional resolution has been performed to provide a more detailed view on the dispatch of single transmission lines.

Together with the overall renewable cover rates of the simulations, these parameters allow conclusions about suitable dimensions of future flexibility options and their dependency from different renewable expansion strategies.

III. Results

A. *Storage technologies*

The two reference scenarios result in a very similar annual renewable energy balance of 102.2% in the ISI-scenario and 104.3% in the GP/EREC scenario respectively. However looking at the dynamic (hourly resolved) energy balance, the latter (solar dominated) scenario shows a better matching of renewable supply and demand, because its dynamic renewable cover rate with 88.1% is higher in relation to the scenario specific RE-energy balance than in the ISI-run with 85.6%. Thus, although the installed RE-capacities vary significantly, the simulations result in only small differences regarding the RE cover rates. One reason for this could be the differing contributions of the assumed flexibility options within the performed simulations. This is analysed in the following steps. As the installed storage and transmission capacities are the same for both, ISI and GP/EREC scenario (see section II.B), the following analysis will focus on the comparison of such units.

Looking at the resulting storage dispatch, we need to distinguish between two types of storage units. When comparing the dispatch of the hydroelectric storage (HS) plants, no significant differences can be seen between the two scenarios. Thus, the analysis concentrates on the storage types with charging power. The number of equivalent full load cycles is the first parameter to be analysed. Figure 4 depicts that almost in any region (2-7), the storage units in the wind dominated ISI scenario are less utilised than in the solar dominated GP/EREC scenario. The overall equivalent full load cycles in the ISI run are around 20% lower than in the compared simulation. The reason for that can be found in the relatively high excess powers resulting from the wind focused scenario. Comparing the gaps of the weekly infeed of all RE technologies in the ISI scenario with the average load as shown in figure 1, one can see that even the average difference frequently exceeds the installed charging capacity of all storage units of 39.4 GW. The GP/EREC infeed (figure 2) on the other hand is much more homogeneous over the year and does not show such significant seasonal effects. This leads to the conclusion that for energy systems with high shares of wind energy an increased flexibilisation power (charging capacity) is required in comparison to a rather solar based infrastructure.

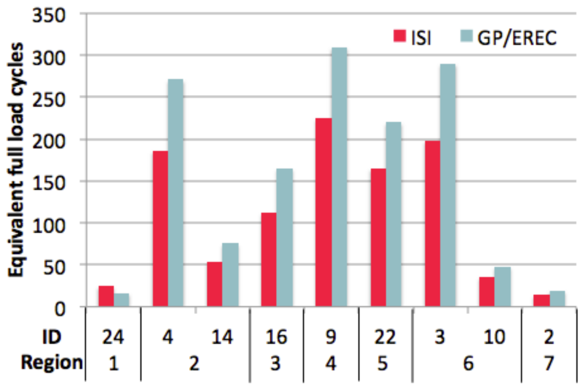

Fig. 4. Number of equivalent full load cycles of storage units in the two simulations.

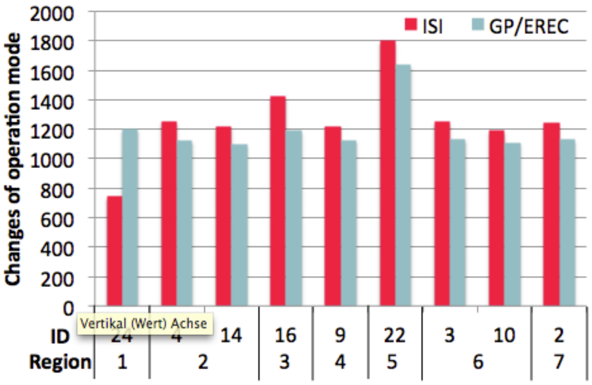

Fig. 5. Number of changes of operation mode for the analysed storage units

Analysing the dispatch of storage units regarding their fluctuation in operation mode can help to determine weather a technology focus of future power systems is beneficial for the expected lifetime of the flexibilisation infrastructure or not. Figure 5 shows the overall number of changes in the operation mode (charging to discharging and vice versa) for each storage unit. Although the storage units are less utilised in the wind

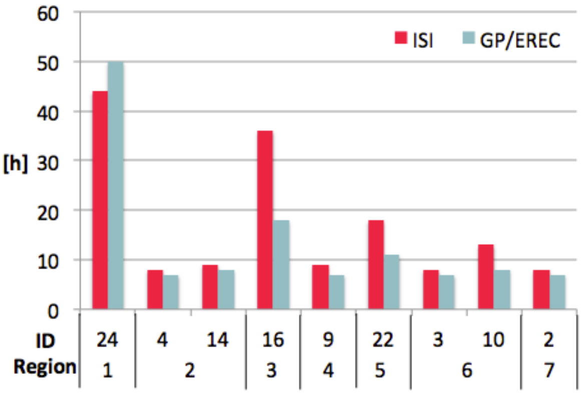

Fig. 6. Average residence time of energy in storage units

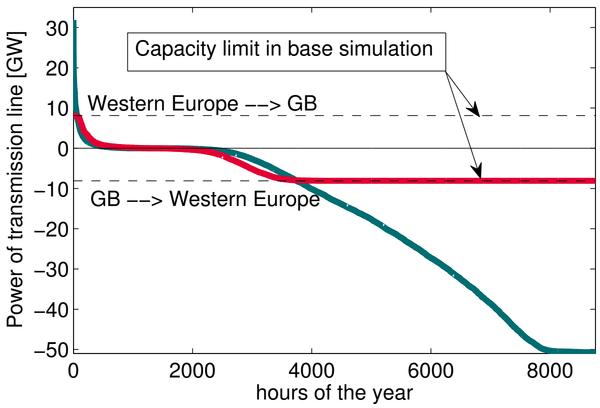

Fig. 7. Sorted transmission line power of interconnection between GB and Western Europe in base simulation (red, CF=0.7) and simulation with increased grid capacity (green).

dominated ISI scenario, their load changes are around 5.5% higher than in the GP/EREC-run. Thus, alongside the need for increased charging power, a more flexible technology with high partial load efficiency is required for power systems with high shares of wind energy.

To assess, which of the two different RE-strategies results in a higher flexibilisation demand in terms of temporal shifting, one can analyse the time the energy is stored until it is finally re-electrified. Figure 6 shows the average residence time for each of the selected storage units. In the regions Western Europe (2), Germany (4), Eastern Europe (6) and the Alpine region (7) no significant differences can be derived from the simulations. The mean residence time shows that most of the energy is shifted within a daily pattern in both scenarios. However the way the storage units are utilised differs in the regions Iberian Peninsula (1), GB (3), and Scandinavia (5). Here, an increased time of residence can be observed. Prior analyses in [10] have shown that these storage units are mainly utilised to buffer the energy export of these regions as they are the hot spots of RE-energy generation. For the ISI scenario, GB and Scandinavia have extensive capacities of wind energy and the interconnections to adjacent regions are highly utilised for energy export. In the GP/EREC-run this is the case for the connections from region 1. Hence, it can be concluded that storage units are utilised for both, temporal and spatial flexibilisation of the generated energy and the technology focus has a clear impact on local storage operation.

Previous simulations in context of the RESTORE2050 project included also five sectoral demand side management (DSM) applications per region [10]. Due of the comparable parameters of DSM and storage units, especially with regard to the E2P-ratio, the analysis came to the conclusion that these technologies provide temporal flexibility in a very similar range. Thus, the derived conclusions about storage dispatch also apply for the integration of DSM.

B. Transmission grid

In order to assess the impact of different renewable expansion strategies on the utilisation of transmission interconnections between regions/countries, parameters of the transmission line utilisation are compared for the two scenarios. To discuss the effects for specific interconnections, additional simulations with high spatial resolution and an increased grid capacity are taken into account.

Concentrating on the capacity factors (CF) of interconnections, resulting from the two base simulations (as described in II-A), the 13 interconnections roughly split into two groups. One group with CF of around 0.25 to 0.45 and another group with very high CF around 0.60 up to 0.90. It is striking that all interconnections in the class of high CF connect regions with excess energy generation from RE-capacities (Iberian peninsula (1), GB (3) and Scandinavia (5)). Yet, with the assumed interconnection capacities both scenarios result in comparable utilisation of all interconnections (average CF of 0.56). The reason for that is illustrated in figure 7. Here, the annual transmission of the interconnection in the ISI-run is compared to a simulation of the identical scenario but with increased grid capacity. This comparison shows that the majority of energy in the base simulation cannot be exported due to the limited grid capacity. This applies for all connections with high capacity factors. Thus, the authors conclude that for both base scenarios the assumed grid capacities represent a strong limitation for the spatial energy flexibilisation.

Figure 8 illustrates the transferred energy for all considered transmission lines and also resolves the direction of the energy exchange. For the excess regions (1, 3, 5), a clear export orientation is noticeable while for the remaining interconnections a more or less balanced energy transfer results from the simulations. Although the two reference scenarios have diverging locations of primary energy generation (ISI in northwest, GP/EREC in the south), only very few interconnections show alternating directions of the predominant energy transfer. In the RESTORE2050 Project a rough estimation on scenario specific interconnection capacities was carried out with the target to achieve a near 'copper plate' transmission grid. Although no economic parameters were considered, transmission lines were scaled to ensure that 90% of the overall possi-

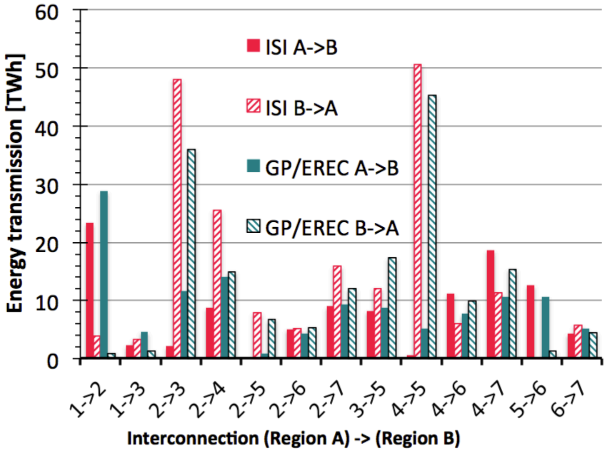

Fig. 8. Sorted transmission line power of interconnection between GB and Western Europe in base simulation (red, CF=0.7) and simulation with increased grid capacity (green).

ble inter-regional energy exchange is realised. These highly resolved simulations result in a total installed transmission capacity in the ISI scenario that is around 9% lower than the grid resulting from GP/EREC. The latter also accounts for the three connections to North Africa which alone constitute for 10% of the installed capacity. Having analysed the utilisation of a rather restrictive grid extension up to 2050 on the one hand and having estimated very ambitious dimensions on the other hand, the authors come to the following conclusion: Extension of the transmission capacity in Europe is a central task that needs to be approached concertedly with the extension of renewable generation capacities. The requirements for overall inner European transmission capacities do not differ significantly for the two RE-strategies. Yet, for the proper utilisation of energy from regions with concentrated electricity generation, transmission capacities to/from these regions need to be prioritised.

IV. CONCLUSIONS

The analyses performed in this work address the impact of varying renewable energy expansion strategies for the European power system on flexibilisation options. For two scenarios, one with a focus on wind energy and the other one with a prioritisation of solar generation technologies, the dispatch of an identical infrastructure of storage units and transmission grid was simulated.

For the utilisation of the considered storage units, the solar dominated scenario seems beneficial as excess powers are more often in range of the assumed charging capacities. Alongside larger charging capacity, the wind dominated scenario requires a more dynamic operation of storage units and demand side management. For both scenarios, storage units show increased utilisation in regions with concentrated electricity generation. Here storage units act as temporal buffers for the spatial energy transmission as the assumed transmission capacities are permanently exhausted in times of RE-generation.

Regardless of the RE-strategy, the results show that the transmission capacities in Europe planned today according to the used base scenarios do not allow for suitable spatial flexibilisation of the generated energy. Thus, the overall required interconnection capacity for such renewable based energy systems will increase substantially when the power system is transformed. Yet, further simulations show that for ambitious goals, the final overall grid capacities do not differ significantly for the two RE expansion scenarios while single interconnections to scenario specific 'hot spots' of RE-generation vary according to the pursued strategy.

ACKNOWLEDGMENT

The research project this paper is based on was supported with funds from the German ministry of education and research (BMBF) under the project code number (FKZ 03SF0439B). Responsibility for the contents of this publication rests with the authors. The authors would like to thank the project partners of the RESTORE2050 project (Dr. Thomas Vogt and colleagues form Next Energy, EWE Forschungszentrum and Dr. Detlev Heinemann and colleagues from ForWind - University of Oldenburg) who have contributed substantially to the RESTORE project, being the baseline for the results shown in this work.

REFERENCES

[1] S. Samadi, "Zwischenbericht zu Arbeitspaket 1 - Auswahl von Szenarien und Meta-Analyse," Wuppertal Institut, Tech. Rep. joint project RESTORE2050, 2013.
[2] B. Pfluger, F. Sensfu, G. Schubert, and J. Leisentritt, "Tangible ways towards climate protection in the European Union (EU Long-term scenarios 2050)," Fraunhofer ISI, Tech. Rep., 2011.
[3] S. Teske, J. Muth, T. Pregger, F. Thoma, T. Conolly, N. T. Simon, Sonja, and M. O'Sullivan, "energy [r]evolution A Sustainable EU 27 Energy Outlook," Greenpeace, EREC, Tech. Rep., 2012.
[4] A. Kies, K. Chattopadhyay, E. Lorenz, L. von Bremen, and D. Heinemann, "Report for Work Package 2/3 in RESTORE2050: Simulation of renewable feed-in for power system studies," Universitaet Oldenburg, Tech. Rep. joint project RESTORE2050, 2016.
[5] S. Eckstein, F. Merten, and M. Buddeke, "Arbeitspaket 4: Europaeischer Lastgang fuer 2050," Wuppertal Institut, Tech. Rep. joint project RESTORE2050, 2015.
[6] C. Krueger, M. Buddeke, A. Nebel, and F. Merten, "Modelling the interdependencies of storage, DSM and grid-extension for Europe," European Energy Market (EEM), 2015 12th International Conference on the European Energy Market, Tech. Rep., 2015.
[7] Entso-E, "ENTSO-E NTC Matrix. https://www.entsoe.eu/publications/market-reports/ntc-values/ntc-matrix/Pages/default.aspx. Letzter Zugriff: 23.09.2014," Entso-E, Tech. Rep., 2013.
[8] EntsoE, "Ten Year Net Development Plan 2014," Entso-E, Tech. Rep., 2014.
[9] M. Buddeke, C. Krueger, and F. Merten, "Arbeitspaket 7: Modellbeschreibung: Einsatzmodell fuer Flexibilitaetsoptionen im europaeischen Stromsystem," Wuppertal Institut, Tech. Rep. joint project RESTORE2050, 2016.
[10] T. Vogt, L. von Bremen, M. Buddeke, D. Heinemann, A. Kies, D. Kleinhans, C. Krueger, F. Merten, M. Preute, and L. Wienholt, "Ergebnisse und Handlungsempfehlungen- Abschlussbericht des BMBF-Forschungsprojektes - Regenerative Stromversorgung & Speicherbedarf in 2050 - RESTORE2050," Next Energy, Wuppertal Institut, Carl von Ossietzky Universitaet Oldenburg, Tech. Rep., 2016.