Final report

1.1 Project details

Project title	Best Paths for DK
Project identification (program abbrev. and file)	12264
Name of the programme which has funded the project	
Project managing company/institution (name and address)	Danmarks Tekniske Universitet, Anker Engelunds Vej 1, 2800 Kgs. Lyngby
Project partners	EU Best Paths project (33 Partners in total)
CVR (central business register)	
Date for submission	

1.2 Short description of project objective and results

The BEST PATHS project demonstrates through large scale demonstrations, the capabilities of several critical network technologies required to increase pan-European transmission network capacity and electric system flexibility, thus enabling Europe to respond to the increasing share of renewables in its energy mix by 2020 and beyond, while maintaining its present level of reliability performance. The BEST PATHS project will bring affordable technological solutions before 2020 to address the following overarching issues:

- What are the best paths to move from HVDC lines to HVDC grids?
- What are the new promising capacity upgrading techniques for existing AC parts of the grid?
- How replicable and scalable are the promising demonstration results within the entire pan-European electricity system?

These intertwined overarching issues are addressed through a set of five high level demonstration objectives, two replication objectives and one dissemination objective. The demonstrations aim to validate, at a scale adapted to technology maturity, the costs and benefits of the tested grid technologies allowing for innovative grid capacity and flexibility increases at Pan European level, while keeping system reliability at current levels. These demonstrations were carried out by the EU Best Paths partners. The work carried out by DTU and funded by EUDP in order to participate in this large-scale project focused on the large-scale simulations of the whole European network the assess the three aforementioned bullet points.

1.3 Executive summary

The objective of the work carried out within this project is to assess the scalability of the Best Paths technologies considering the whole European system. The goal was not to necessarily arrive at a cost-optimal solution, but to identify the performance boundaries of each Best Paths technology when applied on a pan-European scale. Deliverables within the EU Best Paths project, using this work as a basis, presented a complete cost-benefit analysis.

Our analysis uses an 8,000 node pan-European system, reflecting the expected system topology for 2030. It is based on the full ENTSO-E system of 2016, and includes all transmission upgrades described in the Ten Year Network Development Plan 2016 by ENTSO-E and the project of common interest defined by the European Commision. All our simulations are carried out for the year 2030. We adopt the installed generation capacities and projected demand from the EUCO30 scenario, which is developed by the European Commission. We use hourly wind, solar, and generation profiles for a whole year. Most of the input data has been prepared by our project partners, CIRCE, while for this deliverable we mostly worked at the nodes connected to the distribution level, disaggregating the net demand to distributed RES production and actual demand.

For the assessment of the scalability performance of each technology, we used specific KPIs. These are: RES Penetration (%), RES Curtailment (%), Load Shedding (%), and Generation Cost (€).

To better assess the performance boundaries for each technology, we split our analysis into AC upgrades and DC upgrades. The AC upgrades comprise Dynamic Line Rating (DLR) and High Temperature Low Sag lines (HTLS), two out of the various technologies demonstrated in Demo 4. In the AC upgrade scenarios, we do not assume the building of any new AC line, but only the refurbishment of existing corridors. The DC upgrade scenarios, on the other hand, comprise the building of new DC lines (overhead lines, underground or submarine cables), and refer to the group of technologies demonstrated in Demo 1-3. In this analysis, we omitted the assessment of the DC superconducting cables (Demo 5), since in the short term they are expected to be primarily used in very short distances (less than 10 km long).

It must also be noted that for the DC upgrade scenarios, we developed and presented a rigorous analytical approach for the placement of the new HVDC corridors, which guarantees the maximum performance of each newly placed DC line, in term of increasing RES penetration, reducing RES curtailment and load shedding, and decreasing generation cost.

The main takeaways from our analysis are the following:

- Controllable flows are necessary in highly meshed systems, such as the European network. The DC upgrade scenarios have shown a substantially better performance than AC upgrades in all our simulations. The controllability in the power flows, that the HVDC lines offer, allow for a more efficient routing of the power and the substantial relief of congestions with less installed transmission capacity.

- A combination of both AC and DC upgrades is necessary. Even though DC upgrades achieve better results than the AC counterpart, the AC upgrades are necessary to enable the full potential of the DC lines. Upgrading the underlying AC grid is essential in order to accomodate the new flows injected by the newly installed DC lines. Without a coordinated upgrade of both the AC and DC network, we cannot achieve the full potential of either technology.

- Transformer bottlenecks need to be considered. For a successful AC upgrade, the reinforcement of the substations and AC transformers is necessary. The focus of this work was on Best Paths technologies, which included primarily DLR and HTLS upgrades for the AC grid. Although initally out of scope, we extended our study with the capacity upgrade of selected substations and transformers, as it became obvious that without such upgrades, we could not reap the benefits of AC reinforcments to their full potential. Voltage upgrade was out of the scope of this work, but it is also expected to be a valuable AC reinforcement measure.

- In the combined AC and DC upgrade scenario which achieved the best performance for 2030, 70.22% of the installed transmission capacity correspond to DC lines and 29.78% correspond to AC lines. Of the total 56 AC lines to be installed, 35% of the lines can be reinforced by Dynamic Line Rating (require less than 20% increase in their capacity), while the rest 65% of the AC lines should be reinforced by installing High Temperature Low Sag conductors (which achieve up to 100% increase in capacity).

1.4 Project objectives

The objectives of this project was to carry out a large-scale scalability analysis in order to determine how the HVDC and AC technologies developed within the EU Best Paths project can scale up at a pan-European level in order to achieve the European energy and climate goals for 2020 and beyond (2030). The project had a duration of 4 years. During the project, we had to amend the definition of the scalability analysis, as defined in the project description, in order to accurately define how the scalability analysis will be carried out. This helped us deliver more meaningful results.

1.5 Project results and dissemination of results

Please see the document in the appendix for the project results.

The project results have been disseminated in several occasions, including conferences, international workshops, journal publications, and project deliverables.

For the list of publications, please see:
http://www.bestpaths-project.eu/en/publications

https://orbit.dtu.dk/en/persons/florian-thams(14165831-1eeb-481a-a509-cd501e5c0ef0)/publications.html

https://orbit.dtu.dk/en/persons/lejla-halilbasic(63a8e611-ec4b-4246-a42d-4aef143030b6)/publications.html

1.6 Utilization of project results

The results produced by the work funded by EUDP has been used by a series of industry and academic partners in the EU Best Paths project, as they substantially helped determine and build a future European grid and Generation and Demand scenario and provided the main input to carry out a detailed cost-benefit analysis of the Best Paths technologies, in order to optimally determine what is the recommended plan for grid reinforcements and use of HVDC technology.

The knowledge generated about the stability and operation of the HVDC grid during the first two years of the project was essential in defining and winning two grant proposals, one from Innovation Fund Denmark and one from EUDP, that deal with the challenges related to the development and operation of the North Sea Wind Power Hub, including stability issues, optimal topology, and development of new simulation tools to address the emerging issues from low-inertia grids.

PhDs generated a series of conference and journal publications from the work they carried out in the project. For a complete list, please see section above.

1.7 Project conclusion and perspective

Please see Section 5 of the document in the appendix for the conclusions.

D13.1

Technical and economical scaling rules for the implementation of demo results

BEST PATHS

BEyond State-of-the-art Technologies for rePowering Ac corridors and multi-Terminal Hvdc Systems

Contract number	**612748**	**Instrument**	**Collaborative project**
Start date	**01-10-2014**	**Duration**	**48 months**

BEST PATHS stands for "BEyond State-of-the-art Technologies for rePowering Ac corridors and multi-Terminal Hvdc Systems". It is co-funded by the European Commission under the Seventh Framework Programme for Research, Technological Development and Demonstration under the grant agreement no. 612748.

BEST PATHS deliverable fact sheet	
Deliverable number:	13.1
Deliverable title:	Technical and economical scaling rules for the implementation of demo results
Responsible partner:	DTU
Work Package no.:	13
Work Package title:	Integrated global assessment for future replication in EU27
Task:	13.5
Due date of deliverable:	30/04/2018
Actual submission date:	22/05/2018
Authors:	Lejla Halilbasic (DTU), Florian Thams (DTU), Riccardo Zanetti (DTU), Georgia Tsoumpa (DTU), Pierre Pinson (DTU), Spyros Chatzivasileiadis (DTU)
Version:	1.1
Version date:	06/06/2018

Approvals

	Name	Organisation
Author (s)		
Task leader		
WP leader		

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Document history			
Version	**Date**	**Main modification**	**Author**
1.0	22/05/2018	First draft	DTU
1.1	06/06/2018	Template change / Implementation of CIRCE's feedback	DTU

Dissemination level (please X one)	
X	PU = Public
	PP = Restricted to other programme participants (including the EC)
	RE = Restricted to a group specified by the consortium (including the EC)
	CO = Confidential, only for members of the consortium (including the EC)

BEST PATHS stands for "Beyond State-of-the-art Technologies for epowering Ac corridors and multi-Terminal HVDC Systems". This project has received funding from the European Union's Seventh Framework Programme for Research, Technological Development and Demonstration under grant agreement no. 612748.

Table of content

List of Figures

BEST PATHS stands for "BEyond State-of-the-art Technologies for rePowering Ac corridors and multi-Terminal HVDC Systems". This project has received funding from the European Union's Seventh Framework Programme for Research, Technological Development and Demonstration under grant agreement no. 612748.

LIST OF TABLES

Executive Summary

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Our analysis uses an 8,000 node pan-European system, reflecting the expected system topology for 2030. It is based on the full ENTSO-E system of 2016, and includes all transmission upgrades described in the Ten Year Network Development Plan 2016 by ENTSO-E and the project of common interest defined by the European Commision. All our simulations are carried out for the year 2030. We adopt the installed generation capacities and projected demand from the EUCO30 scenario, which is developed by the European Commission. We use hourly wind, solar, and generation profiles for a whole year. Most of the input data has been prepared by our project partners, CIRCE, while for this deliverable we mostly worked at the nodes connected to the distribution level, disaggregating the net demand to distributed RES production and actual demand.

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1. Introduction

The large-scale integration of renewable energy sources into Europe's electricity generation mix and the decommissioning of conventional power plants has raised concern about the suitability of the current transmission infrastructure to continue to enable a secure and reliable electricity supply, as major parts of the generation capacity are relocated further away from the load centers, often to high-RES-potential locations at the boundaries of the continent. The European Network of Transmission System Operators (ENTSO-E) has recognized that significant transmission upgrades and expansions will be required within the next few years and has started tackling the challenge through investments in new transmission projects developed within the framework of the Ten Year Network Development Plan (TYNDP), which provides the most up to date reference for upcoming transmission investments in Europe.

To this end, a holistic approach taking into account the entire European transmission grid is required to assess the suitability of current, impending and future grid infrastructure to transport electricity generated by renewable energy sources (RES) at remote generation sites to consumption centers. Increasing the utilization of renewable generation assets by avoiding RES spillage and thus, the dispatch of more expensive non-renewable generation, which would improve renewable energy project economics and increase their competitiveness on the wholesale electricity market, constitutes another challenge on the way to a fully renewable electricity sector.

This work deals with the scalability assessment of the novel transmission technologies developed within the Best Paths project and analyzes how they can contribute to higher levels of renewable energy integration, social welfare and security of supply. It is a high-level impact analysis, which focuses on examining

- the socio-economic impact of a large scale deployment of the technologies in the pan-European transmission system by 2030;
- the bottlenecks of the 2030 European transmission system, which prevent a larger deployment of renewable energy and lead to renewable energy curtailment and an underutilization of renewable generation assets;
- the potential of the Best Paths technologies to reduce transmission bottlenecks and thereby, allow for an increased deployment of available renewable energy, which would be spilled otherwise.

The Best Paths technologies comprise both AC and DC transmission technologies. Therefore, we focus on three possible grid development scenarios within the scalability assessment:

1. AC upgrade scenario
2. DC upgrade scenario
3. Combined upgrade scenario.

Each of the first two upgrade scenarios focuses on grid developments related to the corresponding transmission technology only and considers the part of the grid pertaining to the other transmission technology unchanged. This way, the two grid development scenarios constitute the bounds within which the optimal Best Paths scenario lies, a concept adopted from optimality theory, where approximations can provide an outer approximation to the true optimal solution of very challenging or even intractable problems. An illustration of the optimality bounds on the future grid development is provided in Figure 1.

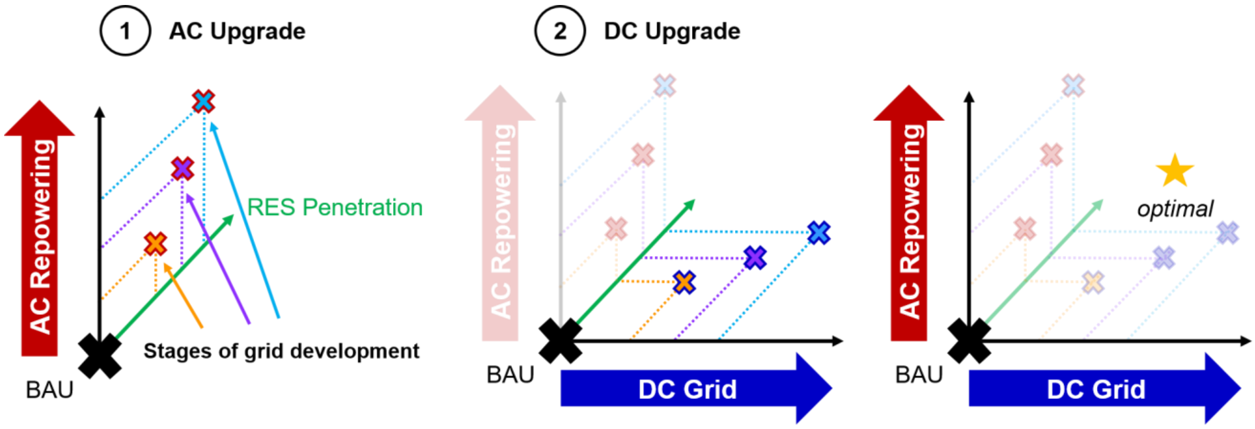

Figure 1: Schematic illustration of how the scalability assessment provides the bounds of the future European grid development.

The *combined upgrade scenario* builds on the *DC upgrade scenario* and determines for each stage of DC grid development the additional gains to be made under a concurrent AC grid development. In this context, we examine the potential of the technologies for repowering AC lines developed within Best Paths to increase the benefits of the underlying DC grid development stage. Furthermore, we also analyze the theoretical gains for each stage of DC grid development if (a) additionally to deploying the technologies for repowering AC lines, there were no limitations imposed by transformers and substations and (b) there were no limitations imposed by the AC grid at all. Note that the *combined upgrade scenario* only represents an approximation to the optimal Best Paths scenario highlighted in Figure 1.

We perform the scalability assessment on a high-resolution European transmission grid model with over 8000 nodes, ~9000 AC and DC transmission lines and ~1200 transformers. The grid model consists of the ENTSO-E network model for continental Europe, simplified network models for the UK and Scandinavia adapted from the eHighway 2050 project [1] as well as Ten Year Network Development Plan (TYNDP) 2016 projects [2] and projects of common interest defined by the European Commision [3] to be commissioned before 2030. As such, the network model represents the transmission grid for 2030 given that it already includes impending transmission projects from the TYNDP 2016, while the load and generation data still represents 2016 levels. In order to fully obtain a 2030 scenario, we first start by adjusting the load and generation data to reflect the observed conditions for 2016 as listed by ENTSO-E in their statistical factsheet and power statistics data base. We then use the load and generation projections for 2030 of the EUCO30 scenario developed by the European Commission to obtain the Business-as-Usual 2030 (BaU2030) scenario. We choose the EUCO30 scenario as it represents a core policy scenario modeling the 2030 climate and energy targets as agreed by the European Council in 2014 and serves as an official reference scenario for 2030 to analyze the potential impact of higher renewable energy deployment. We use the resulting BaU2030 scenario as a starting point for the scalability assessment.

The report is structured as follows: Section 2 outlines the data pre-processing for adjusting the data set of the European transmission grid, while the methodology for performing the transmission grid developments is described in Section 3. We perform the scalability assessment on a large scale case study representing the European transmission grid and present results in Section 4. Section 5 reviews the results and their implications and concludes.

BEST PATHS stands for "BEyond State-of-the-art Technologies for rePowering Ac corridors and multi-Terminal HVDC Systems". This project has received funding from the European Union's Seventh Framework Programme for Research, Technological Development and Demonstration under grant agreement no. 612748.

2. Developing the Business-as-Usual 2030 Scenario

2.1. Input Data

The deliverable "13.2 Definition and Building of BestPaths Scenario" led by CIRCE describes the development of the Business as Usual data set using a combination of a grid model provided by the European Network of Transmission System Operators (ENTSO-E), the ten year network development plan 2016 (TYNDP) [2], projects of common interest defined by the European Commision [3] and data from the e-Highway 2050 project [1]. The load and generation data for 2016 are based on ENTSO-E's statistical factsheet [3] and ENTSO-E's power statistic data base [4], while the projections for 2030 are based on the EUCO30 scenario developed by the European Commission [5]. All results obtained from the simulations and conclusions drawn from them are subject to these input data and dependent on their validity.

2.2. Adjusting Load and Generation Data to ENTSO-E Data for 2016

Due to the inclusion of the TYNDP projects, the data set developed in deliverabe 13.2 already contains the transmission system data for 2030, while the load and generation data still corresponds to the year 2016. In order to fully represent a 2030 scenario, this data needs to be adjusted to consider the nuclear phase-out in Germany [6] as well as the projected increase in electricity consumption and installed capacity of renewable energy sources (RES) [7].

Furthermore, the data set developed within the framework of deliverable 13.2 consists of the network model for voltage levels $V \geq 220\,kV$ (+ a few nodes with $V < 220\,kV$ which are needed to ensure connectivity). Thus, the connected loads represent net demand at the different nodes and already consider (RES) generation at lower voltage levels in the form of lower or negative demand. In Germany for example, 96% of the wind generation [8] and almost 100% of the PV generation [9] is connected to the distribution grid, which means that this share of RES generation is not visible in the data set and only represented through lower demand. This also entails that the installed generation capacities in the data set do not correspond to the official values provided by ENTSO-E [3].

However, in order to be able to upscale the load to projection levels for the year 2030, a more detailed differentiation is required. Otherwise, the upscaling of RES and load could not consider the generation on the distribution level.

To this end, this work takes the grid provided by CIRCE as basis and considers the RES sources in the data set as the share of RES connected to the transmission system. Then, using the power statistics database [4] and the ENTSO-E statistical factsheet [3], we derive the share of installed generation capacity on the transmission level by comparing the currently installed generation capacity in the original data set (for each type of generation separately) with the actual total installed capacity (given in [3]) on a per country basis. This gives us an estimate of how much energy is generated by the different generation types on the transmission and distribution level, respectively, which in turn allows us to determine the share of RES production in the net demand. Note that we do not assume any conventional generation on the distribution level but adjust the installed capacities of conventional generators on the transmission level (and thus, in the data set) to fully reflect the total installed capacity of conventional generation for each country individually. The data on electric energy generation and consumption per country are obtained from ENTSO-E's monthly domestic values reports [4]. Combined with the RES profiles given in CIRCE's data set, the energy E generated by the different RES types x on the distribution level E_x^{DL}, which is 'hidden' in the net demand, can be computed per country:

$$\mathrm{E}_{\mathrm{x,country}}^{\mathrm{CIRCE}} = \sum_{\mathrm{h=1}}^{8760} \sum_{\mathrm{i=1}}^{\mathrm{N_{country}}} \mathrm{P}_{\mathrm{gi,x,country}}^{2016}(\mathrm{h}),$$

$$\mathrm{E}_{\mathrm{x,country}}^{\mathrm{DL}} = \mathrm{E}_{\mathrm{x,country}}^{\mathrm{ENTSOE}} - \mathrm{E}_{\mathrm{x,country}}^{\mathrm{CIRCE}},$$

$$x \in \Psi = \{\text{wind, solar, geo-thermal, hydro, bio fuel, other RES}\},$$

where $N_{country}$ represents the number of nodes in the corresponding country. The net demand of the entire country is calculated by fitting the wind $E^{DL}_{wind,country}$ and solar energy $E^{DL}_{PV,country}$ on the distribution level to wind and solar generation profiles taken, if available, from the CIRCE database or from [10], [11], [12], otherwise. If the data set already contains more than one profile for a specific country, these profiles are interpolated and then fitted to the required energy level:

$$P_{gx,country}(h) = P_{gx,country}(h) \cdot \frac{E^{DL}_{x,country}}{\sum_{h=1}^{8760} P^{2016}_{gx,country}(h)}$$

Generated energy from other RES sources in the distribution level (geothermal, hydro, bio-fuel, renewable waste, others [4]) is uniformly distributed over the whole year due to missing generation profiles. The net demand curves of the different countries $E_{netdemand,country}$ can be computed by subtracting the different distribution level profiles from the electricity consumption profile obtained from ENTSO-E's power statistic data base:

$$E_{netdemand,country} = E_{consumed,country} - \sum_{i=1}^{|\Psi|} E^{DL}_{i,country}$$

The total load of Germany as well as the net demand and the power produced by different RES sources on the distribution level over the course of a whole year is visualized in Figure 2: Visualization of the disaggregation of the total load in net demand and RES production on distribution level for the example of Germany.

The computed net demand is distributed among the different nodes in the countries according to the load values $P_{l,Node\ k,country}$ given in ENTSO-E's grid model.

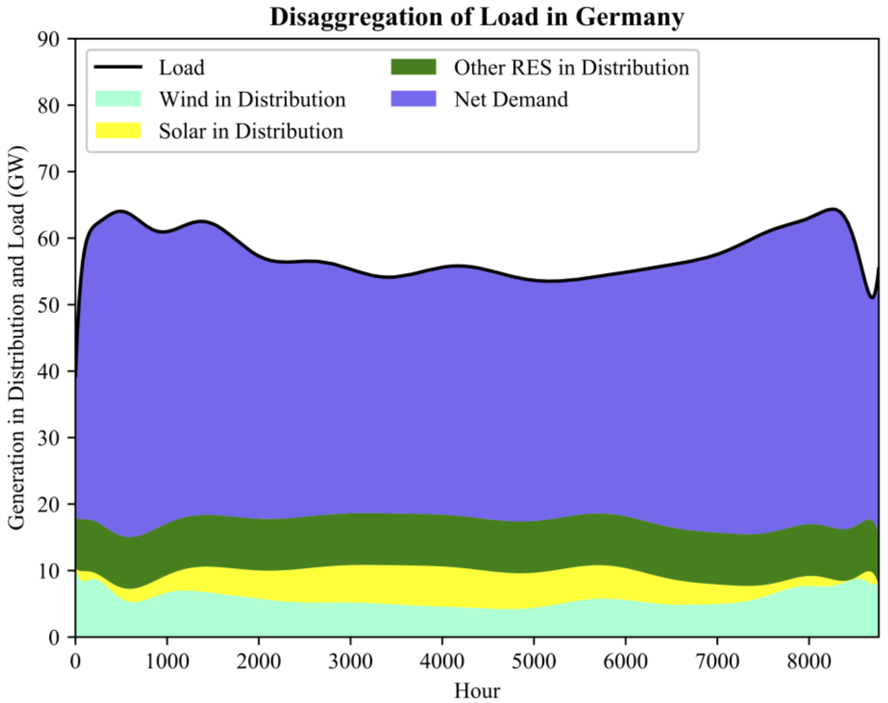

Figure 2: Visualization of the disaggregation of the total load in net demand and RES production on distribution level for the example of Germany

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$$E_{\text{netdemand,Node k,country}} = E_{\text{netdemand,country}} \cdot \frac{P_{\text{l,Node k,country}}}{\sum_{i=1}^{N_{\text{country}}} P_{\text{l,Node i,country}}}$$

Pumped hydro storage power plants are assumed to be able to operate annually for a limited number of hours. We determine the number of hours during which pumped hydro storage power plants are allowed to operate based on the actual generated energy provided in the ENTSO-E statistical factsheet for 2016 [3] and the installed pumped hydro capacity per country. The hours are allocated to the periods with high demand and low availability of other renewable energy (i.e., wind and solar).

The electricity production of run-of-the-river and other hydro power plants depends on seasonal river flows and reservoir/pondage limitations, which often prevent the hydroelectric power plant from operating (at higher output levels). Hence, most hydroelectric power plants are not always dispatchable to their maximum possible level. In order to consider these limitations, we reduce their installed capacities, such that even when operating during each hour of the year at maximum capacity, their production would not exceed the observed hydroelectric energy production in 2016 [3] on the transmission level. The alternative approach to limit the number of operating hours as applied to pumped hydro storages leads to a lot of infeasible hours due to the lack of sufficient base generation. Not changing the installed capacity of run-of-the-river and other hydroelectric power plants (except for pumped storages) while considering them dispatchable throughout the entire year leads to unrealistically high hydro production levels and would not reflect the actual 2016 production levels as listed by ENTSO-E. Therefore, we choose to adjust their installed capacity levels instead while assuming them dispatchable during each hour of the year.

Following this approach, the RES penetration level can be evaluated accurately considering not only the 'visible' RES generation on the transmission level but also the 'hidden' generation on the distribution level. Furthermore, this approach allows us to (a) adjust the load and generation data as accurately as possible to the ones given in the 2016 monthly domestic values reports from ENTSO-E [4] and (b) better include 2030 load and generation projections, as shown in the following section.

2.3. Including Load and Generation Projections for 2030

The scenario for 2030 is based on the EUCO 2030 scenario developed by the European Commission [6]. The scenario reflects the achievements of the 2030 climate and energy targets as agreed by the European Council in 2014 and includes an energy efficiency target of 30% [8].

The following section describes the required upscaling of the load and the different RES generation sources.

ENTSO-E provides a detailed list of installed capacity projections per generation technology on a per country basis for the EUCO 2030 scenario [8]. We adjust the installed generation capacities in our data set c^{2016} to the projected levels for 2030 c^{2030} by determining an upscaling factor per generation type on a per country basis, $up_{x,country}^{2030}$:

$$up_{x,country}^{2030} = \frac{c_{x,country}^{2030}}{c_{x,country}^{2016}}$$

$$P_{gx,node\ y,country}^{2030}(h) = up_{x,country}^{2030} \cdot P_{gx,node\ y,country}^{2016}(h).$$

Furthermore, the actual load within the net demand is also upscaled according to the given values using the same approach. Finally, the installed capacity P_{max} all nuclear power plants in Germany is set to zero considering the planned nuclear phase-out.

Thus, this approach allows to fit the model as accurately as possible to the EUCO 2030 scenario developed by the European Commission [6]. The data for 2016 and 2030 is given on a per country basis in the appendix.

3. Methodology for the Transmission Upgrade Scenarios

All transmission upgrade scenarios are performed for an entire year (i.e., 8760 hours) using DC optimal power flow (DC-OPF) simulations and annual time series for load and renewable energy generation. The DC-OPF is a linear optimization problem widely used in power system operations and electricity market clearing, which minimizes total generation cost and thus, determines the optimal active power generation dispatch, which satisfies all demand under consideration of generator active power limits and active power line flow limits. Note that reactive power and transmission losses are neglected. Despite the availability of sufficient generation capacities, line congestions might prevent to fully supply all demand during certain hours of the year. Therefore, we include the possibility of shedding load, which is a reasonable assumption given that it is common practice to disconnect contracted industrial loads with own generation capabilities in case of a transmission capacity shortage. We minimize, however, the amount of unsupplied load by penalizing the corresponding variable with a high cost in the objective function. This way, load shedding is only applied as a last resort to ensure feasibility and thus, a guaranteed solution of the optimization problem.

Due to the fact, that detailed investment costs of the different technologies are not available

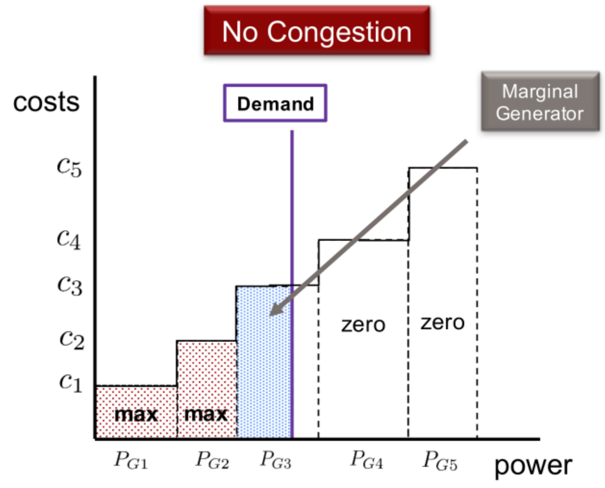

Figure 4: Merit-order curve without a congestion in the system

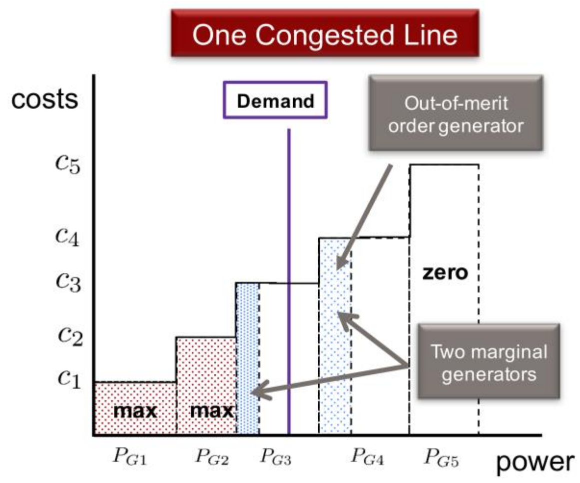

Figure 3.: Merit-order curve with a congestion in the system

and very project specific, our assessment does not consider investment costs but aims at increasing social welfare by a reduction of operating costs. The reduction of operating costs per year serves, however, as an indicator for maximum acceptable investment costs. Furthermore, by aiming at maximizing social welfare, we simultaneously maximize the RES penetration level as RES have zero marginal cost and are ranked first in the marginal cost curve. In [13], the author showed that increasing social welfare is equivalent to relieving congestions, which is visualized in Figure 3.: Merit-order curve with a congestion in the system.

Under the availability of sufficient transmission capacity (i.e., no congestions; Figure 4: Merit-order curve without a congestion in the system), the merit order of the generators when dispatched to supply the demand can be satisfied. In this case, there is only one marginal generator, which is the last one in the merit order to be dispatched to satisfy the demand, i.e., the most expensive one, which sets the price and is only dispatched as much as needed (usually below its capacity limit) to cover the remaining demand. A single congestion, however, might prevent a cheaper generator with sufficient capacity to supply the remaining demand to be dispatched to the required levels as the grid cannot absorb higher power injection levels at the generator's connection point. Given that the congestion prevents a cheap generator in the merit order curve (often a renewable energy generator with very low marginal cost) to produce as

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much power as required to satisfy the demand, another more expensive 'out-of-merit-order' generator is additionally required to be dispatched. This increases the total generation cost and thus, reduces social welfare as well as renewable energy penetration. Therefore, the primary target of all upgrade scenarios is to increase the transmission capacity and reduce grid congestions.

3.1. AC Upgrade Scenario

The technologies for repowering AC transmission lines developed within demo 4 focus on High Temperature Low Sag (HTLS) transmission lines and Dynamic Line Rating (DLR), both of which can increase the efficiency and transmission capacity of already existing lines. Given that the demonstrated technologies focus on AC line repowering only, we do not consider the option of placing new AC transmission lines but only focus on repowering already existing ones. The benefits of the Best Paths technologies for repowering AC lines are also constrained by the capabilities of the substations, which are the determining factor for the improvement potential of already existing lines.

As all participants agreed on during the workshop on feedback to the WP13 questionaires in Brussels on 22nd and 23rd of February 2017, DLR and HTLS can increase the transmission capacity of a line by up to 20% and 100%, respectively. In order to define the optimal bound along the *AC upgrade axis*, which the Best Paths technologies could facilitate, we allow the flow on all transmission lines (i.e., not including transformers) to exceed the capacity limit by 100% and evaluate the required capacity increase ex-post. Any required increase below 20% could be faciliated by both HTLS and DLR, while HTLS is the only upgrade option for increases above 20%.

Additionally, we also analyze the theoretical bounds of (a) using Best Paths technologies for repowering AC lines but having no limitations imposed by transformers and substations (i.e., leaving them unconstrained in the optimization problem) and (b) assuming no limitation by neither AC lines nor transformers and substations at all (i.e., only considering the limitation of the DC lines). Both theoretical analyses can serve as a benchmark for the 2030 AC grid development.

3.2. DC Upgrade Scenario

Four of the five demonstrations within the BestPaths project focus on DC technology. While DEMO 1 aims on reducing risks of HVDC links connecting offshore wind farms, DEMO 2 focuses on multivendor interoperability. DEMO 3 on the other hand investigates potential upgrade scenarios of multi-terminal HVDC links with the specific example of the SACOI link. DEMO 5 works on a prototype scale validation of the technical feasibility of integrating DC superconducting cable links within an AC meshed network.

In this scalability assessment we collected DEMO 1-3 within the DC scalability assessment, because given the aim of the study, as well as the size of the test network, a clear separation between the demonstrators becomes infeasible. In fact, the combined success of all three demonstrators is a prerequisite for our assumption of being able to up-scale single HVDC links to an pan-European network.

DEMO 5 and the superconducting cables are not considered in this study given the limited length of the cables and their area of application being dense populated areas which are represented as single nodes in the high-resolution European transmission grid model.

Within the DC Scalability assessment the focus lies on expanding the current European electricity network by building new HVDC interconnections enabling controllable high power flows along specific transmission corridors over long distance with comparable low losses. Thus, besides additional transmission capacity to relief congestions, HVDC interconnections increase the controlability of the system enabling to route power directly from one specific node to the other allowing to circumvent congestions in the vicinity of the low-cost marginal generator. Furthermore, HVDC interconnections allow a higher integration of offshore wind energy, due to

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the fact that many offshore locations located far away from shore are only accessible by HVDC technology. Finally, additional transmission capacity with controllable flows will enhance the trading capacity between the different countries which is expected to result in significant cost reductions. However, due to the significant investment cost for new HVDC interconnections, every new line should carefully be planned resulting in a high utilization of the new asset and an operating cost reduction making the investment feasible. Thus, the transmission expansion planing, or specifically in this case the problem of choosing the right location for new HVDC interconnections is not trivial considering the size of the European transmission network even without taking all non-technical issues as e.g. social acceptance of new lines into account.

In [13], the author showed that increasing social welfare is synonymous to the relief of existing congestions. The authors relate the number of congestions in a network to the number of marginal generators, i.e. generators which are dispatched neither at their minimum nor at the maximum limit. They prove that in any system an additional line connecting a low-cost marginal generator, i.e with a cost equal or lower than the system marginal cost, with a high-cost marginal generator, i.e. with a cost higher than the system marginal cost, will relieve at least one congested line and enable the low-cost marginal generator to substitute the high-cost marginal generator and by that increase social welfare. Based on this observation the authors developed a methodology for HVDC placement for maximizing social welfare which is based on adding a line with the objective of setting the dispatch of the out-of-merit order generator to zero.

Following this approach, we adapt it to our system under investigation. We analyze a high-resolution European transmission grid model with varying production and demand over a time frame of a whole year. Therefore, we observe varying congestions and marginal generators over the year. Thus, we determine for every generator the number of hours it is neither producing at its minimum nor at its maximum limit ($h_{marg,i}$) and we determine the amount of energy it could potentially produce additionally (in case of low-cost marginal generator) and the amount of energy we potentially need to substitute respectively (in case of a high-cost marginal generator.) Finally, by combining these two features, i.e. the number of hours and the amount of energy of the marginal generator, we create two parameters $e_{low-cost,i}$ and $e_{high-cost,i}$ determining the potential value for every generator i to be interconnected with an marginal-generator of the opposite type (low-cost / high-cost). These parameters represent basically the amount of energy available / needed at the specific node weighted with the amount of hours in which this energy is available / needed with respect to the total amount of hours considered, i.e. the parameters serve as a good indicator for the potential utilization of a HVDC line interconnecting marginal generators:

$$e_{low-cost,i} = \frac{|h_{marg,i}|}{8760} \cdot \sum_{h=1}^{|h_{marg,i}|} P_i\left(h_{marg,i}(h)\right)$$

$$e_{high-cost,i} = \frac{|h_{marg,i}|}{8760} \cdot \sum_{h=1}^{|h_{marg,i}|} \left(\left(P_i^{max}\left(h_{marg,i}(h)\right) - P_i\left(h_{marg,i}(h)\right)\right) - P_i^{min}\left(h_{marg,i}(h)\right)\right)$$

$$h_{marg,i} = \{h = 1, \dots, 8760 \quad \forall\ P_i^{min}(h) < P_i(h) < P_i^{max}(h)\}$$

Thus, parameter $e_{low-cost,i} \geq \epsilon_1$ and $e_{high-cost,i} \geq \epsilon_2$ justify the significant investment of building a new HVDC inter-connection between these marginal generators.

After ranking the marginal generators according to $e_{low-cost}$ and $e_{high-cost}$, we determine heuristically the top ranked marginal generators to be interconnected based on the distance between them. Given the potential large distances between low-cost and high-cost marginal generators, a inter-connection of a low-cost and a high-cost marginal generator may be performed by inter-connecting another high-/low-cost marginal generator in between.

The DC scalability assessment is performed step-wise in order to be able to react to changed power-flows due to the added transmission capacity.

3.3. Combined Upgrade Scenario

The *combined upgrade scenario* is based on the *DC upgrade scenario* and examines potential improvements for each stage of DC grid development by upgrading the underlying AC grid. Similarly to the AC scalability assessment, we first evaluate the benefits of deploying the Best Paths technologies for AC line repowering at each step performed during the DC scalability analysis. We then look at the additional benefits to be gained when neglecting transformer limitations and in a third step, when neglecting the AC grid limitations as a whole. This allows us to assess the impact of the added DC lines on the AC grid and the interactions between the two transmission upgrade/expansion approaches.

4. Case Study - The European Transmission System

We perform the scalability assessment of the Best Paths technologies on a network model representing the European transmission system in 2030. It includes impending transmission projects from the TYNDP 2016 to be commissioned before 2030 as well as projections for load and generation based on the EUCO30 scenario. The AC grid of the network model consists of 7474 buses, 8787 transmission lines, 1148 transformers, 1269 generators and 3361 loads. The DC grid consists of 72 point-to-point DC lines with 144 converters stations and 144 DC buses. There is no load or generation connected to the DC grid. The generators are grouped in the following six categories with the number of generators belonging to the corresponding category indicated in parentheses: conventional (765), run-of-the-river hydro power plants and hydro reservoirs (87), pumped hydro storage power plants (84), solar power plants (42), offshore wind generators (43) and onshore wind generators (248). The data for (net) demand, renewable energy production on the distribution level, which is accounted for in the net demand, and maximum achievable RES penetration level are listed in Table 1: Characteristics of European transmission network 2030 The maximum RES penetration level is calculated based on the renewable energy available from hydro, solar and wind generators and already accounts for the time periods during which renewable energy availability exceeds the demand and needs to be spilled in order to maintain power balance across the entire network. The DC-OPF simulations are carried out on an hourly basis for a whole year (i.e., 8760 hours). Generator cost functions are assumed to be linear. Load shedding is penalized with 300 €/MWh, which is higher than the maximum cost of generation (162.79 €/MWh) and thus, incentivizes to supply the load rather than to disconnect it. Note that the cost of load shedding is usually assumed much higher but in this case needs to be appropriately scaled as high values out of scale with the rest of the cost parameters might raise numerical issues.

Table 1: Characteristics of European transmission network 2030

Net demand (TWh)	RES production in distribution (TWh)	Demand (TWh)	MAX. RES penetration (%)
2733.10	786.60	3519.70	56.47

4.1. Performance Indicators of the Scalability Assessment

The primary target of the scalability assessment is to increase the transmission capacity and reduce grid congestions, which in the context of this case study is equivalent to increasing social welfare and RES penetration levels. To this end, we use the key performance indicators (KPIs) defined in WP2 of the Best Paths project and listed in Table 2: Performance indicators of the scalability assessment for evaluating the results of the different upgrade scenarios.

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Table 2: Performance indicators of the scalability assessment

RES Penetration (%)	Share of total load supplied by renewable energy sources: $\frac{\sum_{g \in \mathcal{G}^{RES}} E_g}{\sum_{n \in \mathcal{N}} E_n^D}$
RES Curtailment (%)	Share of available renewable energy not dispatched due to congestions: $\frac{\sum_{g \in \mathcal{G}^{RES}} E_g^{max} - E_g}{\sum_{g \in \mathcal{G}^{RES}} E_g^{max}}$
Load Shedding (%)	Share of energy demand not supplied due to congestions: $\frac{\sum_{n \in \mathcal{N}} E_n^{shed}}{\sum_{n \in \mathcal{N}} E_n^D}$
Generation Cost (€)	Annual generation cost: $\sum_{g \in \mathcal{G}} c_g \cdot E_g$
Objective Function Value (€)	Annual cost of generation and load shedding: $\sum_{g \in \mathcal{G}} c_g \cdot E_g + \sum_{n \in \mathcal{N}} c^{shed} \cdot E_n^{shed}$

E_g Annual energy produced by generator g (MWh).
$\mathcal{N}$ Set of nodes.
$\mathcal{G}^{(RES)}$ Set of (renewable) generators.
c_g Marginal cost of generator g (€/MWh).
E_g^{max} Annual available energy of generator g (MWh).
E_n^D Annual energy demand at node n (MWh).
E_n^{shed} Annual energy demand not supplied at node n (MWh).
c^{shed} Cost of load shedding (€/MWh).

4.2. Evaluation of the BaU2030

The main results of the BaU2030 without any grid reinforcements are visualized in Figure 5: Load and generation 2030 and Figure 6:Available vs. dispatched power of the different RES. The dark areas represent RES spillage Figure 5: Load and generation 2030 shows the annual dispatch of the different generation categories and the amount of load shedding. 22.35% of the demand is covered by distributed generation on lower voltage levels, while the remainder is covered by generators on the transmission level. The RES penetration level reaches 52.84% and exceeds the penetration level of 50%, which has been projected by the EUCO30 scenario, mainly due to different modeling approaches. The EUCO30 projections have been evaluated using a high-level energy modeling approach based on a mixed complementarity problem, which simultaneously accounts for several different energy objectives (such as energy efficiency targets etc.) and does not account for a high-resolution transmission grid model. Additionally, our assumption on the share of renewable energy generation in the transmission and distribution systems might be another source causing discrepancies. 0.94% of the total load is shed due to grid congestions. Specifically, most of the load shedding occurs in Sweden, Norway and Finland (67.78%), where a simplified grid representation based on the eHighway 2050 project has been developed and is used. This simplified grid representation consists primarily of DC lines, which exhibit a high congestion level due to large exports of hydro and other renewable power to continental Europe. Most of the remaining load shedding occurs in France (30.66%) due to AC grid congestions and particularly transformer congestions.

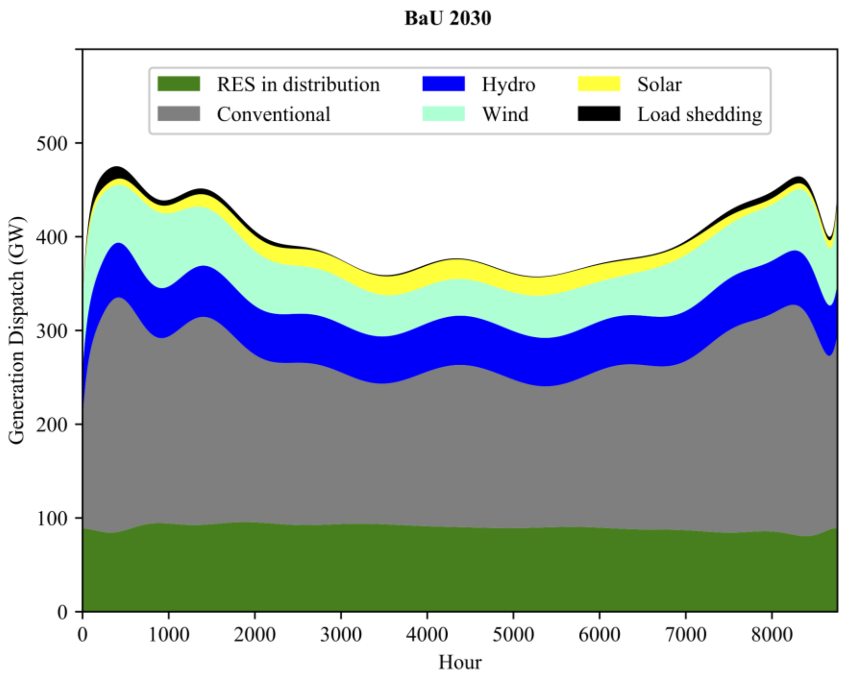

Figure 5: Load and generation 2030

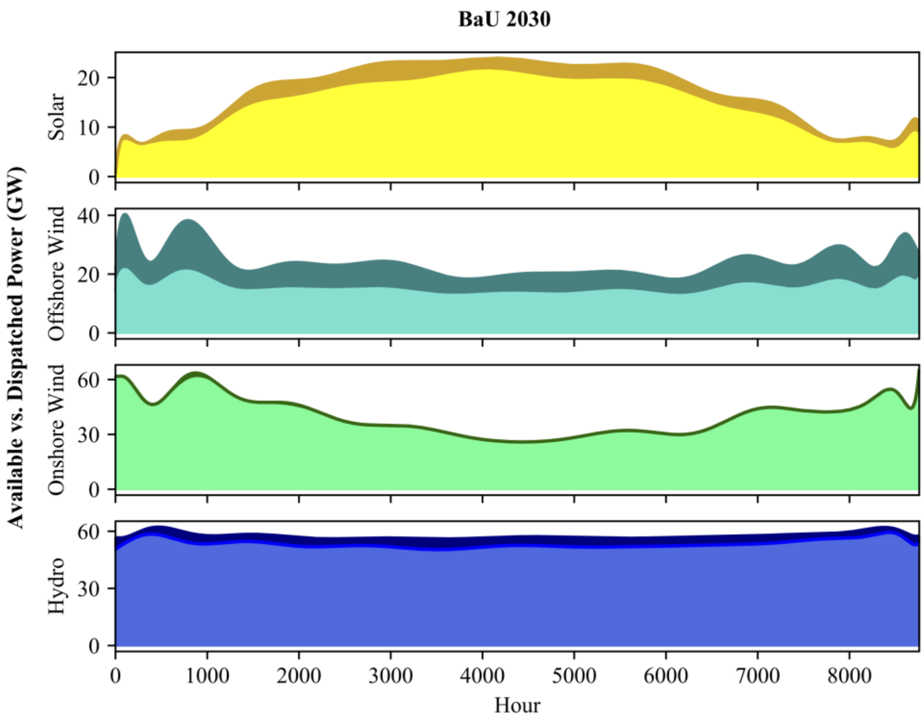

Figure 6:Available vs. dispatched power of the different RES. The dark areas represent RES spillage.

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Figure 6:Available vs. dispatched power of the different RES. The dark areas represent RES spillage depicts the dispatched renewable energy with respect to the available energy for each renewable generation category. The bottom subplot contains all sources of hydro power. As expected, solar power has a peak during the summer months whereas both offshore and onshore wind power are largely available during the winter months. Hydro power has a fairly constant generation profile due to our modeling assumptions of run-of-the-river power plants and hydro reservoirs described in Section 2. Pumped hydro storages do not have a significant impact on the hydro generation profile due to relatively low installed capacities, such that they only supply 1.89% of the total load. The dark areas represent renewable energy curtailment, which amounts to 138.31TWh or 12.10% of the total renewable energy available. It can be seen that there is still potential for increased levels of RES penetration if the available renewable energy could be transported away from where it is generated. Specifically, offshore wind farms and solar generators curtail 36.39% and 15% of their available energy, respectively, which largely accounts for the gap between the current RES penetration level and the maximum achievable of 56.47%. Table 3: Results of BaU 2030 lists the main results of the BaU2030 including the annual generation cost and the objective function value, which additionally to the generation cost also includes the cost of load shedding.

Table 3: Results of BaU 2030

RES penetration (%)	**RES curtailment (%)**	**Load shedding (%)**	**Generation cos (B€/a)**	**Obj. fct. Value (B€/a)**
52.84	12.10	0.94	50.08	57.94

4.3. AC Upgrade Scenario

Grid congestions are the main cause for not being able to fully dispatch all renewable power, which is available. Within the AC scalability assessment we evaluate how Best Paths technologies for AC reinforcements could contribute to releasing congestions and thus, increasing both the RES penetration level and social welfare. Table 4: Results of AC Scalability lists the main results, where *BP reinforcements* denotes the results considering transmission upgrades using Best Paths technologies for AC line repowering only. *BP reinforcements w/o transformer limits* denotes the case using BP reinforcements but neglecting substation and transformer limitations, while $AC \rightarrow \infty$ represents the outermost bound on the *AC upgrade axis* without any AC grid limitations at all.

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Table 4: Results of AC Scalability

	RES penetration (%)	RES curtailment (%)	Load shedding (%)	Generation cost (B€/a)	Obj. fct. Value (B€/a)
BP reinforcements	53.03	11.56	0.94	49.77	57.44
BP reinforcements w/o transformer limits	53.34	10.82	0.63	48.70	53.59
AC → ∞	54.00	8.58	0.63	47.10	52.37

Load shedding remains unchanged in the *BP reinforcements* case as the increased levels of load shedding in France are due to transformer congestions, while the load shedding in Scandinavia is caused by congestions on DC lines, which remain largely unaffected by AC grid reinforcements. This becomes apparent in the *BP reinforcements w/o transformer limits* scenario, where load shedding in France is completely avoided and only remains in Scandinavia.

Figure 7: Renewable energy curtailment for each renewable generation category shows the change in RES curtailment for each RES generation category individually. Solar, onshore wind and hydro power curtailment is decreased to a greater degree than offshore wind, which indicates that AC grid reinforcements alone cannot accommodate the available offshore energy and benefit mostly the dispatch of continental generation distributed throughout the AC grid.

An increase in RES penetration level of 0.19% can be achieved under the *BP reinforcements* scenario, while additionally 0.13% can be added to that under the assumption of sufficient capacity in the substations. Note that transformer upgrades without any additional AC line

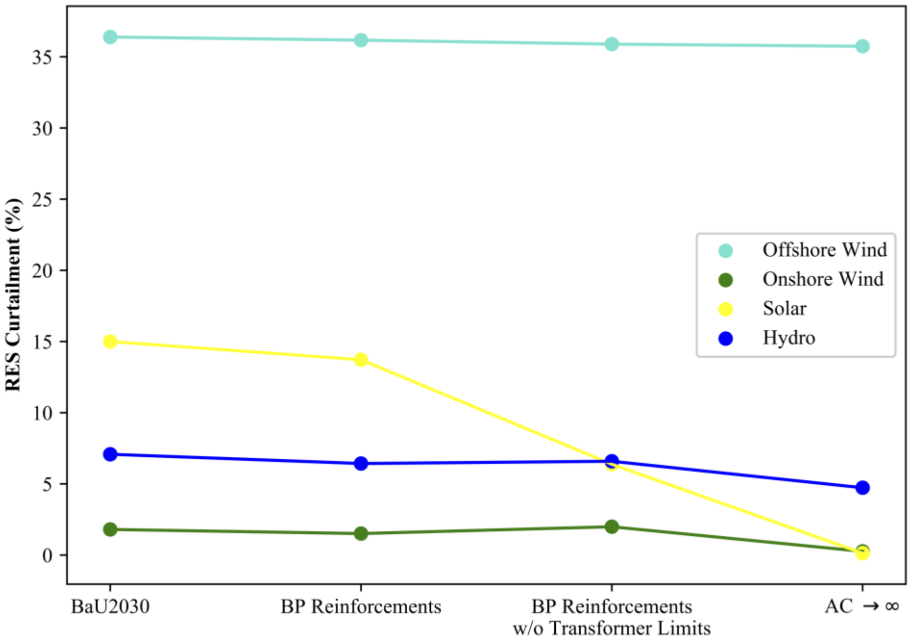

Figure 7: Renewable energy curtailment for each renewable generation category

repowerings cause an increase in RES penetration of 0.15% showing that transformer upgrades are not as effective as the *BP reinforcements*, which alone achieve 0.19%. However, in combination the effect of both upgrade measures are reinforced resulting in an increase of 0.5% to 53.34%. The RES penetration level increases as expected through added transmission capacity but cannot exceed 54% through AC grid reinforcements only and thus, cannot reach the maximum possible penetration level. This and the fact that most of the RES curtailment occurs offshore highlights the need for new transmission corridors, which will transport the power produced at remote offshore locations to consumption centers. Nonetheless, the *BP reinforcements* case results in annual generation cost savings of 310M€ at a required total transmission capacity increase of 11.83GW distributed among 21 AC lines. The required increase corresponds to only 0.03% of the current installed AC transmission capacity.

4.4. DC Upgrade Scenario

The DC upgrade scenario is developed in a step-wise approach allowing to account for the change in power flows due to the added transmission capacity. The development is stopped as soon as $\mathrm{e}_{\mathrm{low-cost}} \leq \epsilon$, which indicates that the highest ranked low-cost marginal generator does not offer enough spillage throughout the year to justify the significant investment costs of an additional DC line. The following subsections will present the step-wise placement of the DC lines, while the main findings of all steps will be summarized in the last subsection as well as in Section 4.5, where we discuss the results of the combined upgrade scenario.

All lines are considered to be built as bipole with a total transmission capacity of 3GW, which has been identified as upper bound for HVDC interconections in Europe by the BestPaths partners during the workshop on feedback to the WP13 questionaires in Brussels on 22nd and 23rd of February 2017. Based on the load duration curves obtained form the simulations the sizing of the lines can potentially be improved afterwards.

4.4.1. Step 1

The first step of the DC scalability assessment uses the BaU 2030 scenario as base case to determine the marginal generators (listed in Table 5: List of top ranked low-cost marginal generators in step 1 and Table 6: List of top ranked high-cost marginal generators in step 1). The added HVDC interconnections are visualized in Figure 9: Step 1 of the DC upgrade scenario (note that the connection points shown on the map is a rough approximation of the actual locations). The analysis of the BaU 2030 scenario already showed that the highest spillage of energy over the year can be observed at the offshore wind farms which is reflected by the top ranked low-cost marginal generators. The high-cost marginal generators on the other hand are located mainly in the UK / Scandinavia and Eastern Europe, i.e. far away from the low-cost marginal generators.

Given the large distance between the offshore wind farms in the North sea and the high-cost marginal generators, two lower ranked low-cost marginal generators ('84NO', 'DK916183') are taken as intermediate points allowing to transfer the generated power from the North sea to Sweden and Eastern Europe.

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Table 5: List of top ranked low-cost marginal generators in step 1

Name	Bus ID	h_{marg} (h)	Energy spillage (TWh)	$e_{low-cost}$
'ES916537'	2169	2627	21.79	6.53
'offshore2'	7465	6662	7.37	5.61
'offshore3'	7469	7008	5.72	4.58
'offshore22'	7466	6333	5.52	3.99
'offshore14'	7460	6681	4.84	3.69
'offshore8'	7474	6620	4.42	3.36
'offshore5'	7471	6671	4.05	3.13
'offshore4'	7470	6563	4.04	3.03
'84NO'	30	1999	0.28	0.06
'DK916183'	2046	619	0.48	0.034

Table 6: List of top ranked high-cost marginal generators in step 1

Name	Bus ID	h_{marg} (h)	Energy spillage (TWh)	$e_{low-cost}$
'AC_95uk'	78	4218	3.89	1.92
'AC-92uk'	67	1916	8.03	1.76
'PL925636'	6664	3832	3.33	1.45
'AC_94uk'	77	2066	5.39	1.27
'AC_96IE'	81	3336	3.10	1.18
'BG911342'	389	8712	0.86	0.86
'74FI'	1	8195	0.74	0.70
'88SE'	47	6542	0.91	0.68
'CZ912108'	652	1679	2.92	0.56
'ES917371'	2769	2310	1.22	0.32

All added dc lines combined transfer 260.26TWh over the whole year which corresponds to an average utilization of 71%. This indicates a high usage of the assets and an increased trading between the countries. The load duration curve of every added DC line is shown in Figure 8: Load duration curve of DC lines added during step 1 of the DC scalability assessment. Most of the new assets are used throughout the entire year at a high rate achieving average rates of $P_{dc} \geq 60\%$ of the line rating. Only two lines ('88SE'-'74FI' / 'offshore3'-'AC_95uk') indicate a

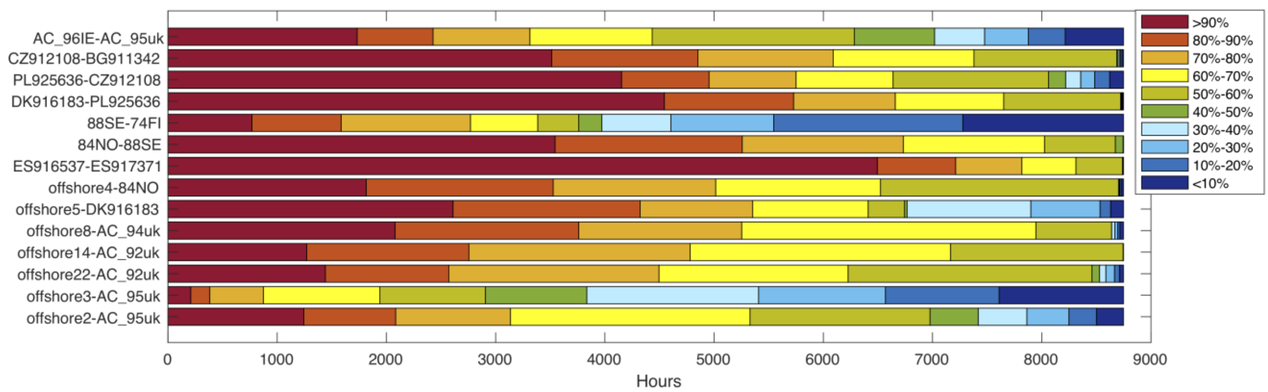

Figure 8: Load duration curve of DC lines added during step 1 of the DC scalability assessment

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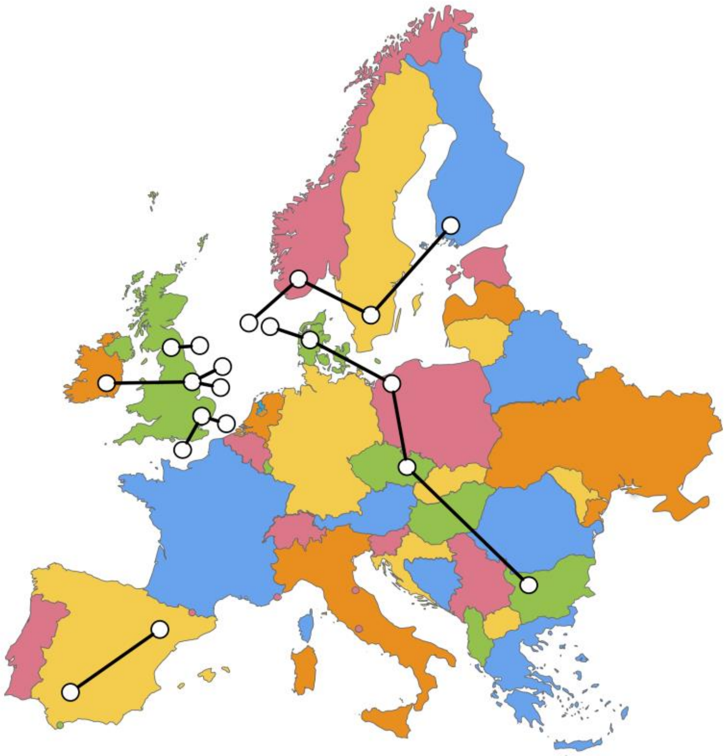

Figure 9: Step 1 of the DC upgrade scenario

comparable low usage with average usage rates of $P_{dc} \approx 40\%$ of the line rating. In these cases a lower line rating might be feasible considering potential cost reductions.

4.4.2. Step 2

The second step of the DC scalability assessment uses the simulation results of step 1 as base case to determine the marginal generators (listed in Table 7: List of top ranked low-cost marginal generators in step 2 and Table 8: List of top ranked high-cost marginal generators in step 2). The added HVDC interconnections are visualized in Figure 10 (note that the connection points shown on the map is a rough approximation of the actual locations). The top ranked low-cost marginal generators still reflect the high spillage of energy at the offshore wind farms observed in the BaU 2030 scenario. However, it is worth emphasizing that the spillage at the marginal generators of stage 1 is significantly reduced and other offshore nodes are identified as marginal generators (with lower $e_{low-cost}$ values). The majority of the high-cost marginal generators on the other hand are located in Eastern Europe, i.e. far away from the low-cost marginal generators.

Given the large distance between the offshore wind farms in the North sea and the high-cost marginal generators in Eastern Europe, the node 'PL925636', in the previous step identified as high-cost marginal generator, serves as interconnection point between Denmark ('DK916155') and the Czech Republik ('CZ912108'/'CZ911895').

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Table 7: List of top ranked low-cost marginal generators in step 2

Name	Bus ID	h_{marg} (h)	Energy spillage (TWh)	$e_{low-cost}$
'ES916537'	2169	2575	20.35	5.74
'offshore1'	7457	6574	4.04	3.03
'Offshore11'	6476	6500	3.73	2.77
'offshore10'	7458	6586	3.45	2.59
'offshore6'	7472	6669	3.40	2.59
'offshore12'	7459	6518	3.43	2.55
'offshore7'	7473	6682	3.55	2.71
'offshore18'	7464	6437	3.49	2.57
'offshore17'	7463	6493	3.32	2.46

Table 8: List of top ranked high-cost marginal generators in step 2

Name	Bus ID	h_{marg} (h)	Energy spillage (TWh)	$e_{low-cost}$
'BG911091'	373	6103	0.8913	0.6210
'CZ912108	652	7371	0.7311	0.6152
'ES917371'	2769	1809	2.8493	0.5884
'AC_92uk'	67	1107	4.3101	0.5447
'DK916155'	2040	7713	0.2642	0.2323
'HU922598'	5533	6374	0.3149	0.2291
'CZ911895'	596	4903	0.3129	0.1752
'HU922547'	5504	8601	0.1738	0.1706

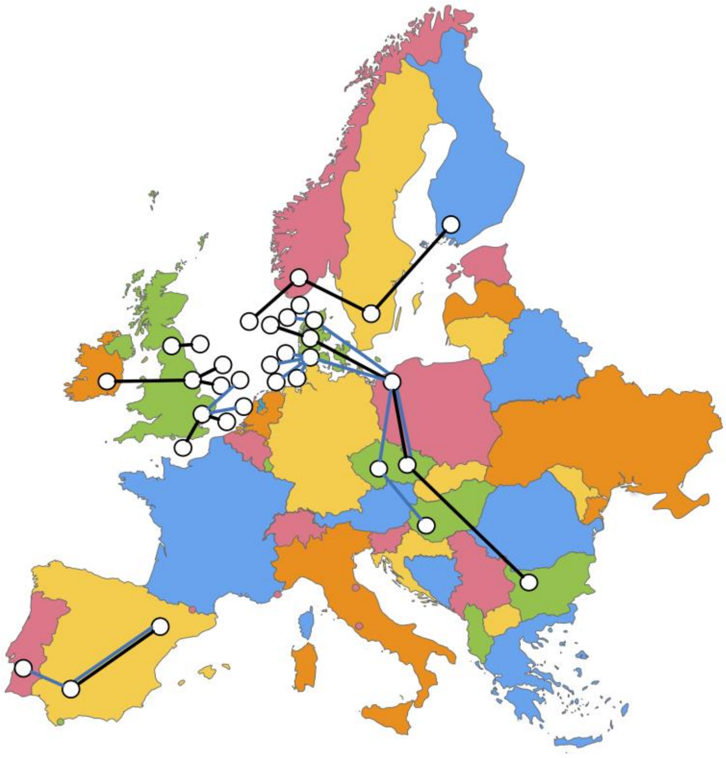

Figure 10: Step 2 of the DC upgrade scenario. Lines added in step 1 are marked in black, while lines added in step 2 are marked in blue.

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'PT925931'	6794	8097	0.1817	0.1680
'DK916424'	2114	8290	0.1247	0.1180

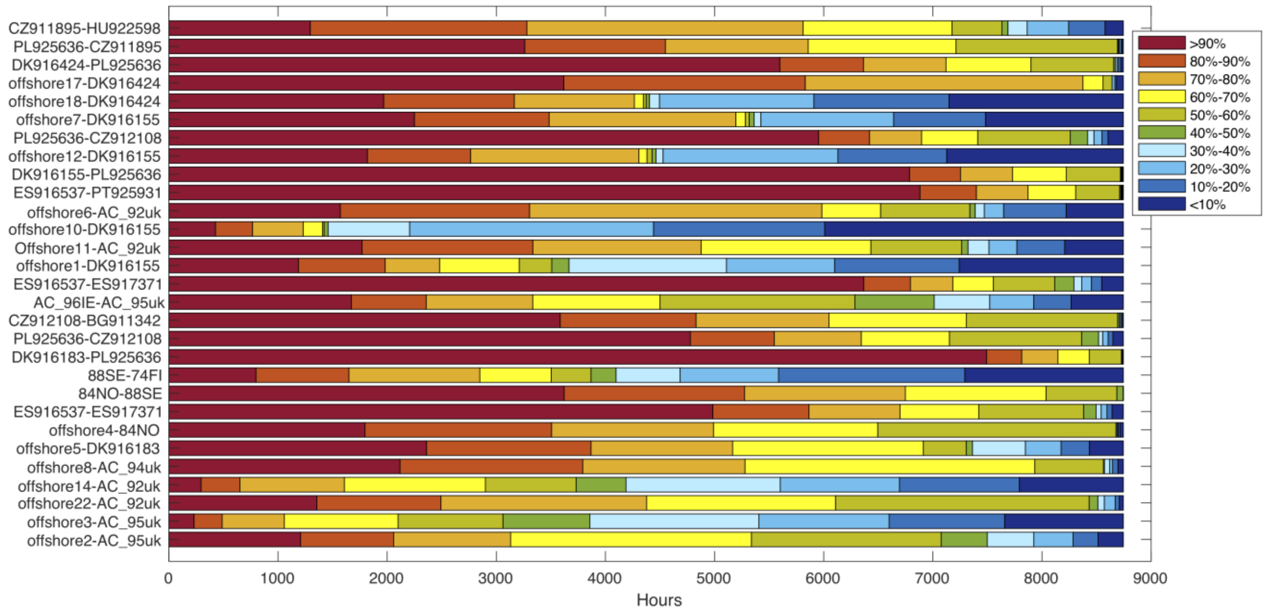

Figure 11: Load duration curve of DC lines added during step 1 and 2 of the DC scalability assessment

All added dc lines (step 1 & 2) combined transfer 530.6TWh over the whole year which corresponds to an average utilization of 70%. This indicates a high usage of the assets and an increased trading between the countries. The load duration curve of every added DC line is shown in Figure 11: Load duration curve of DC lines added during step 1 and 2 of the DC scalability assessment. Note that the addition of 'offshore6'-'AC_92uk' reduced the usage of the previously installed line 'offshore14'-'AC_92uk'. Thus, the installed capacity of those lines may be optimized with respect to asset usage rate but this is out of the scope of this analysis. Furthermore, note that the low usage rate of the line 'offshore10'-'DK916155' is not indicating its redundancy but it is due to insufficient transmission capacity away from 'DK916155' / 'PL925636' / 'CZ912108' as indicated by the high usage of the corresponding lines and the following development steps of the dc upgrade scenario.

4.4.3. Step 3

The third step of the DC scalability assessment uses the simulation results of step 2 as base case to determine the marginal generators (listed in Table 9: List of top ranked low-cost marginal generators in step 3 and Table 10: List of top ranked high-cost marginal generators in step 3). The added HVDC interconnections are visualized in Figure 13 (note that the connection points shown on the map is a rough approximation of the actual locations). The top ranked low-cost marginal generators still reflect the high spillage of energy at the offshore wind farms observed in the BaU 2030 scenario. However, it is worth emphasizing that the spillage at the marginal generators of stage 1 & 2 is significantly reduced and other offshore nodes are identified as marginal generators (with lower $e_{\text{low-cost}}$ values). Furthermore, note that the spillage at the spanish generator ('ES916537') was significantly reduced from 21TWh (BaU) to 16.8TWh (step 2) (also indicated by high usage of the installed lines) but will be reduced further by adding additional transmission capacity. The high-cost marginal generators on the other hand are located in Eastern Europe and South Western Europe.

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Given the large distance between the offshore wind farms in the North sea and the high-cost marginal generators in Eastern Europe the node 'DK916183' previously identified as marginal generator node serves as interconnection point between the North sea and Eastern Europe.

Table 9: List of top ranked low-cost marginal generators in step 3

Name	Bus ID	h_{marg} (h)	Energy spillage (TWh)	$e_{low-cost}$
'ES916537'	2169	2302	16.84	4.42
'offshore15'	7461	6654	2.97	2.26
'Offshore9'	6478	6007	3.28	2.25
'offshore16'	7462	6674	2.90	2.21
'Offshore13'	6477	6648	2.91	2.21
'AC_96IE'	81	830	0.79	0.08
'PT925871'	6776	1119	0.52	0.066

Table 10: List of top ranked high-cost marginal generators in step 3

Name	Bus ID	h_{marg} (h)	Energy spillage (TWh)	$e_{low-cost}$
'BG911091'	373	6834	0.66	0.51
'ES917371'	2769	1482	2.75	0.46
'BG911342'	389	8739	0.32	0.32
'CZ912108'	652	7712	0.34	0.30
'AC_92uk'	67	732	2.70	0.23
'CZ912114'	655	3061	0.46	0.16
'PT925931'	6794	8229	0.15	0.14
'SK928311'	7173	7260	0.15	0.12

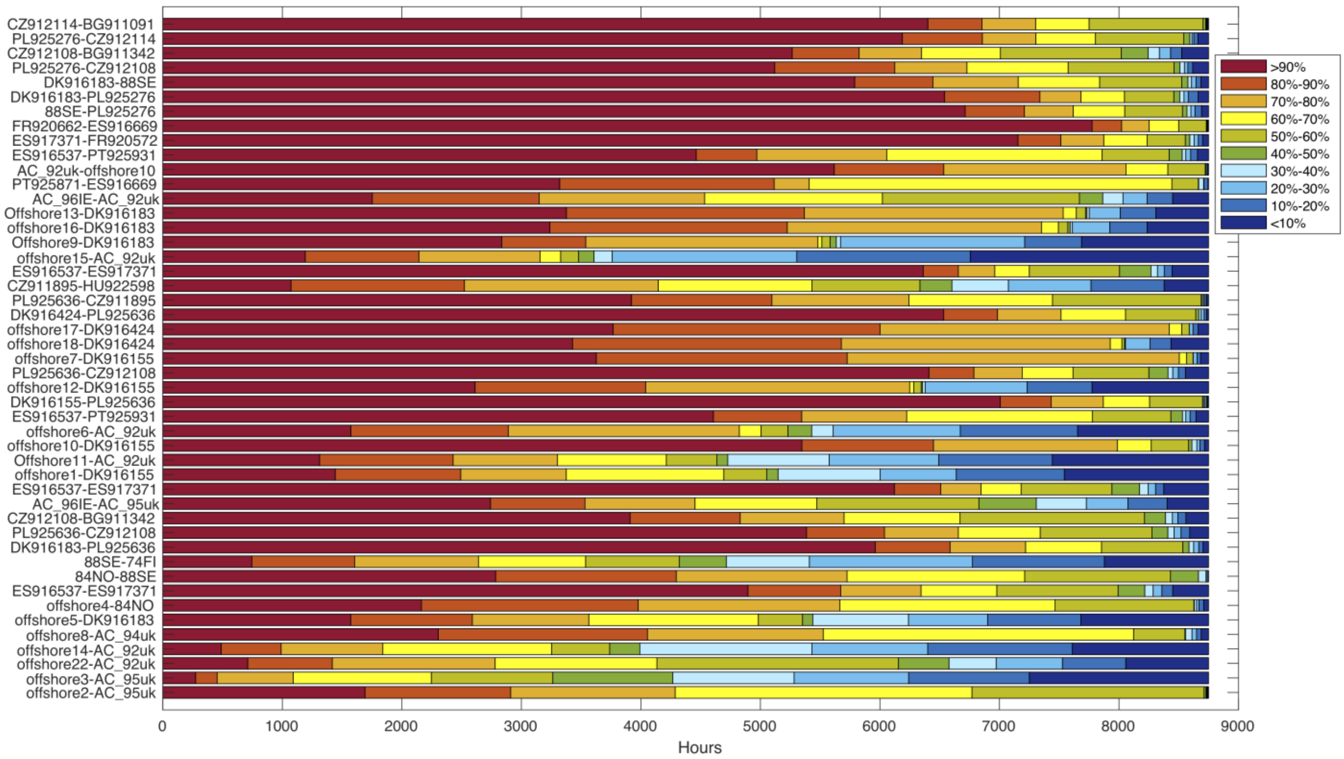

Figure 12: Load duration curve of DC lines added during step 1-3 of the DC scalability assessment

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'ES916669'	2266	6572	0.15	0.12
'PL925276'	6506	6197	0.16	0.11

All added dc lines (step 1-3) combined transfer 938.3TWh over the whole year which corresponds to an average utilization of 76.1%. This indicates a high usage of the assets and an increased trading between the countries. The load duration curve of every added DC line is shown in Figure 12: Load duration curve of DC lines added during step 1-3 of the DC scalability assessment. Note that the usage of 'offshore10'-'DK916155' increased significantly due to the added transmission capacity.

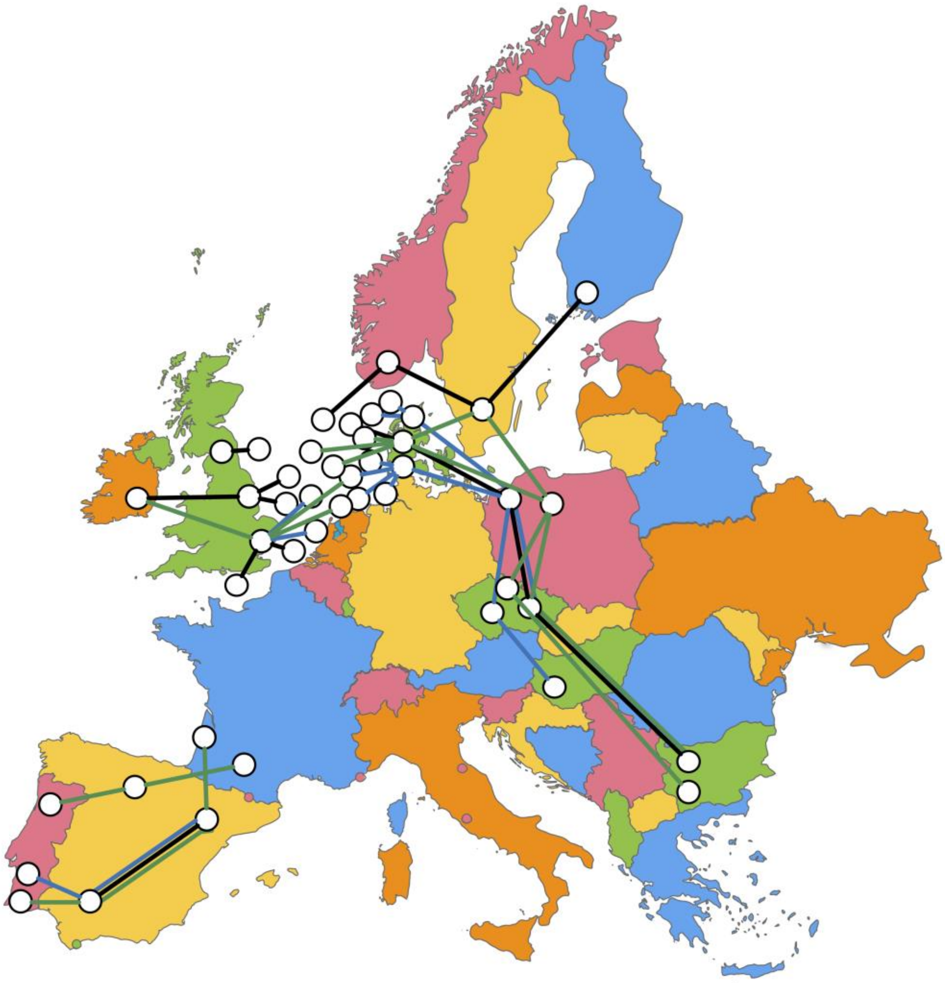

Figure 13: Step 3 of the DC upgrade scenario.Lines added in step 1 and step 2 are marked in black and bluerespectively, while lines added in step 3 are marked in green.

4.4.4. Step 4

The fourth step of the DC scalability assessment uses the simulation results of step 3 as base case to determine the marginal generators (listed in Table 11: List of top ranked low-cost marginal generators in step 4 and Table 12: List of top ranked high-cost marginal generators in step 4). The added HVDC interconnections are visualized in Figure 14 (note that the connection points shown on the map is a rough approximation of the actual locations). Note that the energy spillage is already significantly reduced so that the last low-cost marginal generator listed in Table 11 only offers 0.2TWh in comparable few hours resulting in $e_{\mathrm{low-cost}} < \epsilon_1$ and is therefore not considered anymore.

Table 11: List of top ranked low-cost marginal generators in step 4

Name	Bus ID	h_{marg} (h)	Energy spillage (TWh)	$e_{\mathrm{low-cost}}$
'ES916537'	2169	1622	8.79	1.672
'FR920572'	5139	928	1.82	0.192
'FR918995'	3775	823	0.195	0.018

Table 12: List of top ranked high-cost marginal generators in step 4

Name	Bus ID	h_{marg} (h)	Energy spillage (TWh)	$e_{\mathrm{low-cost}}$
'ES917371'	2769	1034	1.84	0.22
'FR920662'	5222	4485	0.24	0.12

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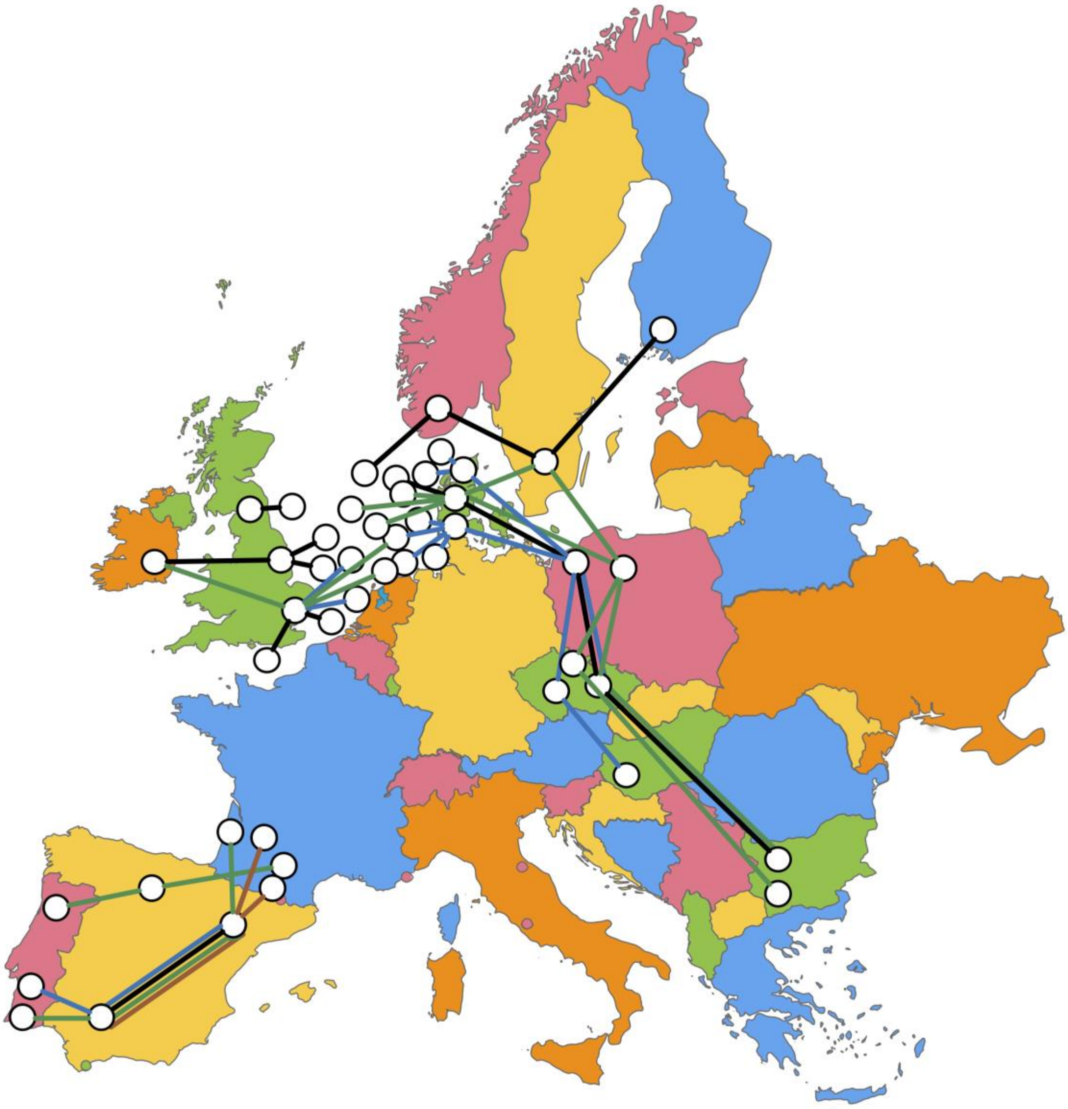

Figure 14: Step 4 of the DC upgrade scenario.Lines added in step 1 and step 2 are marked in black and blue respectively, while lines added in step 3 are marked in green. Lines added in step 4 are highlighted in orange.

All added dc lines (step 1-4) combined transfer 999.98TWh over the whole year which corresponds to an average utilization of 76.22%. This indicates a high usage of the assets and an increased trading between the countries. The load duration curve of every added DC line is shown in Figure 15: Load duration curve of DC lines added during step 1-4 of the DC scalability assessment. Note that mostly those lines connecting offshore nodes with the main grid (e.g. 'offshore3'-'AC_95uk' / 'offshore8'-'AC_94uk') show lower usage rates where the capacity for all connected lines of the specific nodes could be optimized, which is, however, out of the scope of this work.

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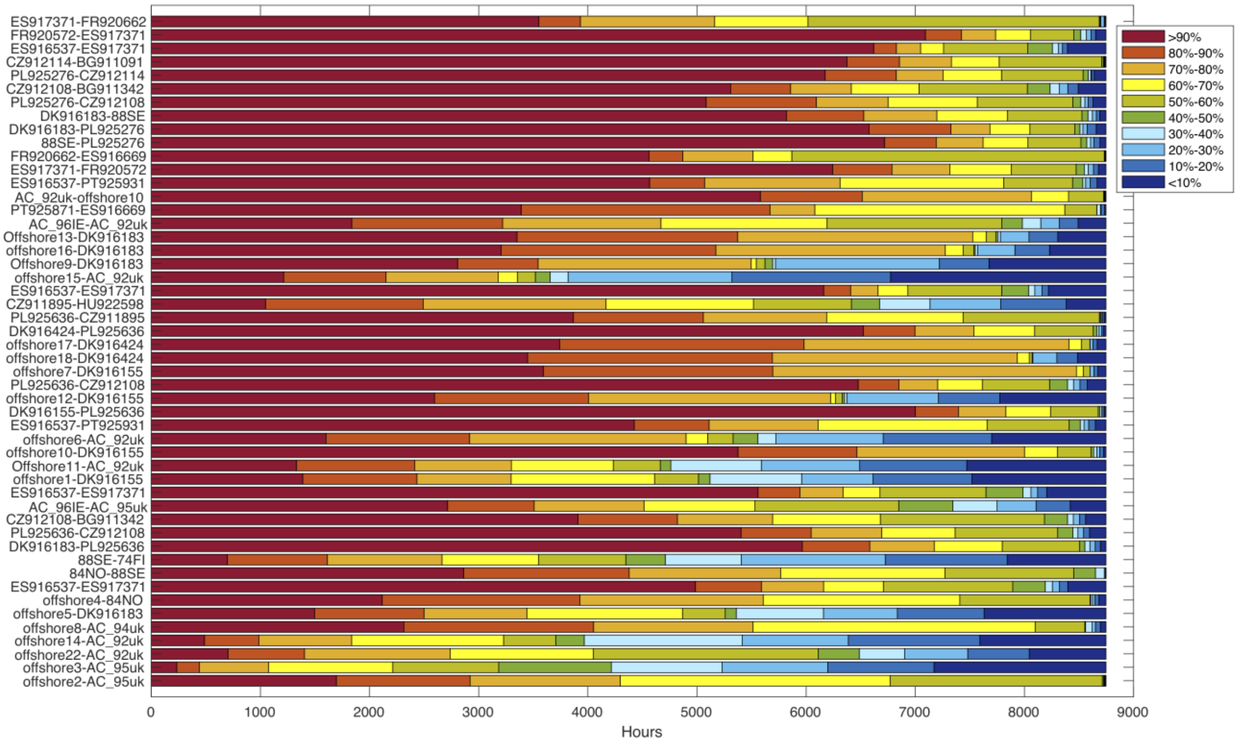
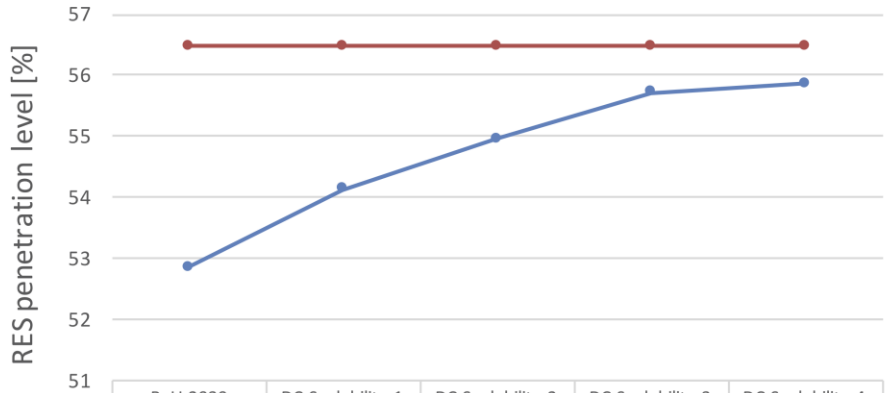


Figure 15: Load duration curve of DC lines added during step 1-4 of the DC scalability assessment

4.4.5. Evaluation

The previous subsections provided insights on which lines have been built and why and visualized the utilization of the added lines. The following subsection discusses the impact this grid development has on specific key performance indicators as the renewable energy penetration level, the curtailment of renewable energy sources, the energy not served and the operating costs.

The development of the RES penetration level is shown in Figure 16: Renewable energy penetration level for each step of DC upgrade while the curtailment of each RES technology is shown in Figure 17: Renewable energy curtailment for each renewable generation category with the BaU scenario as a base level. Figure 16 shows that the RES penetration increases from 52.85% up to 55.86% in step 4 approaching the theoretical maximum of 56.47% considering the theoretical maximum production of all RES sources. As discussed in the previous subsections, most of the low-cost marginal generators are offshore wind farms located in the North sea region which is based on the fact that most spilled RES energy is offshore wind energy as observed in the BaU scenario analysis. The effect of establishing higher transmission capacities from offshore locations to high-cost locations in Eastern Europe is well captured in

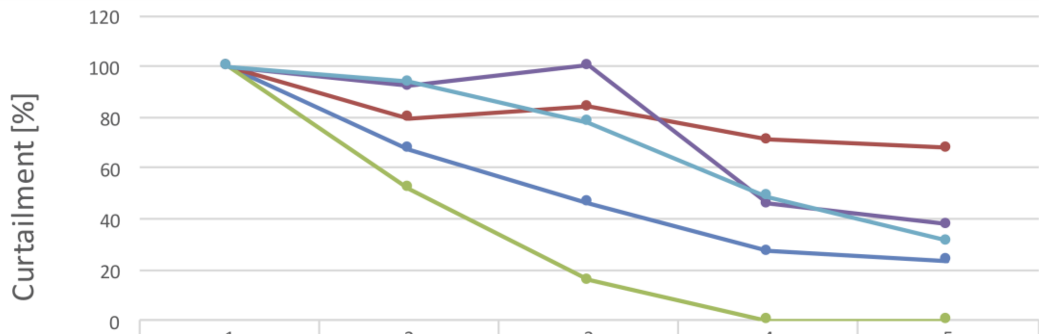


	BaU 2030	DC Scalability 1	DC Scalability 2	DC Scalability 3	DC Scalability 4
Penetration level	52.85	54.13	54.95	55.71	55.86
Theoretical max	56.47	56.47	56.47	56.47	56.47

Figure 16: Renewable energy penetration level for each step of DC upgrade

Figure 17: Renewable energy curtailment for each renewable generation category indicating the significant reduction of curtailment of offshore wind. Furthermore, Figure 17 indicates the benefits of the added lines in South West Europe resulting in reductions of solar energy and onshore energy curtailment. Moreover, Figure 17 indicates that, in particular in step 3, cheap offshore wind substitutes partially more expensive hydro power plants. Note that during the selection of the high-cost marginal generators we neglected hydro power plants aiming to increase RES penetration. However, for every HVDC line connecting a cheap marginal generator with an expensive marginal generator, the potential energy injection at the expensive marginal generator may exceed the energy required to completely substitute the expensive marginal generator. Therefore, the results show that the excess energy may additionally substitute hydro power plants located in the vicinity of the expensive marginal generator because hydro power plants have higher marginal costs. Although, this reduces the gain in terms of RES penetration level it still reduces the generation costs of the system, i.e. our objective function of the OPF.

Furthermore, a significant reduction of load shedding is achieved in particular due to the steps between BaU - DC Scalability 1 and DC Scalability 2 - DC Scalability 3, as shown in Figure 18: Development of the load shedding for each step of DC upgrade. Thus, we show through our method that relieving congestions results in a reduction of load shedding.



	1	2	3	4	5
Total	100.0	67.3	46.5	27.4	23.5
Hydro	100.0	79.8	84.3	71.0	68.1
Offshore wind	100.0	51.9	16.1	0.2	0.3
Onshore wind	100.0	92.3	100.4	45.8	38.0
Solar	100.0	93.8	78.1	49.0	31.5

Figure 17: Renewable energy curtailment for each renewable generation category

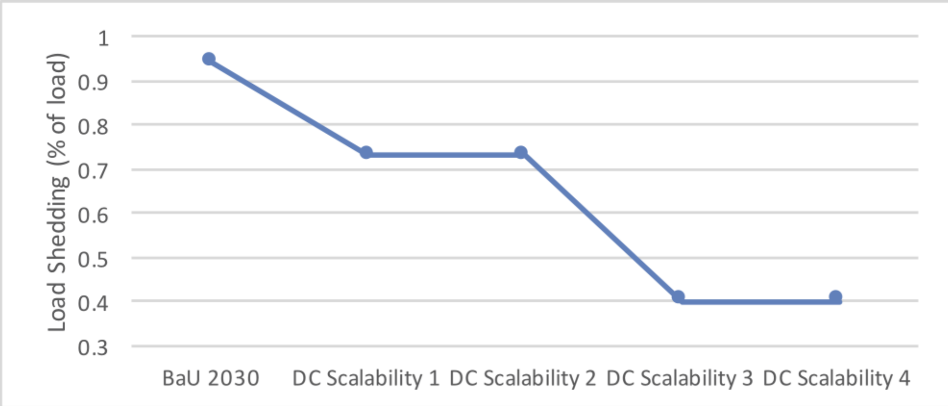
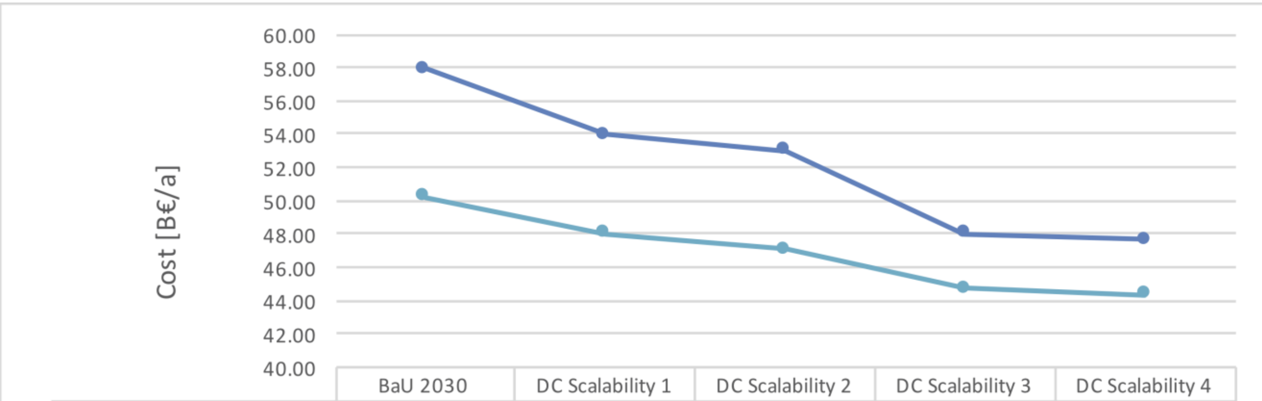


Figure 18: Development of the load shedding for each step of DC upgrade

Although, a detailed cost-benefit analysis for the more realistic BestPaths scenario considering AC and DC grid expansion will be performed in another deliverable led by SINTEF, we briefly want to discuss the potential generation cost reduction by a dc upgrade scenario. The generation costs of the European system as well as objective function value for the different DC upgrade steps are shown in Figure 19: Development of generation costs for each step of DC upgrad. It is shown that significant cost reduction can be achieved reducing the generation costs from 50.2B€ per year to 44.37B€ in step 4. This is a cost reduction of 11.61%. The reduced load shedding is reflected by the objective function value curve approaching the generation costs curve. Considering a life-time of the required DC installations of approx. 25 years, the cost savings sum up to 145.75B€ and considering the (not optimized) additional installed capacity (150GW) it resembles a break-even point for a potential investment decision of 0.9717B€/GW. However, considering an capacity optimization and a more realistic AC and DC grid development, this factor can probably be further increased as a detailed cost-benefit analysis in the corresponding deliverable will show.



	BaU 2030	DC Scalability 1	DC Scalability 2	DC Scalability 3	DC Scalability 4
Annual generation cost	50.20	47.99	47.07	44.69	44.37
Objective function value	57.94	53.95	53.02	47.99	47.64

Figure 19: Development of generation costs for each step of DC upgrade.

4.5. Combined Upgrade Scenario

Within the combined upgrade scenario we take a broader view on the AC and DC upgrade possibilities by combining the AC upgrades with each DC grid development stage. The main results of the AC, DC and combined upgrade scenarios are visualized and compared in Figure

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20 to Figure 22. Figure 20: Congestion level of the AC grid for AC, DC and combined upgrade scenarios clearly shows that connecting more DC lines to the grid increases the congestion level of the AC grid as the grid tries to accommodate the increased injections from offshore wind farms. While DC lines do act as a congestion relief method [13] in some parts of the grid, they also increase the total amount of power flows in the underlying AC grid by allowing to supply previously disconnected load. We define the congestion level of the AC grid ($\mathrm{CL}^{\mathrm{AC}}$) based on the lines' congestion duration $\mathrm{T}_{\mathrm{l}}^{100\backslash\%}$ throughout the year,

$$\mathrm{CL}^{\mathrm{AC}} = \frac{\sum_{\mathrm{l}\in\mathcal{L}^{\mathcal{AC}}} \frac{\mathrm{T}_{\mathrm{l}}^{100\backslash\%}}{8760}}{|\mathcal{L}^{\mathcal{AC}}|},$$

where $\mathcal{L}^{\mathcal{AC}}$ represents the set of AC lines. Hence, the Best Paths technologies for repowering AC lines can have a more profound impact in combination with a concurrent DC grid development and even more so with additional transformer upgradings than when deployed alone.

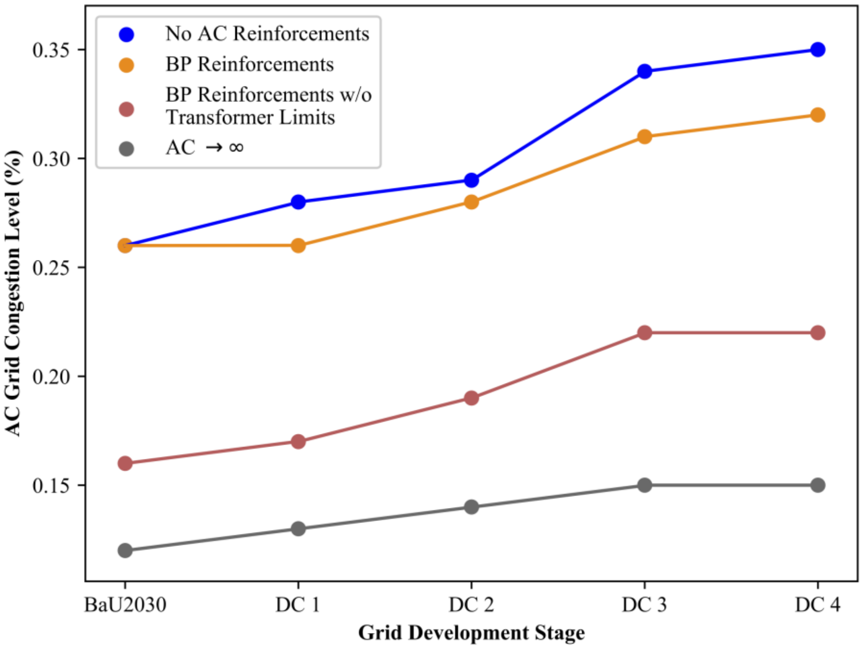

Figure 20: Congestion level of the AC grid for AC, DC and combined upgrade scenarios

The orange dot in the *DC 4* grid development stage represents the highest grid development stage for the 2030 network conditions developed within this case study, which can be facilitated by Best Paths technologies only. 56 AC lines europewide would require a total capacity increase of 63.62GW, out of which 20 require an upgrade of less than 20%. The RES penetration level is increased from 52.85% (BaU2030) to 56.06% approaching the maximum possible level of 56.47% as depicted in Figure 21: RES penetration and total RES spillage for AC, DC and combined upgrade scenarios. RES curtailment is significantly reduced from 12.10% to 2.17%,

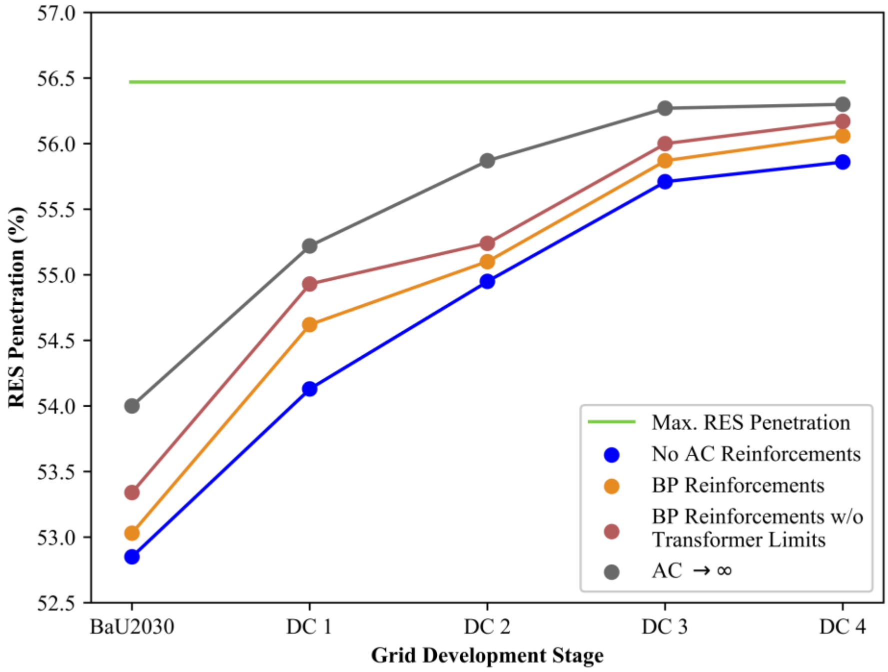

Figure 21: RES penetration and total RES spillage for AC, DC and combined upgrade scenarios

which can greatly affect the economics of renewable energy projects and increase the revenue of wind and solar energy projects improving their competitiveness on the electricity market and possibly allowing for the discontinuation of feed-in tariffs and other subsidies. At the same time, the total cost (including the cost of load shedding) is reduced by 10.84B€. Figure 22: Annual generation cost (excl. cost of load shedding) and annual cost including load shedding for AC, DC and combined upgrade scenarios depicts the change in generation cost and the change in objective function value (i.e., the cost of generation plus the cost of load shedding) for the different stages of grid development. Even though the objective function only considers a fictitious value for load shedding, it is more representative of the actual cost development and makes the different stages of grid development comparable to each other as it considers the same load level at each stage through either dispatched generation or load shedding. The generation cost, however, does not reflect the reduction in load shedding from one stage to the next, which might lead to an increase in generation cost despite higher RES penetration levels due to higher load levels that need to be supplied as becomes apparent through the increase in generation cost from *DC 1* to *DC 2*. The objective function value still decreases, though. Load shedding is reduced by almost 60% from 0.94% to 0.39% of the total load. Most of the remaining load shedding (i.e. 68.84%) needs to be carried out in France, where the new DC line connections to Spain increase the stress on the already highly loaded transformers as discussed in Section 3.1. Nonetheless, load shedding is also reduced in France from 7.89TWh to 7.33TWh, which can be further improved with appropriate transformer upgrades.

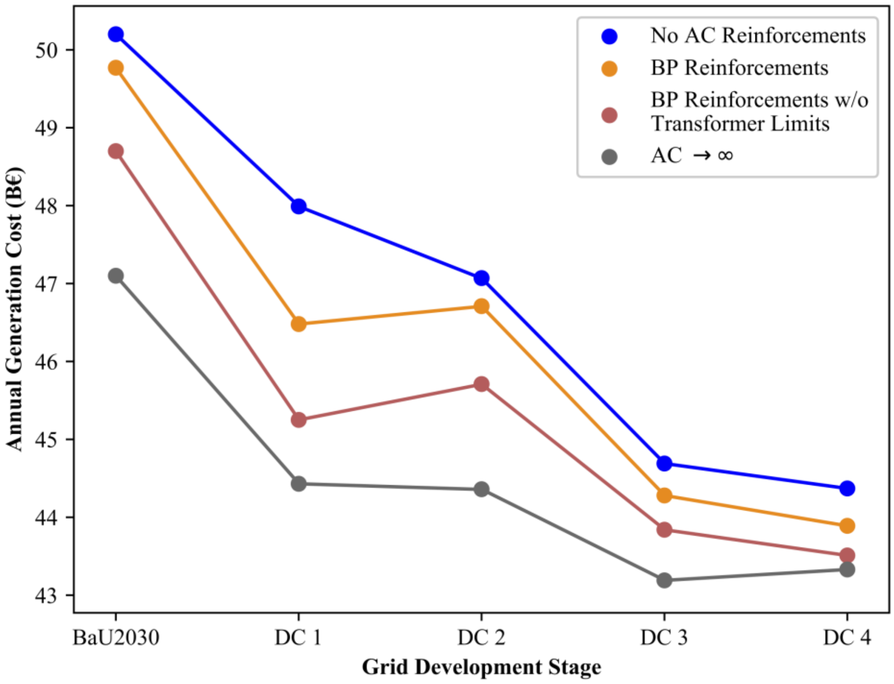

Figure 22: Annual generation cost (excl. cost of load shedding) and annual cost including load shedding for AC, DC and combined upgrade scenarios

5. Conclusion

This work identifies the performance boundaries of the Best Paths technologies when applied on a pan-European scale and evaluates their potential to contribute to the future European mixed AC/DC grid development. We consider the grid development for the two transmission technologies separately and evaluate their individual potential to relieve congestions, increase social welfare and contribute to a more renewable electricity supply. This approach allows us to determine the bounds of the future European grid development as visualized in Figure 23: Schematic illustration of how the scalability assessment provides the bounds of the future European grid development. Our results show that congestions within the AC grid can be partially relieved using technologies for repowering AC lines developed within the Best Paths project. However, we also show that the impact of these Best Paths technologies is highly constrained by the transformer limitations and that their benefits can be reinforced if they were deployed along with transformer upgrades.

Given the RES development projections of the EUCO30 scenario, which considers a substantial increase in offshore wind power capacity (11.7GW in 2016 to 41GW in 2030), a big share of the RES potential is not deployable without additional HVDC lines (or AC lines for offshore wind farms near shore). Therefore, the potential for improvements with AC reinforcements only is relatively small given the mentioned EUCO30 assumptions. The benefits of the AC reinforcements become more apparent when combining them with concurrent DC upgrades. This way, the already substantial increase in RES penetration level and reduction in cost achieved by placing new HVDC transmission corridors can be further reinforced by relieving AC grid congestions in the vicinity of the new injection points, which further reduces the annual cost by 4.2B€ (BestPaths AC reinforcements + transformer upgrades at DC Scalability step 4). 23.7% of the total reduction in cost are related to the AC reinforcements. This also highlights that an optimal grid development will consists of both AC reinforcements and new DC transmission assets. The study also emphasizes the benefits of HVDC lines to reroute power flows from low-cost to high-cost marginal generators in a fully controllable way demonstrating their ability to substitute more expensive generators. Despite the fact that DC lines can reduce congestions in the underlying AC grid, additional AC reinforcements in the vicinity of their injection points are often required in case of increased power injections at that point. Thus,

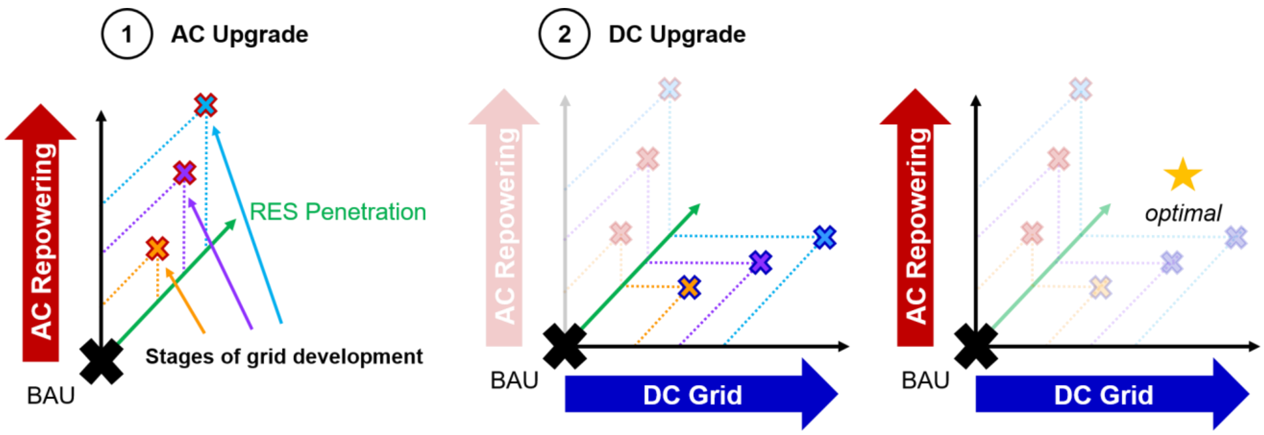

Figure 23: Schematic illustration of how the scalability assessment provides the bounds of the future European grid development.

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substituting larger generators, which already inject a substantial amount of power at their node, will require less AC reinforcements.

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Table 13: Net demand, RES energy and consumption per country 2016

Country	AT	BE	DK	FR	DE	HR	GR	HU	IT	NL	PL	ES	CH	UK	PT	SK	BG	FI	SE	RO	NO	IE	CZ	LU	RS	SI	AL	ME	MK	BA	Total
Consumption according to ENTSO-E (TWh)	69.98	84.77	33.87	478.33	504.38	17.55	51.08	41.77	313.41	114.20	152.47	249.67	62.59	374.81	49.08	28.71	37.59	84.79	138.88	53.43	131.86	26.84	65.10	6.48	38.89	13.76	7.09	3.23	7.08	12.35	3262.42
Wind energy in distribution level (TWh)	3.84	0.24	0.00	0.47	50.68	0.85	2.64	0.44	14.94	0.00	6.27	35.12	0.07	0.00	11.81	0.00	1.04	0.00	0.00	5.40	0.00	0.00	0.32	0.08	0.00	0.00	0.00	0.00	0.11	0.00	134.31
Solar energy in distribution level (TWh)	0.93	2.70	0.63	7.73	33.53	0.06	3.65	0.03	21.55	1.54	0.12	12.95	0.45	0.00	0.78	0.55	1.03	0.00	0.00	1.59	0.00	0.00	2.08	0.10	0.00	0.24	0.07	0.00	0.03	0.00	92.34
Bio fuel energy in distribution level (TWh)	0.00	3.42	2.98	4.13	40.70	0.33	0.25	1.65	16.85	3.47	7.22	3.40	0.32	13.84	2.69	1.63	0.27	10.74	8.98	0.45	0.00	0.00	4.20	0.05	0.00	0.17	0.00	0.00	0.04	0.00	127.78
Geothermal in distribution level (TWh)	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	5.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.04
Renewable waste in distribution level (TWh)	0.00	1.21	1.40	2.34	4.97	0.00	0.00	0.40	2.41	0.00	0.00	0.79	0.64	0.08	0.00	0.00	0.00	0.00	1.23	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15.53
Hydro in distribution level (TWh)	15.85	0.30	0.02	12.09	20.90	4.30	3.47	0.30	38.80	0.10	1.40	28.32	13.20	4.50	12.59	1.55	3.50	0.00	0.00	15.44	0.00	0.00	2.00	0.12	0.00	4.40	0.00	0.00	1.60	3.40	188.15
Other RES in distribution level (TWh)	3.06	0.04	0.00	0.00	1.46	0.07	1.30	0.00	0.00	0.00	0.00	0.04	1.37	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.15	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.00	7.65
Net demand (TWh)	46.31	76.86	28.84	451.59	351.98	11.93	39.77	38.95	218.86	103.23	137.45	169.06	46.54	356.40	21.21	24.95	31.75	74.05	128.68	30.54	131.86	26.63	56.50	6.12	38.89	8.83	7.02	3.23	5.31	8.94	2682.24

Table 14: Net demand, RES energy and consumption per country 2030

Country	AT	BE	DK	FR	DE	HR	GR	HU	IT	NL	PL	ES	CH	UK	PT	SK	BG	FI	SE	RO	NO	IE	CZ	LU	RS	SI	AL	ME	MK	BA	Total
Consumption according to ENTSO-E (TWh)	76.92	95.56	39.00	500.80	575.31	18.09	54.76	42.31	316.55	118.08	184.86	273.40	72.19	371.20	49.39	32.73	33.63	89.68	158.20	60.47	150.45	29.89	71.32	8.14	43.25	15.57	9.29	5.20	11.09	12.55	3519.84
Wind energy in distribution level (TWh)	3.84	0.24	0.00	0.47	50.68	0.85	2.64	0.44	14.94	0.00	6.27	35.12	0.07	0.00	11.81	0.00	1.04	0.00	0.00	5.40	0.00	0.00	0.32	0.08	0.00	0.00	0.31	0.51	0.31	1.96	137.28
Solar energy in distribution level (TWh)	5.89	6.03	0.63	7.73	33.53	1.88	11.04	1.15	21.55	4.48	0.76	12.95	0.00	0.00	3.78	0.70	1.10	0.02	0.00	1.59	0.72	0.02	2.69	0.34	0.00	1.51	0.01	0.00	0.05	0.00	120.14
Bio fuel energy in distribution level (TWh)	0.00	3.36	7.27	15.20	50.47	0.00	1.27	2.14	26.28	19.18	18.26	9.49	0.00	178.52	2.88	2.25	0.38	0.00	9.65	0.83	0.00	2.01	0.00	0.18	0.00	0.48	0.00	0.00	0.00	0.00	350.12
Hydro in distribution level (TWh)	15.85	3.50	0.02	12.09	75.46	4.35	3.98	0.32	68.06	0.10	5.81	34.92	13.20	0.00	16.19	1.55	5.53	0.00	0.00	15.44	4.60	1.82	3.43	5.89	8.84	8.77	6.79	3.01	1.89	3.30	324.74
Other RES in distribution level (TWh)	6.78	0.00	0.00	0.04	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.04	0.00	0.04	0.00	0.00	0.04	0.04	0.00	7.17
Net demand (TWh)	44.57	82.42	31.08	465.28	365.17	10.91	35.83	38.26	185.72	94.32	153.76	180.91	58.88	192.69	14.74	28.22	25.57	89.62	148.54	37.20	145.12	26.04	64.84	1.64	34.36	4.80	2.18	1.64	8.80	7.29	2580.40

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