

# Parametric Study of Variable Renewable Energy Integration in Europe: Advantages and Costs of Transmission Grid Extensions

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## Abstract

Wind and solar energy will play an important role in the decarbonization of the European electricity generation. However, high shares of these variable renewable energies (VREs) challenge the power system considerably due to their temporal fluctuations and geographical dispersion.

In this paper, we systematically analyze transmission grid extensions as an integration measure for VREs in Europe. We show the effects of grid extensions for fundamental properties of the power system as a function of the penetration penetration and mix of wind and solar energy. Backup capacity requirements and overproduction are reduced with a powerful overlay transmission grid. We determine the costs of the grid extensions in dependence of the VRE penetration and mix and find, that the grid integration costs remain below 25% of the VRE investment costs for all conceivable VRE configurations. Furthermore, robust design features of future power systems in

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terms of grid geometry and flexibility requirements for backup technologies are identified.

We apply a spatially and temporally highly resolved techno-economic model of the European power system for our analysis.

*Keywords:* Variable Renewable Energies, grid integration costs, ideal mix

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## 1 **1. Introduction**

2 Large shares of renewable electricity generation are a promising possibility  
3 to address global warming and the rising scarcity of hydrocarbon fuels (IPCC,  
4 2011; McKinsey et al., 2010; PWC et al., 2010). In Europe, an important  
5 part of the renewable generation will come from wind and solar PV energy  
6 due to the observed learning and growth rates and the political support  
7 schemes (Edenhofer et al., 2010; IEA, 2011b). Furthermore, the technical  
8 potential of wind and solar energy is largely sufficient to supply the European  
9 electricity demand (Tzscheuschler, 2005; Brückl, 2005; Hoogwijk, 2004).

10 However, these two resources are geographically dispersed and underlie  
11 strong temporal fluctuations. These characteristics of solar and wind en-  
12 ergy – for which we term them variable renewable energies (VREs) – make  
13 their integration into the existing power supply system difficult. Today’s  
14 electricity system is based on centralized supply in proximity to load cen-  
15 ters. The different power plant types are designed to follow the hourly load.  
16 International transmission of electricity and storage only play a minor role.  
17 This changes significantly in energy systems with high shares of renewable  
18 energy and entails major integration challenges for the power system, such  
19 as the connection of remote sites of high VRE potential, the low reliability

20 of VRE, occurring overproduction etc. (IPCC, 2011). Therefore, a power  
21 supply system with large VRE penetration, should be designed in a way that  
22 integration challenges are kept minimal. Renewable energy policies should  
23 be based on solid knowledge about these challenges and which system design  
24 features can be advantageous. Policy makers may face questions about the  
25 implications of a given VRE penetration level to the power system. How to  
26 design cost-effective renewable supply? Which mix between wind and solar  
27 energy has to be chosen to keep overproduction minimal? How can the re-  
28 liability of VRE be increased, i.e., the required backup<sup>1</sup> capacity reduced?  
29 What benefits arise from grid extensions?

30 In this paper, we provide an overview of the system implication of wind  
31 and solar PV energy and investigate a way to partly overcome these: trans-  
32 mission grid extensions. We compare the integration challenge of a large  
33 range of VRE scenarios in Europe and investigate the role of transmission  
34 grid extensions as a measure to address the temporal fluctuations and the  
35 geographical dispersion of VRE. We systematically analyze the effect of dif-  
36 ferent VRE penetration levels and mixes between wind and solar power on  
37 fundamental power system properties, such as overproduction and required  
38 backup capacity, as function of grid extensions. This allows us to identify  
39 benefits of transmission grid extensions for VRE integration. We quantify the  
40 costs of a powerful overlay transmission grid for VRE integration for different  
41 scenarios. These costs are called “grid integration costs”, i.e., the additional  
42 costs per installed MW capacity due to grid extensions for VRE integration.

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<sup>1</sup>In this study, we define “backup” power plant, as all dispatch-able power plants in the electricity sector, i.e., all capacity except VRE technologies.

43 Finally, robust design features of a power system with high VRE penetration  
44 are presented: We identify crucial grid connections in Europe and study the  
45 role and suitability of different backup technologies.

46 Already in the early 1970s, grid extensions have been identified as a nec-  
47 essary condition to achieve large shares of renewables: Buckminster Fuller  
48 (1971) proposes a global link to harvest energy resources most efficiently.  
49 On the European level, first detailed studies on the feasibility and principal  
50 advantages of a “super-grid”, i.e., a powerful transmission grid, have been  
51 presented by Biberacher (2004); Czisch (2005) and DLR (2006). In the light  
52 of actual growth of wind and solar energy and the institutional and political  
53 barriers to grid extensions, analyses of the actual and near future situation  
54 have been carried out recently. In TradeWind (2009), overall grid extensions  
55 for wind energy until 2030 are quantified. Grid strengthening can furthermore  
56 reduce the impacts of VRE on the electricity market and their participants,  
57 as shown by Schaber et al. (2011). On a longer time horizon, McKinsey et al.  
58 (2010) and PWC et al. (2010) present possible roadmaps towards a carbon  
59 free power supply in 2050 in Europe. McKinsey et al. (2010) present a techni-  
60 cally and economically feasible pathway to a zero-emitting European power  
61 sector in 2050, which includes nuclear power, carbon capture and storage,  
62 and renewable energies. PWC et al. (2010) propose a 100% renewable sce-  
63 nario for Europe under the prerequisite of a European “SuperSmartGrid”.  
64 Furthermore, the amount of necessary backup capacity can be reduced sub-  
65 stantially through grid extensions, as Aboumahboub et al. (2009) show for  
66 the European and the global case.

67 In addition to these detailed techno-economic studies mostly based on

68 advanced power system modeling, important information can be drawn from  
69 statistical analyses of the supply time series. Giebel (2000) and Greenpeace and 3E  
70 (2008) quantify the statistical smoothing of wind volatility through increased  
71 interconnection between generating regions. In Grotz (2009) and Heide et al.  
72 (2010) the seasonal fluctuations of wind and solar availability in Europe are  
73 understood as chance rather than challenge: The optimal combination of  
74 wind energy, mainly available in winter, and solar energy, mainly available  
75 in summer, allows to minimize the need for inter-seasonal storage or backup  
76 power. While analyses based on energy models mostly are based on a limited  
77 number of scenarios, statistical studies cover a larger range of the possible  
78 system configurations.

79 In this study, we apply a complex model to a wide parameter space of  
80 possible system configurations for different VREs penetration levels and mix-  
81 tures. This allows to study the effects of VRE on a power system. For each  
82 system configuration, we determine necessary transmission grid extensions  
83 and analyse their effects on VRE integration. We combine highly resolved  
84 eight-year meteorological time series with a detailed power system model,  
85 which makes our approach very robust.

86 Storage capacities are assumed to remain at today's level, as the fo-  
87 cus of this study lies on grid extension as a measure to integrate VREs.  
88 Storage can provide important contributions to integrate renewable ener-  
89 gies and a variety of application fields for the different technologies exist  
90 (Kuhn and Kühne, 2011). However, today, only few technologies are cost-  
91 competitive (Pieper and Rubel, 2011). Another simplification in our ap-  
92 proach is, that we only model the high-voltage transmission grid. The un-

93 derlying distribution grid is not included in our analysis.

94 Our paper proceeds as follows: the methodology is described in Section 2.  
95 Results are presented in Section 3: we analyze the technical and economic  
96 feasibility and suitability of different VRE supply configurations with and  
97 without grid extensions (Subsection 3.1). The costs and structure of the  
98 European high voltage transmission grid, necessary to integrate VREs, are  
99 quantified in Subsection 3.2. The suitability of different backup technologies  
100 is studied in Subsection 3.3. An illustration of the results is provided in a  
101 casestudy in Subsection 3.4. Finally, we discuss our results and conclude in  
102 Section 4.

## 103 2. Methodology

### 104 2.1. Definition of parameter space

105 To carry out a systematic analysis of VRE integration, we introduce a  
106 two dimensional parameter space, defined by the total share of VREs in the  
107 satisfaction of load  $\alpha$  and the mix between solar and wind energy  $\beta$ .

$$\alpha = \frac{\sum_t \min(E_{WIND}(t) + E_{SUN}(t), D(t))}{\sum_t D(t)}, \quad (1)$$

$$\beta = \frac{\sum_t E_{WIND}(t)}{\sum_t [E_{WIND}(t) + E_{SUN}(t)]} \quad (2)$$

108 where  $E_{WIND}(t)$  is the total hourly energy generation from wind at time  $t$ ,  
109  $E_{SUN}(t)$  the generation from solar photovoltaics, and  $D(t)$  the demand. Note  
110 that oversupply, i.e., renewable generation that exceeds the demand at time  
111  $t$ , is disregarded in the definition of  $\alpha$ . As we assume current and therewith  
112 limited storage possibilities, most excess generation has to be discarded.

113 Traditionally, power supply systems are built to follow the load and this  
114 determines the power generation, grid and storage infrastructure. However,  
115 in highly renewable scenarios the system is mostly determined by the share  
116 and type of the VREs. VREs determine the residual load, which has to be  
117 satisfied by the power supply system. The two parameters  $\alpha$  and  $\beta$  are thus  
118 central in the comparison of systems.

## 119 *2.2. Model structure and assumptions*

120 To determine the behavior of the European power supply system for each  
121  $\alpha$  and  $\beta$ , we employ the European power system model URBS-EU based  
122 on linear optimization of total system costs (Schaber et al., 2011). This re-  
123 gionally and temporally highly resolved model of the European power supply  
124 system computes the cost-optimal production schedules for the dispatchable  
125 (backup) power plants and a cost-optimal electricity transport across Europe.  
126 On request, it can also optimize the infrastructure, i.e., the power plant fleet  
127 or the interregional electricity transmission capacities. Important properties  
128 of the electricity supply system, such as the satisfaction of demand in each  
129 model region and time step or the transmission, storage and conversion losses  
130 are included in the optimization via boundary conditions.

131 In the parametric study, VRE capacities are determined by the requirements  
132 to achieve certain shares  $\alpha$  and  $\beta$ , while the residual power system is subject  
133 to the cost-optimization implemented in the power system model URBS-EU.  
134 Total system costs include VRE, backup and storage capacity, operation,  
135 maintenance and fuel and carbon costs and the electricity transmission grid.  
136 The power system model has hourly resolution and divides Europe geograph-  
137 ically into 83 model regions (see Figure 1). Power plants are aggregated with

138 respect to type and region. The optimization problem is kept linear to allow  
 139 feasible large scale modeling.

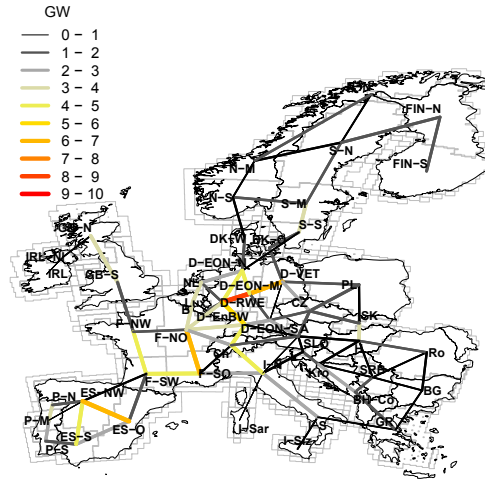


Figure 1: European model regions and capacity of aggregated ENTSO-E transmission capacities.

140 The hourly availability of VREs is taken into account through the ca-  
 141 pacity factor  $s_i(x, t) \in [0, 1]$ , which is computed from an eight-year time  
 142 series (2000-2007) of meteorological data for each region  $x$  and VRE type  
 143  $i \in \{WIND, SUN\}$  (Heide et al., 2010).  $E_{i,\alpha,\beta}(x, t)$ , the hourly power pro-  
 144 duction per region and VRE type is the product of  $C_{i,\alpha,\beta}(x)$ , the capacity  
 145 per model region and type and the time dependent capacity factor  $cf_i(x, t)$   
 146 for each VRE technology. The total energy production from VREs at time  $t$   
 147 is given by  $E_{i,\alpha,\beta}(t) = \sum_x E_{i,\alpha,\beta}(x, t)$ .

148 We assume that the distribution of wind and solar capacities  $C_{i,\alpha,\beta}(x)$  is  
 149 proportional to the potential of wind and solar power production, respec-



150 tively, i.e., to the Full Load Hours (FLHs, shown in Figure 2). This distribu-  
 151 tion of capacities reflects that the costs of electricity from renewable energies  
 152 is cheapest on sites with the largest potential. This is not happening today,  
 153 since different political support schemes and targets have lead to strongly  
 154 differing installation rates in various countries (IEA, 2011a). However, from  
 155 a European perspective, the most cost-effective way to harvest renewables in  
 156 the long term perspective, is to build the largest capacities where the potential  
 157 is highest. As this study departs from a European point of view, we assume,  
 158 that more VRE capacities will be built in regions with higher FLHs. The  
 159 contribution of wind offshore capacity to the total European wind capacity  
 160 is assumed to be 50%.

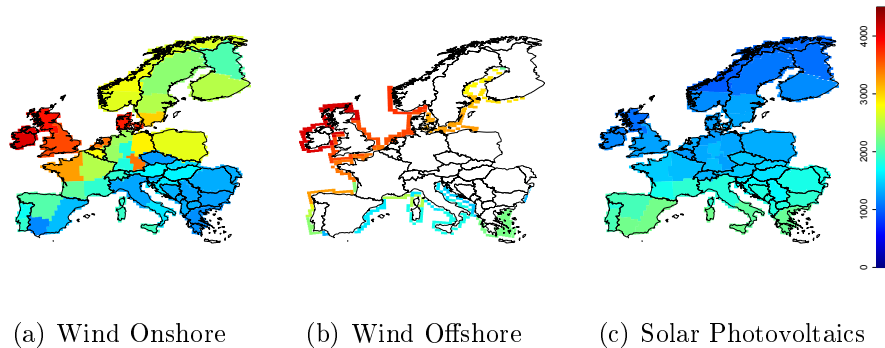


Figure 2: Full Load Hours of wind and solar PV supply

161 Industrial and residential demand for electricity is assumed to remain at  
 162 today's level in the entire study. While population and economic growth raise  
 163 electricity demand, efficiency measures counteract (McKinsey et al., 2010).  
 164 To account for these diametrical trends and to ensure comparability, we use  
 165 current hourly load profiles and current total electricity demand.

166 Today's power system infrastructure is included in the model. The ac-

167 tual generation and storage capacities per model region are determined from  
168 a Geo-referenced power plant database (Schaber et al., 2011). As we focus on  
169 the role of grid extensions only, additional storage capacity is not allowed for.  
170 Today’s transmission grid is obtained from freely available data on the Eu-  
171 ropean high voltage electricity grid (ENTSO-E, 2010b, 220kV and 380 kV).  
172 The capacity of the transmission lines is computed based on their natural  
173 load, i.e., the power level where no reactive losses occur and is benchmarked  
174 with cross boarder net transfer capacities published by ENTSO-E (see Fig-  
175 ure 1 ENTSO-E, 2011b). The costs and technical parameters are based on  
176 scientific studies (IEA, 2010a; McKinsey et al., 2010, see Table A.3). The  
177 hourly load curves for the years 2000-2007 stem from the European Trans-  
178 mission System Operator (ENTSO-E, 2010a). To model the power exchange  
179 along the transmission lines we perform a simplified simulation of electricity  
180 transport between regions. Kirchhoff’s first law, the conservation of currents  
181 in each node of an electricity network, is respected in our model, while the  
182 second, the voltage law is not modeled. This results in a transport model  
183 omitting load flow. Due to computational restrictions and low data avail-  
184 ability, the distribution network is not included.

185 To compare possible VRE supply systems for a wide range of the param-  
186 eters  $\alpha$  and  $\beta$  we need to run the model many times. Yet, the computations  
187 with the fully-detailed model are time- and memory-consuming and are prac-  
188 tically limited to about 6 typical weeks for each  $\alpha$  and  $\beta$  value. We therefore  
189 developed a simplified version of the model where the technical details of the  
190 backup power plants are simulated in less detail. This allows to compute good  
191 approximations of important power system quantities listed in equation 3 to

192 6 using all eight years of available VRE generation time-series (Subsection  
193 3.1). The full model version is applied for the computation of grid extensions  
194 and backup dispatch (Subsection 3.2 to 3.3). Six representative weeks from  
195 meteorological data of 2007 are used. We performed a sensitivity analyses  
196 and the results show that the results in terms of grid extensions and backup  
197 mix do not change significantly if longer timeseries or another meteorological  
198 year are employed.

199 Fundamental power system properties are the necessary VRE and backup  
200 capacities,  $C_{VRE}$  and  $C_B$ , the amount of overproduction  $OP$ , and the distance  
201 between supply and demand time curve  $\Delta$ . If the “misfit parameter”  $\Delta$  was  
202 zero, there would be no VRE integration challenge.

$$C_{VRE}(\alpha, \beta) = \sum_{x,i} C_{i,\alpha,\beta}(x) \quad (3)$$

$$C_B(\alpha, \beta) = \max_t (D(t) - E_{VRE,\alpha,\beta}(t)) \quad (4)$$

$$OP(\alpha, \beta) = \frac{\sum_t \max(E_{VRE,\alpha,\beta}(t) - D(t), 0)}{\sum_t D(t)} \quad (5)$$

$$\Delta(\alpha, \beta) = \sum_t |D(t) - E_{VRE,\alpha,\beta}(t)| \quad (6)$$

203 Here,  $D(t)$  is the sum of the regional demands  $D(x, t)$ ,  $E_{VRE,\alpha,\beta}(x, t) =$   
204  $\sum_i E_{i,\alpha,\beta}(x, t)$ , and  $E_{VRE,\alpha,\beta}(t) = \sum_x E_{VRE,\alpha,\beta}(x, t)$ .

## 205 3. Results

### 206 3.1. Effects of grid extension on VRE integration challenges

207 To study VRE integration, we compute the above described power system  
208 properties for a case with optimal grid extensions and one without. In the  
209 first case, we assume unrestricted electricity transport across the entirety

210 of Europe, in the second case, each model region acts independently. This  
211 allows us to assess the difficulty of VRE integration and the effect of grid  
212 extensions.

213 To aggregate the results in the no-grid case, the regional results are summed  
214 up in accordance to  $\alpha$  and  $\beta$ . In this aggregation we assume that the mix  
215 between wind and solar power ( $\beta$ ) is identical in all regions across Europe.

216 Figure 3 shows the necessary VRE capacity to realise each  $\alpha$ - $\beta$  combina-  
217 tion as well as the required backup capacity, overproduction and the misfit  
218 between supply and demand  $\Delta$  (see equation 6). In the left column, an opti-  
219 mal grid within Europe is assumed, in the right column, no interconnection  
220 is assumed.

221 We present our results through color coding in the parameter space. The  
222 penetration level of VRE  $\alpha$  and the share of wind  $\beta$  span the parameter sur-  
223 face, where  $\alpha$  is plotted on the abscissa and  $\beta$  on the ordinate (see Figure 3).  
224 The value of a variable is represented through color levels. Some combina-  
225 tions of  $\alpha$  and  $\beta$  are infeasible. For these points on the surface, no variable  
226 value exists and the surface remains white: Large VRE shares with high so-  
227 lar contribution are infeasible. With grid extensions, the maximal possible  
228 share amounts about  $\alpha=50\%$ , if only solar PV is used ( $\beta = 0$ , left column of  
229 Figure 3). As the sun only shines during day time and we assume no storage  
230 extensions, it can be easily understood, that 100% satisfaction of demand is  
231 impossible with solar energy only. Without grid extensions larger areas of the  
232 parameter space remain empty and thus infeasible (right column of Figure 3).

233

234 The first row of Figure 3 shows that VRE capacity rises steeply with  
235 increasing  $\alpha$  in the parameter space. The realization of a configuration at  
236 the rim of the colored area in the parameter space translates into a VRE  
237 capacity of 10 times the peakload. In the results shown here, the capacity of  
238 each VRE technology – solar PV, wind Onshore and wind Offshore is limited  
239 to five times the peak load. The theoretical maximal VRE capacity thus  
240 amounts to 15 times the peak load. As for very high shares of VREs mainly  
241 wind capacity is needed, the total VRE capacity is 10 times the peak load. If  
242 larger overcapacity was allowed, higher shares of VRE were possible, if lower  
243 overcapacity is allowed, lower VRE shares can be achieved. The dotted line  
244 in Figure 3 shows the maximal possible shares with a capacity limit of 20  
245 times the peak load for each of the three technologies, the dashed line shows  
246 the maximal shares with a limit of two times the peak load. The first case  
247 corresponds to a 59 fold overcapacity and the second case limits the possible  
248 parameter space considerably. Therefore we chose an intermediate level of  
249 VRE capacity limit of five times the peakload per VRE technology.

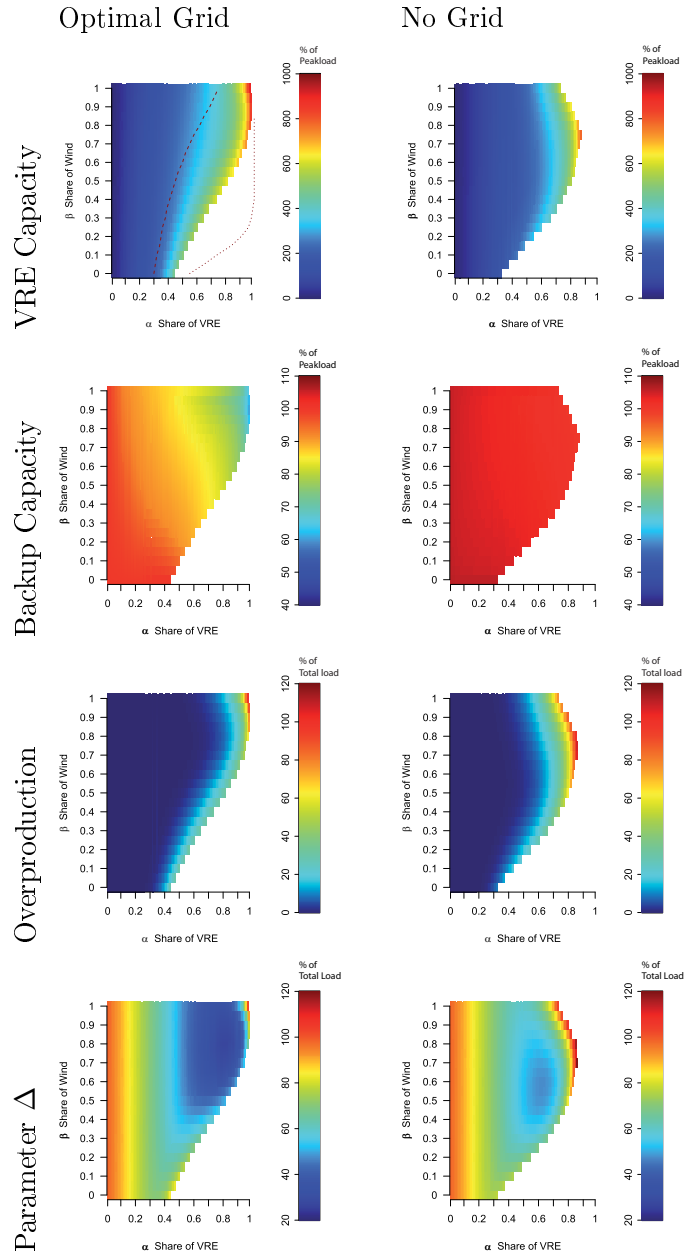


Figure 3: Fundamental properties of VRE power systems in Europe with optimal grid and without grid. The first row indicates the necessary VRE capacities for each  $\alpha$  and  $\beta$ . The three lower rows provide measures for the integration challenge of these VRE capacities. In the results shown here, the capacity of each VRE technology is limited to five times the peak load. The lines in the upper left plot indicate the maximal possible VRE shares with lower or higher VRE capacity limits: a limit of two times peak load per VRE technology results in the dashed lines, a limit of 20 in the dotted line.

250 To ensure reliable electricity supply, sufficient backup capacity is neces-  
251 sary. The second row of Figure 3 shows that all VRE configurations need  
252 considerable backup capacities. This is due to the fluctuating availability  
253 of VREs and the resulting low reliability of these energy sources. With an  
254 an optimal grid necessary backup can be reduced to 60% of the peak load.  
255 Without grid the total backup remains close to 100% of the peak load in  
256 the entire parameter space. For both cases, the maximum of the European  
257 load serves as reference. As the peak load does not happen at the same  
258 time all over Europe, the sum of local peak loads exceeds the European peak  
259 load. This is why the backup capacity requirements can reach values larger  
260 than 100%. The backup capacity is determined using the simplified model  
261 version, which does not include transport losses, ramp up or availability re-  
262 strictions. The presented capacity requirements should thus be understood  
263 as lower limits, which increase if all technical details and security margins  
264 are taken into account. The current power generation capacity in Europe,  
265 for instance, amounts about 1.4 times the peak load (ENTSO-E, 2010b).

266 The VRE overcapacity leads to overproduction, shown in the third row of  
267 Figure 3. The overproduction's dependence on  $\alpha$  is similar to an exponential  
268 function: it is very flat in proximity to the origin, but from a certain VRE  
269 share on, it rises steeply. The detaching point varies with the share of wind  
270 energy: more wind energy leads to less overproduction. Also, higher levels of  
271 linkage entail lower excess production for identical VRE shares. The optimal  
272 mix between wind and solar power to achieve minimal overproduction for a  
273 given VRE share depends on the level of interconnection: With an optimal  
274 grid, a mix of 85% wind to 15% solar energy supply is ideal, while in the

275 non-connected case, lower shares of wind (75%) are favorable. Wind energy  
276 is highly variable, while solar energy supply is less stochastic and closer to  
277 the load pattern in the temporal and spatial domain. Solar capacity is fur-  
278 thermore more evenly distributed than wind (see Figure 2). Therefore, wind  
279 energy profits more from interconnection, while solar energy has a systematic  
280 advantage in low-connection cases.

281 If one considers storage as an integration option for VRE, minimal misfit  
282  $\Delta$  (equation 6) would be desirable, as this translates into minimal energy to  
283 be stored and released in total. With an optimal grid, a VRE share of 82%  
284 and a wind contribution of 80% result in minimal  $\Delta$ , i.e., minimal adaption  
285 needs of the residual power system. Again the lower interconnection cases  
286 favor higher shares of solar energy. However, the absolute misfit is lower  
287 with an ideal grid, i.e., the misfit between VRE supply and demand can be  
288 reduced through grid extensions. The grid smoothens the wind supply and  
289 the resulting total European wind generation pattern is closer to demand  
290 than the solar pattern. Solar generation correlates well with demand on a  
291 diurnal timescale, but can not provide a basis to cover electricity demand at  
292 night. Without grid extensions, wind supply is not smooth enough and thus  
293 does not fit very well to the demand.

294 Based on the VRE and backup capacities, average European Costs of  
295 Electricity (CoE) can be determined. Assuming 40% capacity margin as of  
296 today, and coal and gas combined cycle power plants as backup technologies,  
297 the CoE range between 80 and 170 €/MWh with grid extension and can  
298 reach more than 207 €/MWh without grid extensions (see Table 1). Com-  
299 pared to current CoE of conventional technologies, such as 55€/MWh for



€/MWh	<i>high costs</i>	<i>low costs</i>
	Optimal Grid	
$\alpha=10\%, \beta=50\%$	88	76
$\alpha=50\%, \beta=70\%$	131	79
$\alpha=60\%, \beta=60\%$	140	80
$\alpha=80\%, \beta=90\%$	170	87
	No Grid	
$\alpha=10\%, \beta=50\%$	90	83
$\alpha=60\%, \beta=80\%$	143	90
$\alpha=80\%, \beta=90\%$	207	131

Table 1: Average European Costs of Electricity (CoE) per MWh load for different VRE configuration and different levels of interconnection. Two cost scenarios for VREs are studied. In the *high costs* case, VRE investments costs are assumed at 2500€/kW for Solar PV, 1800€/kW for Wind Onshore and 3370€/kW for Wind Offshore; *low costs* are 800, 1000 and 1300€/kW respectively (see Table A.3).

300 coal power plants and 110€/MWh for gas turbines (with a carbon price of  
301 20€/t, see Table A.3), high VRE scenarios might not be economically viable.  
302 With an increased carbon price of 100€/t, VRE scenarios score better in the  
303 comparison, as the CoE of coal power plants rises to 115€/MWh and the  
304 one of gas turbines to 155€/MWh. The costs vary considerably with VRE  
305 share and mix, but also with the assumed wind and solar investment costs  
306 and we therefore present two costs scenarios in Table 1. For high  $\alpha$ , large  
307 VRE overcapacities are necessary and therefore the CoE, computed with re-  
308 spect to electricity demand, exceed the long run marginal costs of the VRE  
309 technologies themselves. Higher costs in the non-connected case are caused  
310 by larger backup and VRE capacity needs. The CoE exclude costs for grid  
311 extension, treated separately in Subsection 3.2.

312 The comparison of adaption needs of the power system and costs for  
313 highly renewable supply with and without grid extension shows that in-  
314 creased interconnection bears important benefits for VRE integration. Grid  
315 extension reduces VRE and backup capacity needs and with it the costs.  
316 Furthermore, smaller misfit between supply and demand plus lower overpro-  
317 duction occur.

### 318 *3.2. Grid costs and structure*

319 The foregoing section showed, that some impacts of VRE to the power  
320 system can be reduced through a powerful overlay transmission grid across  
321 Europe. The costs and dimensions of this grid are specified in this section.

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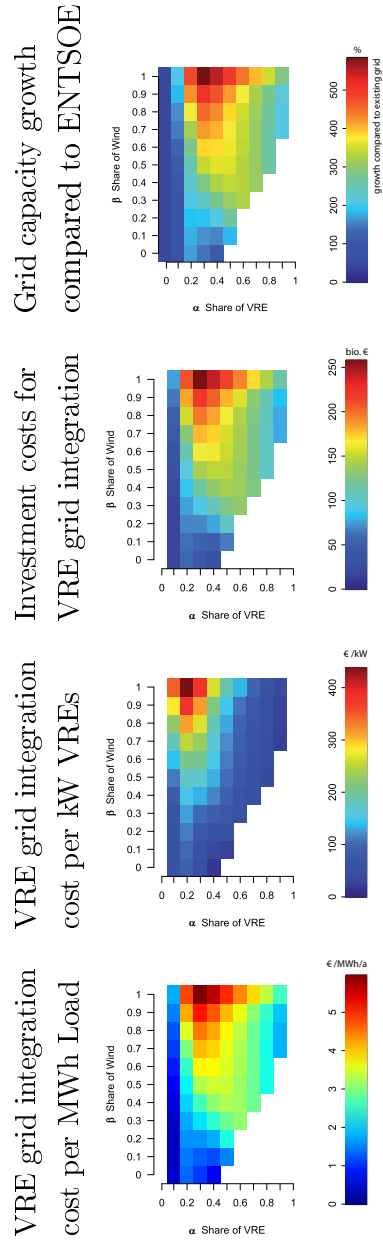


Figure 4: Grid extensions and costs. Grid extensions are the increase in grid capacity and length (MWkm) with respect to the current ENTSO-E grid. Costs are the additional costs due to VRE deployment. They are deduced from incremental grid extensions between the reference case where  $\alpha = \beta = 0$  and configurations with VRE contribution ( $\alpha > 0$ ).

323 Figure 4 shows the total high voltage transmission grid capacity and its  
324 costs resulting from the optimization model URBS-EU. With increasing VRE  
325 share, the total high voltage transmission grid capacity increases to up to the  
326 six fold capacity of today's existing grid. The capacity of the grid is measured  
327 in GWkm and thus contains its length and capacity. For medium VRE shares  
328 of 30% to 50%, an overlay grid is very cost-effective, while in the cases with  
329 very high VRE shares the regional energy production already is high enough  
330 and the advantage of electricity transmission is lower. To assure reliable elec-  
331 tricity supply, sufficient backup capacity has to be built (see Figure 3). We  
332 assume that the distribution of backup capacities in Europe is proportional  
333 to the load in each country, i.e., similar to today's situation. Each country  
334 has the necessary backup capacities available. In cases with very high VRE  
335 shares, these national backup capacities are used to satisfy the demand in the  
336 few hours of regional VRE shortage instead of grid extension for electricity  
337 import. Furthermore, grid capacity rises with  $\beta$ : the linkage between regions  
338 is less preferable for solar than for wind energy. This is due to the long cor-  
339 relation length of solar supply in Europe concerning intradiurnal variations  
340 (Grotz, 2009): it is night at about the same time all over Europe. Also, as  
341 pointed out earlier, solar supply is geographically more evenly dispersed in  
342 Europe and temporally closer to the load.

343 The total investment costs for grid extensions to integrate VRE reach 250  
344 Billion € (second row of Figure 4). Note, that the renewable grid integration  
345 costs are deduced from incremental grid extension between the reference case  
346 where  $\alpha = \beta = 0$  and configuration with VRE contribution ( $\alpha > 0$ ). In the  
347 reference case, transmission grid extensions are cost-optimal as well. These

348 grid extensions, due to a non-cost-optimal structure of the grid today are not  
 349 due to VRE capacity additions and are subtracted to obtain the investment  
 350 costs for VRE integration. The grid investment costs correspond to less than  
 351 20% of the investment costs for VRE capacities for the *high costs* case pre-  
 352 sented in Table 1. Assuming *low costs* for VRE capacities, grid integration  
 353 costs can reach up to 44% in extreme scenarios with  $\alpha=20\%$  and  $\beta=100\%$ .  
 354 In cases with wind contribution  $\beta$  of 70% or lower, the maximal grid integra-  
 355 tion costs amount to 25% of the VRE investment costs. The renewable grid  
 356 integration costs per VRE capacity are shown in the third row of Figure 4.  
 357 In extreme cases, they reach 400 €/kW, but generally they range between 50  
 358 and 250 €/kW. The relative costs peak at medium VRE shares of  $\alpha = 20\%$   
 359 to 40%, which is due to the maximal total grid extensions at medium VRE  
 360 shares and the large VRE capacities for high values of  $\alpha$ .  
 361 The specific renewable grid integration costs resulting from our analysis are  
 362 in accordance with other studies. EWEA (2010) provides an overview of  
 363 different studies, where the specific grid integration costs range between 10  
 364 and 370 €/kW for scenarios of intermediate VRE share. McKinsey et al.  
 365 (2010) find the grid integration costs to amount 83 €/kW for the integration  
 366 of 430 GW wind and 816 GW solar PV in Europe ( $\alpha \approx 40\%$ ,  $\beta=30\%$ ). The  
 367 IEA (2010b) estimates the investment costs for additional interconnection  
 368 to be about 110 €/kW for a scenario, which corresponds to  $\alpha =40\%$  and  
 369  $\beta=80\%$ .  
 370 Sharing the annuity of investment costs for renewable grid integration be-  
 371 tween the consumers, additional CoE arise. They are shown in the last row  
 372 of Figure 4 and reach at most 6 € per MWh load. We assume 40 years

373 economic lifetime of the grid and a weighted average cost of capital of 7%.  
374 Comparing the grid integration costs per MWh load to the CoE, our results  
375 show that they would increase by less than 5% due to the costs for grid  
376 extension (see Table 1 and Figure 4).

377 For the computation of VRE grid integration costs, we assume, that each  
378 country disposes of the necessary backup capacity. However, if national con-  
379 cerns about security of supply are disregarded and a cost-optimal distribution  
380 of backup capacities assumed, the amount of cost-optimal grid extensions in-  
381 creases. Figure 5 shows the total grid extensions for a case with cost-optimal  
382 backup capacity distribution. Here, grid extensions and backup capacities are  
383 optimized simultaneously in the model. This results in a cost-optimal distri-  
384 bution of backup capacities across Europe, which is largely driven by the grid  
385 geometry and VRE capacities. Backup capacity will in this case be built in  
386 well-connected regions to provide backup energy for all Europe across a pow-  
387 erful grid. Through international electricity transmission the total backup  
388 capacity is reduced and can be run more efficiently. It is cheaper to build  
389 more grid and reduce the costs for backup in turn, than to provide backup  
390 energy locally. Therefore, larger grid extensions result. From a system de-  
391 sign perspective, this scenario would be very efficient, but politically it is  
392 highly unlikely, because countries would depend on its neighbours more than  
393 necessary.

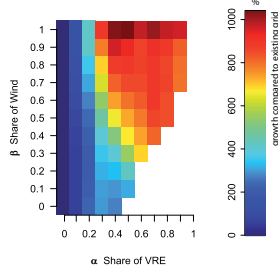


Figure 5: Grid extensions with cost-optimal backup capacity.

394 The geographical structure of the interregional transmission grid, which  
 395 facilitates the VRE integration, is presented in Figure 6. It depicts the  
 396 minimal grid extensions for any scenario with wind share between 60% and  
 397 100% for  $\alpha=30\%$  and 60%. This “must have” grid shows the interconnections,  
 398 which are cost optimal in any case. The structure of the grid is determined  
 399 by the relative distribution of VRE capacities and load centers. Strong north-  
 400 south connections from north-western Europe to the load centers further  
 401 north are prominent features. These power transmission “highways” across  
 402 Germany and France traversing the BeNeLux states and also across Poland  
 403 export the wind energy generated in and around the North Sea southwards.  
 404 Furthermore, an offshore grid in the North Sea as well as the connection of  
 405 Spain and France across the Pyrenees, are crucial. With increasing VRE  
 406 share, north-south connections in central Europe and the connection of Italy  
 407 over the Alps to the rest of Europe gain importance.

$\alpha=30\%$ ,  $\beta=60\%$  to 100%

$\alpha=30\%$ ,  $\beta=60\%$  to 100%

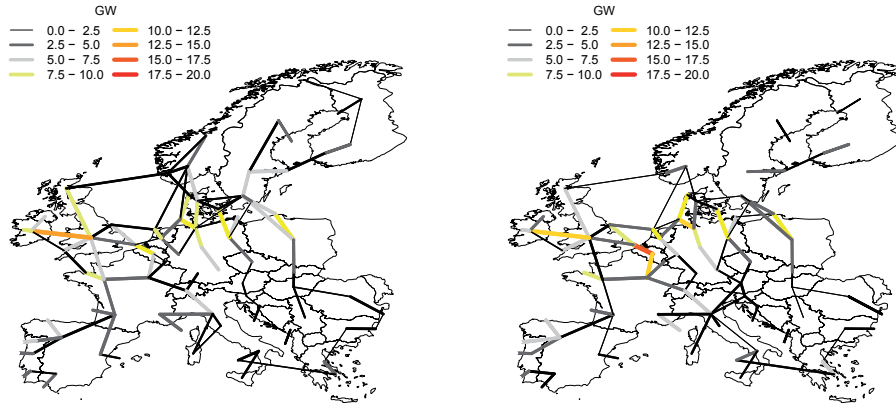


Figure 6: “Must have” grid. Minimal grid extensions on top of existing ENTSO-E grid for varying wind share between 60% and 100%.

### 408 3.3. Mix of backup supply and emissions reduction

409 The major grid extensions presented in the previous section facilitate the  
410 integration of VREs to the power system considerably, but do not solve all  
411 problems. Dispatchable power plants still have to adopt to the fluctuating  
412 supply of VREs. In our model URBS-EU, power plant dispatch is optimized  
413 as well and we can therefore analyse the suitability of different backup tech-  
414 nologies for each VRE configuration: Increasing flexibility is needed with  
415 VRE penetration rise.

416 Figure 7 shows the contribution of different power plant types to the satisfac-  
417 tion of residual load and the resulting emission reductions. As the backup en-  
418 ergy mix strongly depends on the installed capacity of thermal power plants,  
419 we analyse two scenarios. The left column of Figure 7 shows the backup



420 energy mix for a scenario, where today's capacity mix is assumed. The right  
421 column shows the backup energy mix for a cost-optimal capacity mix for  
422 each VRE scenario.

423 With increasing VRE share, more flexible backup technologies are nec-  
424 essary. Coal and nuclear, today's rather inflexible mid- and baseload power  
425 plants, become unsuitable with increasing VRE shares. In turn, more flexible  
426 technologies, such as gas, hydro and biomass power plants, are needed. The  
427 extent of this fuel switch however depends on the speed of VRE capacity  
428 build up. If Europe realized one of the VRE scenarios instantaneously, to-  
429 day's backup capacities would still be on line and the left column would be  
430 valid. If the build up of VRE capacity takes longer than the lifetime of the  
431 existing power plants, the right column is closer to reality.

432 While existing coal and nuclear power plants can still supply backup up to  
433 larger shares of VRE, the reduction of FLHs for coal and nuclear power plants  
434 through VRE penetration renders new investments in these capital-intensive  
435 technologies uneconomic in terms of overall costs. This will be the case for  
436 VRE penetration above 30%. A remarkably sharp threshold occurs, as can  
437 be seen in the right column of Figure 7.

438 As both scenarios contain cost-optimal grid extensions, the thresholds for  
439 technology suitability have to be understood as upper limits. Especially  
440 for regions with high VRE shares inflexible backup technologies face eco-  
441 nomic difficulties at lower overall  $\alpha$  if fewer grid extensions are realized  
442 (Schaber et al., 2011).

443 The last row of Figure 7 shows the emission reduction for both scenarios. It  
444 increases with  $\alpha$  and is determined by coal phase-out and the role of gas for

445 higher VRE shares.

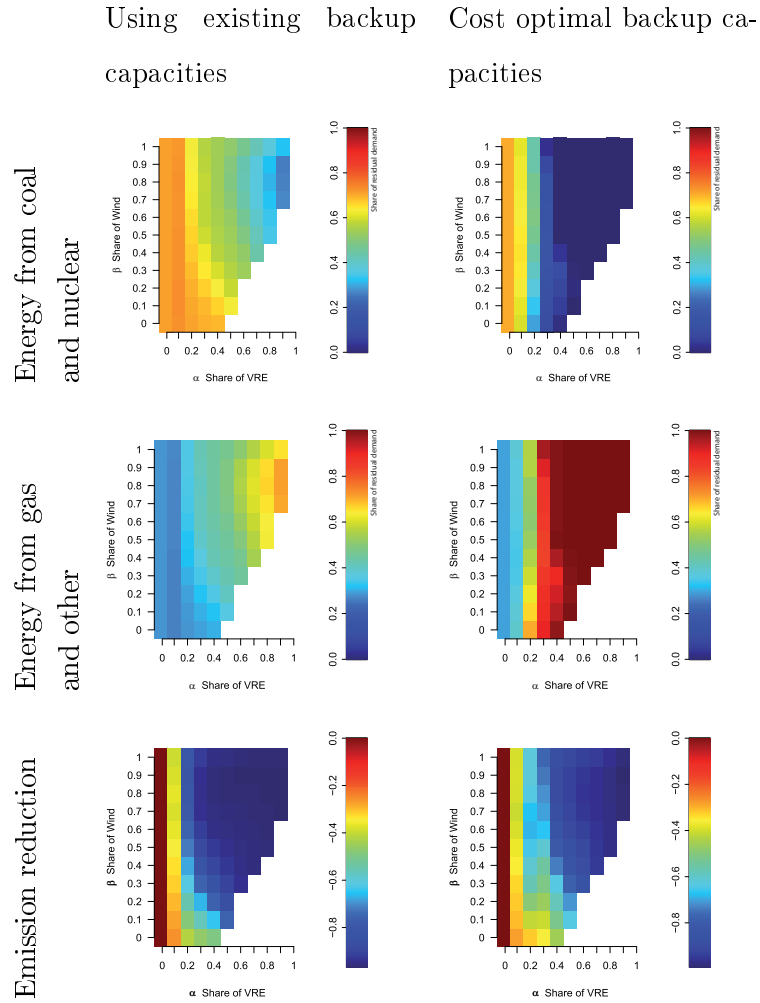


Figure 7: Energy by conventional power plants and emission reduction. The backup energy is shown as share of total residual demand, being total load to be supplied by backup power plants. “Other” stands for bioenergy, hydro and oil power plants.

### 446 3.4. Casestudy: 60% VRE penetration in 2050

447 We studied a large range of VRE scenarios and presented their respective  
 448 impacts on the power system. To provide guidance to the reader, we apply

449 our results to an exemplary VRE scenario and sketch a possible roadmap  
 450 how to reach this scenario from today's situation.

451 We define our exemplary scenario based on the following assumptions.  
 452 Until 2050, strong emission reductions have to be achieved by the Euro-  
 453 pean power sector. Wind and solar energy will play an important role in  
 454 the electricity supply in 2050 and satisfy 60% of electricity load. Based on  
 455 our results, advantageous design features of a power system with 60% VRE  
 456 penetration can be determined.

	Optimal Grid	No Grid
Ideal mix to achieve minimal $\Delta$ at $\alpha=60\%$	$\beta=85\%$	$\beta=65\%$
Parameter values at the identified point		
Misfit $\Delta$	40% of total demand	50% of total demand
Overproduction	<1% of total demand	10% of total demand
Backup capacity	80% of peak load	100% of peak load
CoE (high VRE costs)	140€/MWh	150€/MWh
CoE (low VRE costs)	80€/MWh	90€/MWh
Grid integration costs	3€/MWh (load)	-

Table 2: Power system properties with VRE penetration of 60%.

457 Figure 3 provides a good overview on the integration challenges of 60%  
 458 VRE penetration and the role of grid extensions. With minimal misfit  $\Delta$ ,  
 459 lowest adaption needs of the power system occur, as supply is closest to  
 460 demand. As can be read from the last row of Figure 3, minimal misfit  $\Delta$   
 461 for a VRE share of 60% translates to wind share of 85% with and to 65%

462 without grid extension (see Table 2). The absolute misfit is lower with grid.  
463 Without grid extensions, wind supply is not smooth enough and thus does  
464 not fit very well to the demand. The systematic advantage of solar energy for  
465 low connection cases due its good fit to the diurnal load pattern re-emerges.  
466 Table 2 also shows that through grid extension, the necessary backup can  
467 be reduced by 20%, i.e., around 100 GW. Overproduction amounts to 10%  
468 without grid and less then 1% with grid extension. About 300 TWh excess  
469 production can thus be avoided with grid extensions. Also, the CoE, driven  
470 by total – backup and VRE – capacity can be lowered by 10€/MWh, while  
471 the costs for the grid only amount to 3€/MWh. Thus, the transmission  
472 grid extensions, coming at total investment costs of 150 billion €, are cost-  
473 effective. Until 2050, large parts of today’s power plants will be shut down  
474 and an adapted backup capacity mix is possible. Following our analysis  
475 in Figure 7, only flexible power plants, mainly gas, will be suitable for a  
476 VRE penetration of 60%. The achieved emission reduction through the VRE  
477 capacity is roughly 85% (Figure 7) in the case with grid extension. Due to  
478 the fuel switch to gas power plants, a more flexible technology, the emission  
479 reduction is larger than the share of VRE.

480 An advantageous system with 60% VRE should thus have a high share of  
481 wind energy, ideally 80% and a powerful transmission grid to integrate wind  
482 and solar energy. It should also provide backup energy from flexible power  
483 plants, such as biogas, hydro or gas power plants.

484 Today’s VRE penetration in Europe amounts to 5% with a contribution  
485 of wind of 86% (IEA, 2011b). The necessary steps in terms of system design  
486 to reach 60% VRE penetration with more than 60% wind in 2050 can be

487 identified from our results. A total of about 1500 GW wind and solar capacity  
488 has to be built until 2050, i.e., 38 GW/year in Europe. In 2009 and 2010, each  
489 year the last two years, 18.5 GW of new wind and solar PV capacities have  
490 been installed on average (GWEC, 2011; EPIA, 2011). The build up speed  
491 thus has to be doubled. Second, transmission grid extensions should be built  
492 to integrate these large capacities. The necessary grid capacity extensions  
493 amount to about the triple of the existing grid and planning should therefore  
494 start as soon as possible. Important grid corridors are shown in Figure 6.  
495 Finally, new dispatchable capacities, which will serve as backup for the VREs,  
496 should be chosen in accordance to the increasing flexibility requirement.

#### 497 4. Discussion and Conclusion

498 In this paper, we analyze the integration challenges of VREs in Europe  
499 and the role of grid extensions as a measure to alleviate these. We apply  
500 the model URBS-EU, an advanced model of the European power system,  
501 to analyze each possible VRE configuration on the defined parameter space,  
502 spanned by the VRE penetration  $\alpha$  and the mix between wind and solar PV  
503 energy  $\beta$ . This parametric study allows us to identify advantageous system  
504 designs features for each level of VRE penetration, insights of high relevance  
505 for the conception of renewable energy policies and long term targets.

506 We find that generally, major integration challenges occur with increasing  
507 VRE penetration: Large backup capacity is required and important overpro-  
508 duction and misfit between supply and demand occur. Grid extensions allevi-  
509 ate these challenges, as they smoothen the temporal fluctuations and remedy  
510 the geographical dispersion of VRE. As a consequence, required backup ca-  
511 pacity, overproduction and the misfit between VRE supply and demand are  
512 reduced. Grid integration costs remain below 25% of the VRE investment  
513 costs for all conceivable VRE scenario. From our results the most important  
514 corridors for new transmission lines can be identified. Finally, we show that  
515 increasingly more flexible power plants are needed with rising VRE penetra-  
516 tion.

517 Based on eight-year meteorological timeseries of wind and solar availabil-  
518 ity, it is proven, that VRE penetration of more than 80% is possible. These  
519 high VRE shares, however come at the cost of large wind and solar capacities,  
520 excelling the peak load by up to 10 times. Due to the restricted availability  
521 of VRE with annual utilization rates of 30% or lower (i.e., FLHs of 2600 or

522 lower), a VRE powered system always needs larger total capacity, than a sys-  
523 tem with dispatchable power plants. On top of that, large backup capacities  
524 are needed to ensure reliable power supply. These large capacities lead to  
525 high CoE generation of up to 130 €/MWh in the most extreme cases (*low*  
526 *costs* case). With grid extensions, the necessary backup and VRE capacities  
527 can be reduced and with it the costs of producing electricity. With an op-  
528 timal CoE of roughly 80 €/MWh result. These are below the CoE of coal  
529 power plants of 115€/MWh, if a high carbon costs of 100€/t is assumed.  
530 Furthermore, the overproduction and the misfit between supply and demand  
531 are lowered through grid extensions. This entails less adaption need for the  
532 remaining power system, being backup power plants and storage.

533 The mix between wind and solar energy also influences the above dis-  
534 cussed system properties. Firstly, solar PV cannot provide power at night  
535 and thus, VRE shares above 40% can not be realized with solar energy only.  
536 To reach higher VRE shares, an important contribution of wind energy –  
537 40% or more – is necessary. Wind energy can – especially in combination  
538 with grid extensions – provide a “fairly smooth” supply. For large  $\alpha$  ( $>40\%$ )  
539 this furthermore results in lower backup capacity requirements and misfit be-  
540 tween supply. Wind is necessary for high VRE penetration and has further  
541 important advantages compared to solar energy, especially in combination  
542 with grid extensions. Without grid extensions, wind supply is less smooth  
543 and does not fit very well to the demand, while the diurnal pattern of solar  
544 energy fits rather well to the diurnal load pattern. Thus, without grid exten-  
545 sions, a larger share of solar energy is favorable to have important shares of  
546 solar energy, around 30-50% in the system..

547 Having identified the advantages of a powerful overlay grid, for the in-  
548 tegration of VRE in Europe, the costs of such a “super-grid” are of high  
549 relevance. We quantified the grid integration costs for all possible VRE sce-  
550 narios and find that the costs for such a grid reaches at most 6 €/MWh load  
551 for all VRE scenarios. This is roughly the double of the tariffs paid today in  
552 Germany, for example (ENTSO-E, 2011a). Grid integration costs generally  
553 increase with VRE share, but for very high shares, saturation effects occur.  
554 Solar energy needs less grid extension. This is due to the long correlation  
555 length of the solar availability pattern: It is night at about the same time  
556 all over Europe (see also Grotz, 2009) and therefore solar energy profits less  
557 from grid extension, than wind energy.  
558 Generally, the additional grid capacities to be build are large. For the sce-  
559 nario investigated in our casestudy, the triple of today’s grid capacity would  
560 be necessary. As the acceptance and building process for new transmission  
561 lines can reach up to ten years, early planning is crucial for the integration  
562 of VREs in Europe. We identified important connections in Europe for the  
563 integration of VREs. Those are strong north-south connections from North-  
564 ern Scandinavia and Denmark to the load centers in Germany and France  
565 traversing the BeNeLux states and an offshore grid in the North Sea. Better  
566 connection of Spain and France and the connection of Italy over the Alps to  
567 the rest of Europe are crucial as well. To enable large shares of renewable  
568 energies, these transmission grid extensions should be on the EU’s priority  
569 agenda for the next years.  
570 The model only accounts for a macroscopic interregional energy transmission  
571 network, a European overlay network. The computations do not include net-



572 work costs for upgrading the distribution networks, important especially for  
573 PV.

574     Apart from a powerful grid, future power systems with important VRE  
575 penetration need flexible backup power plants. Through increased interlink-  
576 age, VRE generation can be smoothed to some extent, but the high vari-  
577 ability of the residual load remains. For investment in new power plants, the  
578 contribution of VRE to the future power supply should be taken into account.  
579 Our results show that for coal and especially for nuclear power plants a clear  
580 limit in suitability occurs: at VRE shares above 30%, these power plants  
581 are uneconomic from a total system cost perspective, but flexible technologies  
582 such as gas power plants are adequate.

583     Our analysis does not investigate storage as an integration option. We  
584 acknowledge its importance for VRE integration and recommend further re-  
585 search on the interaction of grid and storage, possibly based on these results.  
586 A related topic, which is not treated in this study, is the very short term vari-  
587 ability of supply and ramping requirements for backup power plants. A closer  
588 look into the role and value of flexibility appears very promising. We fur-  
589 thermore recommend the application of a comparable methodology to other  
590 regions of the world to gain more general understanding of the drivers of grid  
591 extensions identified here.

592     The above described results of our parametric study can provide a helpful  
593 overview for the design of renewable energy policies. In a casestudy for VRE  
594 penetration of 60% in 2050, we illustrate that our results can guide deci-  
595 sions about how to design a power system that is well adapted to the desired  
596 VRE share and thus faces minimal integration challenges. Transmission grid

597 extensions are cost-effective and allow to reduce the required backup power  
598 by 100 GW and overproduction by 300 TWh. To realize this target, politi-  
599 cal support is crucial: for capacity build-up of VREs and for planning and  
600 investment in grid extensions on the crucial corridors, that we identified.

601 VRE integration in Europe is very challenging and detailed information  
602 about the implications of high wind and/or solar shares in the power sup-  
603 ply are vital for investment decisions, the conception of policies and VRE  
604 integration measures. We provide an overview of the system implication  
605 of all possible VRE scenarios in Europe and show, that a powerful overlay  
606 transmission grid reduces the adaption need of the remaining power system  
607 considerably, while its costs remain below 6€/MWh for all VRE configura-  
608 tions.

609 **Appendix A. Model setup**

	Inv. Costs	Fix O&M	Var. O&M	Fuel prices	$\eta$	$pc$	$af$	Life-time
			Costs					
Biomass/fuel power plants	2500	50	0.4	0.54	38%	25%	40%	25
Coal steam turbine	1400	35	0.4	0.79	46%	22%	80%	30
Gas combined cycle	400	18	0.19	2.52	38%	100%	100%	25
Gas turbine	650	18	0.19	2.52	60%	22%	90%	25
Geothermal power plants	2800	80	0.4		100%	25%	100%	25
Lignite steam turbine	2300	40	0.4	0.39	43%	14%	80%	30
Oil combined cycle	900	18	0.2	4.38	50%	22%	90%	25
Oil gas turbine	800	18	0.1	4.38	35%	100%	100%	25
Nuclear	3000	65	0.2	0.32	33%	8%	80%	40
Hydro run of river	1400	20	0.5		75%	0.5%	100%	40
Solar PV	800-	25	0		100%	100%	100%	25
	2500							
Wind power onshore	1000-	30	0		100%	100%	100%	25
	1800							
Wind power offshore	1300-	40	0		100%	100%	100%	25
	3370							
Hydro pumped storage	1539	20	0.01		85%	100%	100%	40
Transmission grid	800	0	1e-5		4% loss/1000km	1	100%	40

Table A.3: Technical and economic parameters. Investment and Operation and Maintenance (O&M) costs are given in €/kW<sub>el</sub> and €/kWh<sub>el</sub>, €/MWkm and €/kWh<sub>el</sub>km respectively. Additionally to the fuel costs a carbon price of 20 €/t is assumed. The technical parameters efficiency  $\eta$ , power change  $pc$  and availability factor  $af$  are given in %.

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