Curtailment: an option for cost-efficient integration of variable renewable generation?

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According to the European Directive 2009/28/EC [1], renewable energy systems (RES) enjoy preferential treatment in the electricity grid in so far as the secure operation of the power system permits. However, there will be times when it is not possible to accommodate all priority dispatch generation such as variable renewable generation (VRG) sources like wind and solar while maintaining the safe operation of the power system. Security-based limits have to be imposed, due to both local network and system-wide security issues. Therefore, it is necessary to reduce the output of variable renewable generators below their maximum available level on occasions when these security limits are reached. This reduction of VRG is referred to as "curtailment" and is consistent with the principle of priority dispatch.

In the directive, Member States are explicitly requested to minimise the use of curtailment. Simultaneously, ambitious targets for the development of RES are set. In some countries this leads to a remarkable increase in the production of electricity from variable renewable sources, such as wind and solar. Beside the supply security issue, the question of cost-efficient integration of this rapidly growing source of generation is also crucial from an economy and social acceptance viewpoint. Jacobsen et al. (2012)[2] argue that the curtailment of a small percentage of VRG feed-in may be optimal from a power systems operation and cost-efficient perspective.

This paper gives a brief overview of the current situation and future prospects concerning variable renewable curtailment in the EU. Furthermore, it suggests a closer look at the potential risks and benefits of curtailment.

Selected Member States

Figure 1 displays the share of wind, photovoltaics and their sum in electricity consumption in EU Member States in 2012 and 2020 according to the National Renewable Energy Action Plan targets.

The graph illustrates the disparity between the different Member States concerning the actual and future role of VRG in their electricity mix. The distinctions can be explained by different Member States specific RES targets and the different availability of other RES sources like hydro power or biomass. The figure makes clear that the integration of VRG is currently an eminent issue in Denmark, Germany, Ireland, Spain, Italy and Portugal. Therefore, the analysis of the situation concerning VRG curtailment is only assessed for these Member

[1] Article 16(2)

[2] Jacobsen, H.K., Schröder, S. T., 'Curtailment of renewable generation : Economic optimality and incentives', *Energy Policy*, vol. 49, 2012, p. 663-675

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States. Nevertheless, according to their NREAP targets, other Member States like Greece, the Netherlands and the United Kingdom will also need to deal with a considerable variable wind and solar feed-in in the years to come.

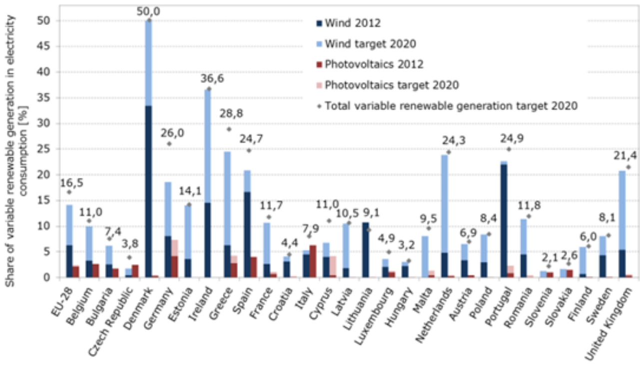

Figure 1 : Share of variable RES in electricity consumption in 2012 and 2020 (according to National Renewable Energy Action Plan targets)[3]

Status quo

The amount of curtailed VRG feed-in in the EU in the period 2009-2012 can be seen in Table 1. Motives for curtailing differ in the concerned Member States. This section gives an overview of the different situations leading to the use of curtailment for VRG.

	Curtailed VRG feed-in[4] [GWh]			
	2009	**2010**	**2011**	**2012**
Germany	74 (0.2%)	127 (0.3%)	421 (0.6%)	385 (0.5%)
Ireland	n.a.	26 (1.0 %)	106 (2.4%)	103 (2.5%)
Spain	40 (0.1%)	320 (0.6%)	202 (0.4%)	148 (0.3%)
Italy	700 (9.7%)	527 (4.8%)	264 (1.3%)	166 (0.5%)

Table 1: Curtailed VRG in EU Member States in GWh and as percentage of total VRG feed-in.[5,6,7,8]

Denmark

An interesting situation concerning VRG curtailment is occurring in Denmark. Even though wind feed-in exceeded demand for 848 hours or nearly 10% of the time in the Western Danish electricity system in 2012, curtailment was close to zero[4]. This is due to strong interconnection with Germany and Norway and the availability of hydro resources in Nordic Countries. If spot market prices fall below a minimum price floor, which is currently -500 €/MWh selling bids beyond this limit would be curtailed. This happens very rarely even though negative prices occur about 0.5% of the time[9].

Germany

In Germany, congestion in the distribution system is the main driver for VRG curtailment. To date 98% of the curtailed energy in 2012 was caused by scaling back on the distribution grid level, while only the remaining 2% was curtailed on the transmission grid level. Also in 2012, 93% of the curtailed VRG was from wind power, which is concentrated in northern Germany and a cause of congestion. However, in 2012 for the first time, southern Germany's distribution grids were also affected by curtailment as the growing PV share strained the distribution grid. However, PV accounts for only 4% of the curtailed VRG with the remaining 3% coming from other RES source[10]. A situation where variable renewable generation exceeds demand hasn't yet been observed in Germany, but negative electricity prices occur even more often than in Denmark. This can be attributed to a relatively high base of conventional must-run capacity. A current study[11] states that if this must-run capacity doesn't decrease by 2022, the number of hours with negative prices could

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[3] Eurostat and National Renewable Energy Action Plans
[4] No considerable amounts of VRG feed-in have been curtailed in Denmark and Portugal
[5] Lew, D. et al., 'Wind and Solar Curtailment', NREL, 2013
[6] Bundesnetzagentur, 'Monitoringreport 2013
[7] EirGrid, 'Curtailment Report', 2011 and 2012

[8] Red Eléctrica de España (REE)
[9] Nord Pool Spot, 2014
[10] Bundesnetzagentur, 'Monitoringreport 2013'
[11] Agora Energiewende, 'Negative Electricity Prices : Cause and Effect', 2014

exceed 1,000. Further background concerning negative electricity prices can be found in Appendix A.

Ireland

The situation in Ireland is worth special attention as the power system currently faces challenges concerning the integration of VRG that may face larger systems in the future. Real time instantaneous penetration of wind power plants of 50% poses operational challenges to the power system operation. The fundamental issues which give rise to curtailment in Ireland are being addressed by the DS3 programme[12]. This programme has been specifically designed to securely and efficiently increase the level of System Non-Synchronous Penetration (SNSP) which can be accommodated on the system and also address other system wide limitations (see Equation 1 in Appendix B for definition).

Studies from the DS3 programme indicate that it would not be prudent to operate the power system above aggregate levels of SNSP of 50% without addressing a number of important issues. Specifically, the main limitations are in the frequency response of the system following the loss of the largest in-feed which could result in rates of change of frequency (RoCoF) greater than 0.5 Hz/s. This could lead to the cascade tripping of all generators on the system as they are not currently obliged under the grid code to withstand such a rate of change. In addition, protection settings on distribution connected units, which use RoCoF protection to manage islanding situations, would also be a factor. It is likely that, even by addressing all these issues, it would not be prudent to operate the power system above SNSP levels of 75%[13]. While mitigation measures can be employed, it will be necessary, in order to operate a secure power system, to curtail VRG output at times. A study assessing the possible future development of grid security based curtailment in Ireland is presented in Appendix C.

The level of VRG curtailment in Ireland is affected by a number of factors which vary from year to year. The amount of wind installed on the system and the capacity factor of the wind generation will have an impact on the levels of curtailment. The level of demand is another important factor which can change between the years. The testing and commissioning of new units can lead to increased levels of curtailment as new units are afforded priority during this commissioning process. Generally, curtailment typically occurs during periods of low demand most often overnight and in the morning, when the minimum generation levels of conventional plants are imposed.

Spain

Throughout most of 2009, VRG curtailment in Spain was primarily due to inadequate transmission and distribution system capacity. Since the end of 2009, however, a growing share of wind energy is also curtailed due to limited demand[4]. As Figure 2 illustrates, limited transmission capacity of the Iberian Peninsula to France is a bottleneck.

Figure 2 details the electricity import capacities of the Member States in relation to the respective generation capacities in 2011 and according to the ENTSO-E Ten Year Network Development Plan for 2020[14].

The Spanish system operator Red Eléctrica de España in consequence expects to curtail 1.6 TWh or 2.2 % of variable RES by 2016. For 2020, it is estimated that 3.6 % of wind and solar generation may be curtailed. Short assessments of the current situation

[12] http://www.eirgrid.com/operations/ds3/

[13] O'Sullivan, J. et al., 2012. 'Achieving the Highest Levels of Wind Integration', IEEE Transactions on Sustainable Energy 3, 2012, p. 819–826

[14] ENTSO-E, '10-Year Network Development Plan 2012'

concerning VRG curtailment in Italy and Portugal can be found in Appendix D and E.

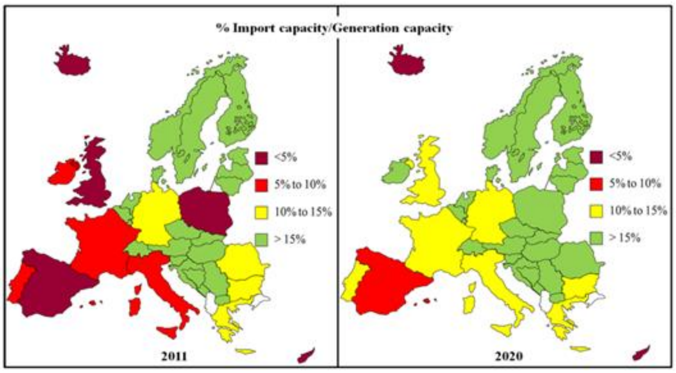

Figure 2: Proportion between import capacity and generation capacity in 2011 and 2020 (Ten Year Network Development Plan target)[14]

Future prospects

As the foregoing analysis showed, curtailment of VRG feed-in in the EU to date is driven by technical grid security reasons and not by economic reasons. Negative residual loads are not yet occurring often and only in a few regions of the EU. If the targets concerning the share of RES in electricity consumption are met, this will heavily reshape the residual load curves in a number of Member States.

Possible development of the residual load and possible impacts

As an example, Figure 3 highlights possible patterns of the residual load duration curve in Germany with a RES share of 50%, 80% and 100%, illustrating the expected magnitude of surplus energy and power in the years to come.

European regulation requests Member States to take appropriate grid and market-related operational measures in order to minimise curtailment. In consequence, the current energy infrastructure in the concerned regions and countries has to be strengthened to be able to accommodate the distributed and temporal unsteady feed-in of high shares of VRG. If innovative approaches like demand side integration, power-to-heat or power-to gas remain out of consideration, this implies major investments in grid infrastructure and storages. Beside their environmental implications, these investments are potentially highly inefficient from a micro- and macro-economic point of view as their capacity utilisation might be very low. This is due to the reason that local and system wide peaks in renewable feed-in occur only in a small number of hours a year. Thus, the current regulation in place could potentially lead to a future electricity system that is not cost-efficient and further the likelihood of increasing electricity retail prices and decreasing social acceptance for renewable energy systems.

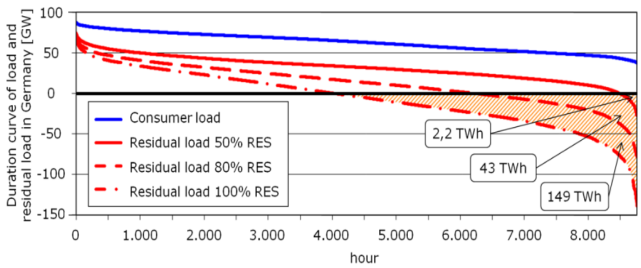

Figure 3: Possible development of the German residual load at different shares of renewable energy systems[15]

Possible economic effects of curtailment

The use of VRG curtailment not only for grid security but also for economic reasons can potentially contribute to a significant reduction of investment needs in both grid and storage extension. For that purpose, the power output of VRG plants would have to be limited in some hours of the year, but their energy production over the year would only decrease by a small percentage (see further assessment in Appendix F). A current study by the German Energy Agency[16] indicates that the costs for

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[15] Source: Institute of Energy Economics and the Rational Use of Energy, University of Stuttgart
[16] Deutsche Energie-Agentur, 'dena Smart Meter Study', 2014

distribution grid extension in Germany to the year 2030 could decrease by 30% if limitation of VRG plants to 70% of their maximum power output was allowed.

A study by Jacobsen et al. (2012)[2] states that curtailment of VRG may not only lead to avoided investment costs in energy infrastructure but also to avoided operational costs for systems reserve procurement and regulating energy. This is due to the reduction of possible forecast errors for VRG feed-in influencing the necessary reserve provision. The economical importance of this effect depends on the future development of the forecast accuracy and of market coupling effects on the reserve procurement need.

However, there is also an effect of curtailment on the systems operation costs that goes in the opposite direction. Curtailment reduces the share of the consumer load covered by renewable energies. When curtailment occurs because of network congestion, the 'missing' electricity production must be met elsewhere by conventional capacities. When curtailment occurs because of excess power supply, the curtailed energy cannot be brought back into the system later when the residual load is positive. Consequently, curtailment increases fuel use and generation related emissions of the conventional power plants. This has negative implications on the systems operation costs and the external costs that aren't covered by the EU Emissions Trading System.

Conclusions and way forward

An obvious policy ambition is to achieve a level of curtailment that balances socio-economic benefits with all costs (including externalities)[2]. From a theoretical perspective, curtailment should take place up to the point where the marginal system cost of avoiding this curtailment equals the marginal value of spilled energy. For an adequate economic evaluation, however, the use of curtailment has to be compared to other options for balancing the feed-in of VRG.

Recommendation: a model-based assessment of the optimal use of curtailment considering all relevant alternatives

Concurrent or additive flexibility options for an efficient integration of variable renewable generation are the extension of networks, the installation of bulk and distributed storage, the use of demand side integration, the flexible operation of conventional power stations as well as the use of power-to-heat and power-to-gas. In all these fields, it is very important to invest resources to speed up innovation in order to manage energy more efficiently. An integral assessment of curtailment should be supported by a comprehensive optimisation model with high temporal and regional resolution considering all relevant flexibility options. For example, an approach like in Pudjianto et al. (2014)[17] could be adapted with a focus on the possible role of curtailment and application for the whole EU. The mentioned study suggests a whole-systems approach that simultaneously optimises investment into new generation, network and storage capacity, while minimising system operation cost, and also considering reserve and security requirements.

Consideration of all relevant impacts

However, it should be mentioned that possible adjustments of the European regulation concerning curtailment might negatively affect investor confidence and, consequently, could increase the interest rate in the project financing of VRG plants. Another possible impact of facilitating the use of curtailment for economic reasons is that innovation may be

[17] Pudjianto, D. et al., 'Whole-Systems Assessment of the Value of Energy Storage in Low-Carbon Electricity Systems', *IEEE Transactions on Smart Grid*, vol. 5, no. 2, 2014, p. 1098-1109

less stimulated in the field of energy storage and other technologies enabling a reduction of the necessary curtailment for grid security reasons. These innovations potentially can make a significant contribution to a cost-efficient integration of VRG. Not least, uniform and transparent rules concerning curtailment between countries and neighbour systems are important to avoid asymmetrical impacts. These aspects must be carefully taken into account when adjustments of the European regulation concerning curtailment are made and could, therefore, be part of a wider assessment.

For further reading or information, please visit *www.insightenergy.org*

Appendix A: Negative electricity prices

To date, negative electricity prices have been allowed in the countries covered by the European Power Exchange (EPEX), i.e., France, Germany, Austria and Switzerland, in the countries covered by Nord Pool, i.e., Denmark, Estonia, Finland, Latvia, Lithuania, Norway, and Sweden, as well as in Belgium and the Netherlands. Electricity markets with particularly frequent occurrences of negative prices are Germany and Denmark. Situations with extremely low prices were observed, for example in October 2009 in Germany reaching −500 €/MWh or at Christmas 2012 in Germany and Denmark reaching -200 €/MWh[18].

Appendix B: Definition of the System Non-Synchronous Penetration (SNSP)

Equation 1:

$$\text{SNSP} = \frac{\text{wind generation} + \text{HVDC imports}}{\text{system demand} + \text{HVDC exports}}$$

Appendix C: Possible development of grid security based curtailment in Ireland

A study for the 2020 Irish electricity system[19] shows where the level of grid security based curtailment could continue in the years to come. It indicates that wind curtailment levels of 7% could exist if a SNSP level of 75% was achieved. A lower SNSP would lead to higher levels of curtailment.

Figure 4 presents results from an hourly production cost model for the Irish system in the year 2020 with over 6000 MW of wind power plants assumed to be connected[13]. Sensitivities with respect to SNSP limits from 60% to 100% are modelled as well as varying levels of HVDC exports. The maximum allowable SNSP level has a direct impact on the annual curtailment of wind power plants. In particular, the higher the maximum allowable SNSP the lower the curtailment levels on wind power plants in all cases. Significantly, this has a direct effect on the annual percentage of electricity from renewable energy and ultimately the efficacy of the investment in wind power plants.

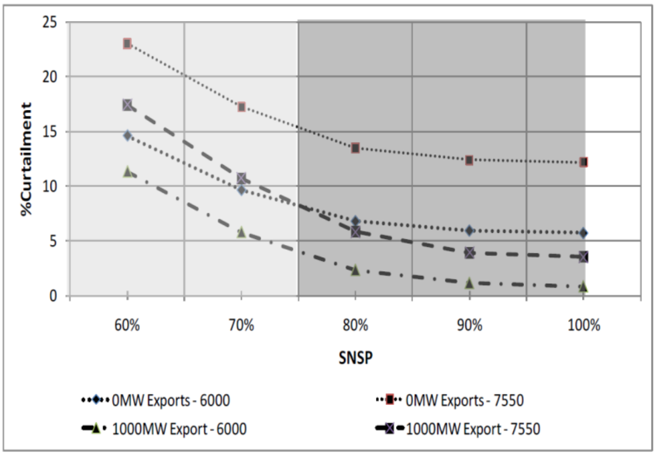

Figure 4: Curtailment levels on wind power plants with respect to maximum allowable SNSP operational limit[13].

Appendix D: Status quo concerning curtailment in Italy

As the majority of wind power plants in Italy are connected to the transmission grid and located in Southern Italy, transmission grid congestion is a very important reason for curtailment. In the past years, network upgrades and extensions have improved the situation considerably. From a 10% share of VRG feed-in curtailed in 2009, the figure went down to less than 1% in three years (see Table 1).

[18] European Power Exchange, 2014
[19] McGarrigle, E.V. et al., 'How much wind energy will be curtailed on the 2020 Irish power system?' Renewable Energy 55, 2013, p. 544–553.

Appendix E: Status quo concerning curtailment in Portugal

In Portugal, legislation allows curtailment of renewable energy generation only for contracts signed after 2007, and then only for technical reasons. Several instances of wind and other non-dispatchable sources of generation exceeding demand have already occurred.

Appendix F: Impact of power limitation on the energy output of wind and photovoltaic plants

Krzikalla et al. (2013)[20] analysed historic feed-in curves for Germany and concluded that the reduction of the wind power plants to 70 % of their maximum power output would decreased their energy output by only 1.3% in the year 2011. A power limitation to 80% would have led to an energy output reduction of 0.5%. For PV a limitation to 70% of the maximum power would have caused a loss of 2% of the energy output in 2012. With a limitation to 80% this figure would have been 0.5%.

[20] Krzikalla, N. et al., 'Möglichkeiten zum Ausgleich fluktuierender Einspeisungen aus Erneuerbaren Energien', 2013