Too Much of a Good Thing: Reducing Emissions by Curtailing Renewables in Power Systems Operation

Conference Paper · June 2021

Too Much of a Good Thing: Reducing Emissions by Curtailing Renewables in Power Systems Operation

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Abstract

To lower pollution, it became imperative to integrate as much renewable energies as possible in power systems. This has been translated into forcing the maximum production of variable renewable energy (VRE) ---wind and solar--- into power systems operation. The increasing operational costs to maximize the VRE output became the price to pay in order to lower pollution. However, here we show that it is a common misconception that forcing VRE production always lowers pollution. We present some examples illustrating that, apart from increasing costs, forcing VRE production can also increase pollution.

Keywords

Flexibility, DC optimal power flow, optimal dispatch, power systems operation, variable renewable energy, wind and solar energy.

1 Introduction

Variable renewable energy sources (VRE), such as wind and solar, are the key sources to reach a sustainable future with zero emissions. Wind and solar sources are the leading renewable technologies in the electricity sector, and they have been firmly penetrating current power systems worldwide. This is mainly due to technological maturity, zero emissions, costless and abundance fuel resources, and widespread availability.

In order to reach high shares of VRE in power systems, renewable energy producers are receiving many incentives to guarantee their recovery of investment costs. Usually these incentives go from investment and/or operational subsidies to guaranteed (and preferred) priority access to the grid. The clear objective anyway is to increase the VRE energy production by fully dispatching them into power systems.

However, dispatching VRE as much as possible poses new challenges to power systems operation, some of the main challenges are [1]: 1) variability, 2) uncertainty, 3) non-synchronous generation[1], 4) low capacity factor (VRE production is weather dependent), and 5) location-specificity, where more transmission is required to release the full VRE potential from different locations. Note that all the 5 challenges require conventional generation to remain functioning. Especially for the first 4 challenges, a significant amount of conventional generation is needed to provide flexibility to the system (usually through reserves) to face the VRE's variability and uncertainty as well as to keep the system stable (challenge 3). For the sake of a secure system operation, conventional units providing reserves have a higher priority dispatch than VRE. That is, when there is a high VRE production, units providing reserves inevitably produce a minimum energy level that supplies part of the demand, then to keep the perfect balance between supply and demand, the excess of VRE must be curtailed. Finally, to maximize the dispatch of VRE despite their location in the network (challenge 5), again

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[1] More VRE production displaces traditional synchronous generation, which is needed to provide voltage and frequency stability to the system. To keep a stable operation of the system, a minimum amount of synchronous generation is needed, and when this minimum is reached, VRE must be curtailed.

Table 1: Generator Data

		Max Output [MW]	Max ramp rate [MW/h]	Marginal cost [$/MWh]	Marginal CO2 Emissions [ton/MWh]
G1	CCGT (natural gas)	300	120	20	0.320
G2	Gasturbine (petroleum)	150	100	285	0.985
G3	Wind	–	–	0	0

highly dispatchable (usually) conventional units are required to alleviate congestion in meshed grids[2], as shown in Section 2.1.

Curtailing VRE is considered undesirable, and is usually accepted when it is caused by emergencies or technical limitations of the system. The general believe is that curtailing VRE leads to unnecessary cost for fuel, more pollution, and less value of VRE power assets [2].

Accommodating all possible VRE output demands such a high flexibility from the system that, from a certain level on, it increases costs [3]. Increasing VRE shares beyond 35% becomes "increasingly difficult," i.e., increasingly expensive. Although there are some technical challenges to obtain a 100% renewable system, the main barrier is economical: for example, a 100% penetration of wind and solar can be reached with a system deploying extremely large amounts of transmission and storage (or some other technologies) [1]. Apart that energy prices will be zero most of the time, the investments costs of such a system would be unimaginably huge and not sustainable.

The usual green policy is to give dispatch priority to VRE technologies, since they are the least pollutive and also the cheapest. This dispatch priority commonly comes in two forms: 1) by avoiding curtailment at all costs, unless the security of the system is at risk, and 2) by providing economic (energy) incentives to VRE producers (e.g., feed-in tariffs), who then internalize them in form of negative bids in energy markets, giving VRE the highest dispatch priority [4,5]. Increasing operational costs to integrate high amounts of VRE became the price to pay in order to lower pollution. However, here we show that it is a misconception that forcing VRE production always lowers pollution. This paper provides some examples illustrating that, apart from increasing costs, forcing VRE production can also increase pollution.

2 Examples of Too Much of a Good Thing

This section provides two illustrative examples showing how by curtailing a resource of zero marginal cost and zero emissions can reduce the total system costs and emissions. These examples are solved through an optimal power flow/dispatch (thus simulating some real-time and imbalance markets). The first example (Section 2.1) focuses on the impact of network constraints, and the second example (Section 2.2) on ramping constraints.

These two examples are based on the generator data presented in Table 1, based on data provided in [5]. Wind production, as VRE source, time periods and power demand are specified in each example. It is important to notice that this data helps to illustrate the problem, and should not be seen as absolute numbers. Similar results can be obtained with different generator data, as long as there are differences in marginal costs and emissions between different units, as is commonly the case.

2.1 Network constraints

The first example illustrates how network constraints change the ideal dispatch of generating units, also the CO_2 footprint of the system. For this example, a DC optimal power flow (DCOPF) [5] for one time period is solved, and the only constraints that are included are network constraints and maximum output of the units.

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[2] AC power systems are usually highly meshed, which is also the desired topology because it adds redundancy, making the system more stable and reliable.

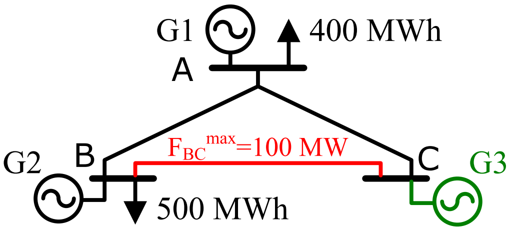

Fig. 1: Example with network constraints. All reactances have the same value (e.g., 1 ohm), and just line B-C has a power limit of 100 MW.

Table 2: DCOPF with maximum wind production

		Output [MWh]	Total Cost [Eur]	Total CO_2 Emissions [ton]
G1	CCGT (natural gas)	10	200	3.2
G2	Gasturbine (petroleum)	545	155325	536.83
G3	Wind	345	0	0
Total		900	155525	540.03
Total average (per MWh)			172.81	0.60

Let us consider a power system with the three generating units shown in Fig. 1, which should supply a total demand of 900 MWh for one period (e.g., one hour). There are only two conventional units G1 and G2. G3 is a wind generator which can produce a maximum of 345 MWh. For this example, we assume that the maximum output of both G1 and G2 is 1000 MW, and their minimum output is 0 MW.

Now, by imposing that wind (G3) must be completely dispatched (350 MWh) and then solving a DCOPF, we obtain the results presented in Table 2. Due to the congestion of line BC, the units cannot be fully dispatched from cheaper to expensive, that is, to obtain a feasible solution and not overload the line BC, the most expensive unit (G2) needs to produce 10 MWh and the next cheaper unit (G1) can only produce 545 MWh.

If we allow the wind to be optimally dispatched, by optimally curtailing it as long as it minimizes costs and CO2 emissions, we obtain the results shown in Table 3. Now, the optimal wind dispatch is 0 resulting in a reduction of 54% in cost 22% in CO2 emissions.

This counterintuitive result can be explained as follows: optimal wind curtailment allows to completely avoid the dispatch of the most expensive and most pollutive unit (G3), which was needed before to alleviate congestion in line BC. This result is also reflected in the locational marginal prices[3] (LMP) and locational marginal emissions[4] at bus C where the wind generator is located: -245 Eur/MWh and -0.345 ton/MWh, respectively. These marginal values are the same for both cases where curtailment is and is not allowed. These marginal values indicate that producing an extra unit of wind energy will increase costs by 245 Eur/MWh and emissions by 0.345 ton/MWh, likewise decreasing an energy unit

Table 3: DCOPF with optimal wind dispatch

		Output [MWh]	Total Cost [Eur]	Total CO2 Emissions [ton]
G1	CCGT (natural gas)	700	14000	224
G2	Gasturbine (petroleum)	200	57000	197
G3	Wind	0	0	0
Total		900	71000	421
Total average (per MWh)			78.89	0.47

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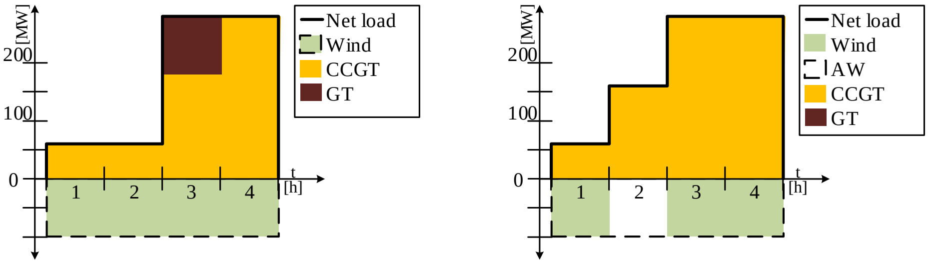
[3] By definition, LMP is the cost of supplying an increment of load at a particular location.

[4] Similarly to LMP, we define the locational marginal emissions as the emissions of supplying an increment of load at a particular location.



(a) Forcing wind production

(b) Optimally dispatching wind

Fig. 2: Example with ramping constraints

Table 4: RAMP: forcing wind

		Output [MWh]	Total Cost [$]	Total CO2 Emissions [ton]
G1	CCGT (natural gas)	580	11600	185.6
G2	Gasturbine (oil)	100	28500	98.5
G3	Wind	400	0	0
Total		1080	40100	284.1
Total average (per MWh)			37.13	0.26

of wind (or increasing demand at C) will reduce costs and emissions by these values. Therefore, for this example, forcing wind production makes the system more expensive and more pollutive in average (per MWh) than the second more expensive and more pollutive unit G1.

2.2 Ramping constraints

The example of this section shows how wind dispatch can help to increase the ramp capabilities of the system, thus increasing the flexibility of the system. This example consists of three units, a wind unit and the two generating units G1 and G2, which must supply the demand shown in Fig. 2 for 4 hours. Wind can provide a steady supply of 100 MWh for all periods. Table 1 presents the maximum output of the units G1 and G2 as well as their ramping capabilities, their production costs and emissions.

When wind is forced to produce its maximum possible output (100 MWh) for all the periods, the optimal dispatch for the remaining units is then to dispatch the next more expensive unit G1 (60 MWh), thus covering the demand completely for the first two hours, and then increasing its production to 180 MWh by ramping up at its maximum ramping capability (120 MW/h). However, since G1 cannot cover the complete demand ramping requirement of 160 MW/h, then G2 has to provide the ramping and energy deficit in hour 3.

Table 4 shows the total cost and emissions of this example. The marginal prices and emissions for hours 1 and 4 are set by the marginal unit G1, and for hour 3 the marginal values are set by the marginal unit G2. However, for hour 2 the marginal price and emissions are -245 $/MWh and -0.345 ton/MWh, respectively. Similarly to the previous example, this negative marginal costs (emissions) appear because an additional unit of load at hour 2 would be supplied by G1 also allowing to increase its production at hour 3 by 1, which in turn would reduce the production of G2 by 1, as there is less ramp-up demanded from G2. Consequently, G1 provides additional energy for both hours 2 and 3, delivering 2 additional MWh in total. The total electricity output of G2 is reduced by 1 MWh. The marginal cost of this 1 MWh increased demand, or wind reduction, at hour 2 is then $2\cdot 20 - 285 = -245\,\$/\mathrm{MWh}$, similarly the marginal emissions are $2\cdot 0.32 - 0.985 = -0.345\,\mathrm{ton/MWh}$.

From these negative marginal price and emissions at hour 2, we can conclude that forcing the maximum wind output at hour 2 is increasing costs and emissions. On the other hand, by optimally dispatching wind, the ramping up capability of the system increases, that is, wind is now supplying ramp-up flexibility to the system. As shown in Fig. 2b, wind is optimally dispatched (curtailed) during

Table 5: RAMP: Optimally dispatching wind

		Output [MWh]	Total Cost [Eur]	Total CO2 Emissions [ton]
G1	CCGT (natural gas)	780	15600	249.6
G2	Gasturbine (petroleum)	0	0	0
G3	Wind	300	0	0
Total		1080	15600	249.6
Total average (per MWh)			14.44	0.23

the second hour, making that wind can supply a 100 MW ramp from hours 2 to 3, thus lowering the (residual) ramping needs of the system and completely replacing the flexibility previously provided by unit G2.

Table 5 presents the result of the optimal wind dispatch, where although there is 25% less wind production, the total costs and emissions are lowered by 61% and 12%, respectively, compared with the case where no curtailment is allowed (Table 4).

3 Conclusions and Reflection

Here, we presented some examples illustrating that forcing variable renewable energy (VRE) production into power systems can increase pollution, apart from increasing operation costs. That is, by blindly forcing VRE production we then get too much of a good thing. The illustrative examples are based on the basic constraints of power systems, and they are by no means a complete list of possibilities where curtailing VRE can lower emissions, we foresee even worse cases when considering a more complete list of constraints of actual power systems (e.g., by including the non-linear integer operation of generating units).

Ideally, power systems should be so flexible that they can perfectly integrate all the variability and uncertainty of VRE without any compromise in costs and pollution. But this is not the case for current power systems, and might not even be the case in the future, since making that highly flexible system could be far too expensive.

VRE is demanding a huge amount of flexibility posing new challenges to power systems. We showed here that VRE can provide flexibility to the system, thus becoming part of the solution instead of continuing to increase the problem. Conventional generation should not have the solely responsibility to provide flexibility to the system to integrate VRE, because this will increase the need for conventional generation even further. Instead VRE can provide flexibility to the system, thus lowering the dependency on conventional units in two different ways: first, by decreasing the demand of flexibility [6], e.g., by controlling its output to lower its variability. And second, by providing reserves [6, 7], e.g., inertia response, primary and secondary reserves [8].

However, current regulation and market incentives aim solely towards maximal VRE output, not maximal VRE value to the system. With the right market design, VRE is ready to support the security of supply, with potentially even stronger capabilities than conventional generation assets – such as coal and gas [8, 9].

During the energy transition, VRE should become part of the solution instead of being the solely source of the problem. As the resource mix continues to evolve, it is imperative to fully exploit the VRE flexibility since it can lower costs and can even lower pollution, as demonstrated in this paper.

Acknowledgment

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 864276. This work was also partially supported by TNO's internal R&D projects Innovative Flexibility Options and Energy Market Modelling (project numbers 060.42856 and 060.47628).

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