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Original
The value of carbon emission reduction induced by Renewable Energy Sources in the Italian power market / Beltrami, F.; Fontini, F.; Grossi, L.. - In: ECOLOGICAL ECONOMICS. - ISSN 0921-8009. - 189:(2021), pp. 107149.1-107149.20. [10.1016/j.ecolecon.2021.107149]

Publisher:
Elsevier B.V.

Published
DOI:10.1016/j.ecolecon.2021.107149

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Abstract

In this paper we investigate the role of Renewable Energy Sources (RES) on the Italian power exchange. The purpose of this analysis is to assess the impact of electricity generation from RES on the reduction of CO_2 emissions and on the value of the power supply. The study is based on hourly zonal micro-data for 2018, from the Italian power market and identifies the amount of avoided carbon emissions related both to crowded-out thermal units and to potential "load-shedding" situations. Finally, the investigation leads to the assessment of both the economic value of RES penetration and to the economic value of the CO_2 emissions avoided by renewable power generation. The results show that the annual savings of carbon emissions nationwide amount to nearly 22 Mt CO_2 whereas the value of CO_2 reduction is estimated at €348 million. The economic savings from large and small-scale wind and solar generation in 2018 account for nearly €19 billion and welfare is increased by 44%, thus confirming the net positive effect arising from RES promotion.

Keywords: *CO_2 emissions; electricity markets; load shedding; merit-order; Renewable Energy Sources*

JEL Codes: P18; Q41; Q42; Q51

1 Introduction

In electricity markets, at the wholesale level, equilibrium prices and quantities are the result of the intersection between the supply and demand curves. When the market clears, the *System Marginal Price (SMP)* and the total power exchanged for each settlement period (and in each zone, if any) emerge. The criterion leading to the identification of the supply curve is the merit-order dispatching, which calls for a ranking of supply according to the marginal cost of power production. The cheapest generators are dispatched first, followed in order by more costly generators, until load is fully served.

The final equilibrium is affected by the different technologies that are called to produce power and by the position of each technology type on the supply curve. *Renewable Energy Sources* (RES)[1] are

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[1] Hereafter, RES are referred as renewable energy sources (as distinct from conventional energy sources) which include bio-energies (biomass, biogas and waste), hydroelectric, photovoltaic, geothermic and wind. This group can be further divided into predictable dispatchable (like hydroelectric) and variable non-dispatchable (such as wind and solar) renewable energy sources. The classification adopted in this paper is specified further below.

dispatched on the market with the highest priority and are progressively integrated into modern grids because of their low environmental impact.

The penetration of RES on electricity markets has attracted growing attention from energy policy makers interested in reducing the global warming consequences of electricity generated from fossil fuels (Fowlie, 2010; Goulder, 2013). In the literature, several scholars agree on the net positive effects of RES on merit-order dispatching (Gelabert et al., 2011; Würzburg et al., 2013; O'Mahoney and Denny, 2011). Jarke and Perino (2017) argue that, in a cap and trade system with feed-in tariffs, the leakage effects between the electricity sector and other industries generate a net positive effect on emissions. The effect of the introduction of large-scale storage plants combined with RES on the reduction of carbon emissions has been explored by Linn and Shih (2019). A study of the pass-through of emission costs to electricity prices in the Spanish electricity market has been carried out by Fabra and Reguant (2014) using micro-data on public offers and bids.

The rise in electricity generation from RES reduces the amount of costly fossil-fueled electricity required to clear the market, lowering the market-clearing equilibrium prices especially at peak hours. Thus, conventional plants are crowded-out by RES, which can supply electricity at low (or even zero) marginal costs. A twofold benefit arises from this effect. On one hand, consumers can experience a reduction in final retail prices in energy bills and a corresponding increase in the available quantities for the system as a whole, thus leading to a consistent rise in the net economic surplus (Espinosa and Pizarro-Irizar, 2018). On the other hand, the displacement of fossil fuel power plants raises the social welfare by lowering CO_2 emissions (Di Cosmo and Valeri, 2018), since power produced by more polluting plants is substituted by power produced from carbon-neutral generating technologies.

An important element to be considered is the different random nature of the several types of RES that contribute to the supply of energy in different ways. Clò et al. (2015) carry out an econometric analysis for the calculation of the merit-order effect in the Italian market due to wind and solar generation over the period 2009-2013, showing that monetary savings attributable to wind penetration outweigh the costs of incentive supporting schemes, while the opposite is true for solar production. Other scholars (Sensfuss et al., 2008; Haas et al., 2013; Nicolosi and Fürsch, 2009) evaluated the impact of specific RES types in power markets, by simulating the equilibrium outcomes of the day-ahead markets and assessing how the additional contribution of the specific type of RES generation affects electricity equilibrium prices.

Despite of the relevant economic and environmental benefits arising from RES dispatch, several scholars pointed out counterbalancing factors from the uncontrolled participation of RES in wholesale power markets. Siler-Evans et al. (2013) argue that there are regional variations in the benefits conveyed by increased generation from RES plants. In some specific regional contexts, the benefits arising from RES dispatching can be negative, in light of the (private and social) costs. This in turn depends on several factors, such as the technology type that is displaced by RES participation, the regional potential of RES penetration and zonal differences in electricity prices.

The role of capacity constraints from the supply of RES when different levels of market competition are considered is discussed by Wang and Zhao (2018). Under conditions of perfect competition in the electricity market, the supports to constrained RES might lead to increased fossil fuel supply and thus to negative climate effects in terms of emissions.

The recent literature warns on the costs arising from the integration of RES into power grids. Heptonstall and Gross (2020) report that the costs from RES integration are larger for higher contribution of RES in the supply mix, thus requiring regulators to further enhance system flexibility.[2] Gullì and Lo Balbo (2015) point out that under situations of market power, an increase in RES generation might increase wholesale prices when market power is beyond a critical threshold. Moreover, RES might indirectly (and endogenously) increase the possibility of creating grid congestions, which can increase system costs and distort the choice of investors in favor of large fossil-fuel rather than RES power plants, particularly in areas characterized by higher likelihood of bottlenecks (GSE, 2015). In this regard, security is a priority that might be undermined due to unbalanced RES penetration. In fact, RES tend to crowd out CCGT plants reducing the investment incentives in these technologies and ultimately the electricity security of supply. Moreover, the absence of RES supply, especially during off-peak hours, may trigger market power and increase congestion rents which, in the medium-run, threaten the security of modern European electricity systems (Bigerna et al., 2016). Under these circumstances, the increase in line congestions may partially offset the benefits due to merit-order dispatching of RES, creating local inefficiencies.

This paper is focused on the Italian electricity market, which is being studied by several authors (Clò et al., 2015; Sapio, 2015; Graf et al., 2020) for three main reasons: wide spatial heterogeneity; large data transparency and availability;[3] high RES penetration in the market.[4]

We measure both the economic savings induced by the displacement of costly fossil-fueled plants due to RES participation, i.e., the merit order effect, as well as the environmental benefit accruing from avoiding CO_2 emissions into the atmosphere.[5]

Our methodological approach is close to the one by Marcantonini and Valero (2017) and Espinosa and Pizarro-Irizar (2018). We rely on the identification of multiple simulation scenarios under varying RES production assumptions, with the target of assessing both the quantity of CO_2 emissions avoided and the merit order effect due to RES participation. The economic value of

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[2] Heptonstall and Gross (2020) classify three main impact categories from RES participation. The unpredictability and/or incorrect forecasting of RES output can give rise to (1) operating reserve (or balancing) costs over short timescales (seconds to a few hours). Secondly, the uncontrolled output from RES and the lack of correlation between output and demand may lead to the occurrence of (2) profile (or capacity adequacy) costs, which are to be met by conventional generators in terms of imposed changes in the capacity factor. This affects their ability to reliably meet peaks of demand during the year. Lastly, the authors document the presence of (3) grid costs that are linked to geography and the technical features of RES.

[3] Micro-data on bids and offers are publicly available and have the highest possible frequency, i.e. hourly, which is the actual frequency at which the market operates. The use of such a large database not only proves the necessity to implement very efficient monitoring algorithms, but also points out the possibility to get information which is crucial for market operators (end users, regulators and policy-makers).

[4] The Renewable Energy Directive 2009/28/EC - which is part of the broad EU 2020 Climate and Energy Package - defined the set of binding and non-binding targets for member States to be met by 2020. The package included three key targets: 20% cut in greenhouse gas emissions (from 1990 levels), 20% of EU energy from renewables and 20% improvement in energy efficiency. Remarkably, Italy was able to meet its non-binding target (share of RES over gross final electricity consumption) already in 2012 by reaching 27.1% resulting share, thus overcoming the required 26.39% percentage. Note that, as concerns Italy, the overall binding target (share of RES over the gross final energy consumption) is set to 17%. Instead, the target for the cut of GHG emissions specifically for the sectors that are not covered by the ETS negotiations is 13% (with respect to 2005 levels). Overall, all these important attainments represent a valid opportunity to explore the structural composition of the Italian power generation mix and the distribution of the technologies that mostly drive this achievement.

[5] Note that this paper is focused only on direct effects and does not consider the indirect effects due to CO_2 emissions. Nevertheless, the authors are well aware that there can be different social impacts of carbon emissions. In order to take them into account, in Section 5 we provide a comparison of the range of values for the social cost of carbon (SSC) derived from the literature (Aliprandi et al., 2016).

avoided CO_2 emissions is obtained from the levels of carbon prices arising from ETS negotiations[6], and then compared with the costs of incentives for renewables, to obtain a full evaluation of the cost-benefit ratio from RES penetration. Moreover, we provide the evaluation of the impact of RES on fuel substitution from an ecological point of view calculating the value of the replacement of electricity produced by using fossil fuels with energy from RES. Regarding the database construction, to cope with the different characteristics of units of power generation and the carbon intensity related to their normal operations, the entire work stems from a preliminary codification process. This led to maintain a comprehensive database which identifies the technical characteristics (installed capacity, power plant type, fuel used, efficiency) of the majority of the Italian power generation plants that are currently active.[7] The obtained technical encoding of power plants was then matched and integrated with available market data. Then, the usage of plant-level efficiency parameters allowed to translate the quantity scheduled for production into fuel needs of relevant conventional power plants;[8] lastly, using coherent CO_2 emission factors derived from the literature, the series of *hourly plant-level* CO_2 *emissions* was constructed.

We contribute to the relevant literature by empirically assessing the economic and environmental impact of RES in the Italian day-ahead wholesale power market (*Mercato del Giorno Prima, MGP*) in the year 2018. Other interesting papers have been published on the same topic, using methodological approaches that can be compared with the theoretical procedure suggested in this paper. Aliprandi et al. (2016) introduced a thorough computation of electricity generation emissions based on Terna's final data. However, the analysis is limited to a 8-week period. The method we use to estimate the effect of RES penetration on carbon emissions, based on the comparison between actual and counterfactual scenarios, is very similar to the one introduced by Marcantonini and Valero (2017) and by Espinosa and Pizarro-Irizar (2018). However, with respect to the existing literature, our original contribution can be summarized as follows.

Our scenario analysis relies on the construction of all possible RES impacts on the equilibria. Differently from all the analyses performed so far, we study not only the impact of wind and solar generation, but also other RES, including pumped hydro which is very interesting, particularly in the North zone, because is, at present, the only possible large-scale storage of electricity.

The database has been built by merging the online Terna data-set, containing micro-data on auction bids and offers, with the data-set provided by an Italian private company[9], containing information about generators cost curves.

We emphasize the differences between independent and cumulative approach. This is strictly related to the empirical application of the merit-order method and the varying technological structure of the generation mix (see section 3.2, where the difference is pointed out). In this way, it is possible to calculate the overall saved CO2 independently of the order of removal of different RES (cumulative approach).

Saved emissions are computed considering possible load shedding events. We integrate in our approach the issue of security of supply in case when high penetration of RES could induce the

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[6] The *Emission Trading System (ETS)* is the European carbon market, which is the main EU's policy to tackle climate change. It covers nearly 40% of EU's greenhouse gases emissions.

[7] We encode power generation plants, by distinguishing them between conventional and RES power units.

[8] We collect data about the efficiency of all relevant thermoelectric power plants, namely, those conventional plants whose capacity is above 10 MW. See Section 4 for details.

[9] The authors wish to thank REF-4E for providing data which are crucial for the analysis. The information contained in the data-set is recognized also by other authors (Aliprandi et al., 2016) who claim that data on cost curves would have help to improve their analysis.

exclusion of thermal capacity form the dispatched generation mix (see section 3.1 and Figure 1).

The main limit of the analysis, shared with the previous literature on the topic (Aliprandi et al., 2016; Espinosa and Pizarro-Irizar, 2018; Marcantonini and Valero, 2017) is that the impact of transnational transmission in the CO2 emission abatement is neglected. This problem is intrinsic to the available data which are limited to one single country and contain detailed information only about the set of plants located in that country. It is then hard to determine the type the plants involved in the generation of imported energy.

This article is organised as follows. Section 2 reviews previous econometric and simulation studies on the merit-order effect. Section 3 introduces the simulation methodology followed by the present study, while Section 4 describes the data used for our investigation. Section 5 presents the main results of the analysis. Section 6 concludes with final remarks.

2 Literature review

There is a vast amount of literature on the impact of RES participation in electricity markets adopting mostly three approaches: theoretical modeling, empirical analyses and simulation-based studies. The first group includes articles focused on the definition of the *Merit-order effect*, i.e. the reduction of the wholesale electricity price triggered by increased generation from RES. This crowds out less efficient technologies, since the zero-marginal cost generation from RES substitutes conventional generators (Jensen and Skytte, 2002; Fischer, 2006). Following this framework, empirical studies exploit econometric models to explain the behaviour of electricity prices as a function of several explanatory regressors (Gianfreda and Grossi, 2012), including generation from RES (as well as from other primary energy sources; Grossi and Nan, 2019). Simulation-based models identify alternative counterfactual scenarios to calculate the impact on the market equilibrium from different assumptions regarding generation from RES. Several authors carried out simulation analyses focusing on different markets.

Sensfuss et al. (2008) study the impact of increased infeed of electricity generation from RES in Germany through the shift of the residual demand curve. They show that the size of the merit-order effect mainly depends on the slope of the merit-order supply curve, which in turn is linked to CO_2 prices and the fuel replacement effect. They also emphasise the role of fuel prices such as natural gas and coal as important drivers of final electricity equilibrium prices.

Nicolosi and Fürsch (2009) clarify that in Germany the increase of electricity generation from RES leads to a short-run effect, the crowding-out of non renewable sources due to the priority of dispatching RES, and to long-run structural adaptations of the conventional installed generation capacity. Haas et al. (2013) shed some light on the two possible effects of commissioning additional RES capacity within the German power grid. The direct impact is given by the shift of the supply merit-order curve where the RES push the conventional generators out of the market, hence leading to temporary very low (or even negative) electricity prices. However, the impact of photovoltaic and wind plants also has an indirect effect on the costs at which fossil and natural gas capacities are provided during hours in which there is a lack of supply from RES. The authors also stress the increased volatility of German electricity prices in hours with a large excess supply from RES.

O'Mahoney and Denny (2011) analyse the impact of wind generation within the Irish electricity market in 2009. They compute the total savings attributable to wind generation which amount to €141 million. Therefore, benefits in Ireland outweigh the costs of the subsidies for wind, which in turn amount to €48 million. They also calculate the value of CO_2 emissions avoided by wind generation. Specifically, they estimate an average emission factor of 0.582 $kgCO_2/MWh$ from electricity generation in Ireland. They conclude that, on the basis of available daily data on carbon prices in 2009, the value of avoided CO_2 was equal to €29.3 million.

Fell and Linn (2013) explore the effect of incremental market and environmental values of investment in RES on the market equilibrium under various public schemes supporting the introduction of RES. The environmental value is defined as the reduction of carbon emissions induced by the generation of electricity using wind or solar plants. The authors find that the cost effectiveness of renewable electricity policies depends on the steepness of the demand curve. The simulation model is applied to the ERCOT market,[10] leading to the conclusion that Renewable Portfolio Standards (RPS) policies, which mandate that a share of total electricity is generated by RES, are more cost effective than feed-in tariff policies.

Espinosa and Pizarro-Irizar (2018) perform a simulation analysis applied to the case of the Spanish electricity market to measure the cost-effectiveness of renewable energy policy promotion. The authors provide an estimate of the net social cost which incorporates both the net monetary cost (the net effect of RES on final prices for consumers, including the merit-order effect and the incentives to RES) and the environmental benefits in monetary terms (the CO_2 abatement). The results for the period 2002-2017 show that the economic savings due to RES were not able to compensate the rapidly growing regulatory costs of RES after 2010. As a consequence, the promotion of RES had a positive net unit social cost (estimated around 20€/MWh) which was eventually imposed on consumers.

In Italy all nuclear plants have been phased-out after the 1987 referendum as a consequence of the Chernobyl nuclear accident. As RES are intermittent, they can't be used to replace the baseload capacity removed after the nuclear phase-out. For this reason, about 8% of the Italian electricity consumptions are currently covered by imported nuclear power (mainly from France). Bianco and Scarpa (2018) claim that, if nuclear plants in France were removed, this would provoke an increase of the clean spark of 13 EUR/MWh and an increase of the load factor of gas turbines from 0.5% to 4%. This, of course, would also have an impact on the price, emission and fuel use reductions entailed by RES.[11]

Among the econometric works, a comprehensive comparison of the results regarding the empirical estimation of the merit-order effect across several countries is set out by Würzburg et al. (2013).

Gelabert et al. (2011) provide an estimation of the merit-order effect for Spain. The authors show that the average price reduction from RES generation lies in the range between -1.1 €/MWh and -3.99 €/MWh. Moreover, they calculate that the merit-order effect represents only 10% of the total support costs for RES in Spain.

Siler-Evans et al. (2013) carry out a broad cost-benefit analysis through the adoption of econometric techniques taking into account health, environmental and climate benefits from wind and solar generation in the U.S. The authors calculate the different impacts of energy produced by RES across states and per different type of source, by addressing critical policy considerations according to the location of PV and wind unit plants for the correct assessment of the benefits brought by intermittent RES generation.

Some authors have empirically studied the impact of RES in the Italian market through the adoption of econometric and simulation models.

Clò et al. (2015) show that over the period 2009-2013 an increase of 1 GWh in average hourly pro-

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[10] ERCOT is the Electricity Reliability Council of Texas in the US.

[11] The authors wish to thank one anonymous reviewer for this comment.

duction from solar and wind sources has reduced wholesale electricity prices in Italy by 2.3€/MWh and 4.2€/MWh, respectively. They highlight the different effects of solar and wind generation in terms of net economic welfare. As regards solar, the cumulated savings from solar infeed in the period 2009-2013 were not sufficient to offset the aggregate cost of the incentive scheme boosting the investments in this technology. The opposite occurred for wind, which has delivered higher benefits than the absolute cost of the corresponding supporting schemes thus resulting in an increase in consumer surplus. For the time span 2009-2013, the overall monetary savings were not sufficient to offset the cost of the incentivising mechanisms.[12]

Gullì and Lo Balbo (2015) investigate the impact of intermittent PV production on Italian wholesale electricity prices. The authors estimate a merit-order effect for the period 2010-2012 of around 10€/MWh, almost offset by a rise in market power. Hence, prices remained unchanged despite a significant drop in demand. They identify a threshold of 50% of the peak power demand as the level beyond which an RES increase of 1% induces a reduction of the wholesale electricity prices of -0.88€/MWh.

Aliprandi et al. (2016) design a complex simulation model based on conventional power plants' technical constraints to calculate the amount of CO_2 emissions reduction at the Italian national level. They include considerations about reserve margins to incorporate operators' strategies to ramp-up and down. They catch the effects of seasonal variability focusing on 8 representative weeks, and find that on average, 1 kWh of electricity from RES displaces 0.8 kWh from fossil fuel power plants, with a higher impact as RES penetration rises.[13]

Marcantonini and Valero (2017) provide an estimation of the cost of abating CO_2 emissions from power generated by wind and solar in Italy for the period 2008-2011 through the definition of the carbon surcharge and the implicit carbon price. They find that the average costs for wind were around 165 €/tCO_2. For solar, they were much higher, around 1000 €/tCO_2, due to the huge remuneration received to solar energy as compared to wind energy.

3 Methodology

3.1 Merit-order calculation

This paper follows the production-based carbon accounting method,[14] using national carbon intensities from local generation and identifies alternative counterfactual scenarios to assess the impact

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[12] Power plants producing electricity from RES receive a variety of incentives, in the form of feed-in tariffs, premium and green certificates. For the purpose of this paper, it is worth noting that RES have priority of dispatch. The small-scale ones are remunerated by a purposely built public company, the GSE (*Gestore del Sistema Energetico*, in Italian - Energy System Manager), that groups most of them and submit offers in the day-ahead market at zero prices. Large renewable power plants directly submit their offers in the market. All RES have the highest priority of dispatching, due to their nearly null marginal cost of generation.

[13] Moreover, the authors consider real-time data about RES production and load dispatched and not market ones, as it is in the present paper.

[14] There are two approaches to carbon accounting. One is consumption-based, while the other is production-based, and the difference is due to imports and network losses. We focus on the production-based accounting method, since it relies on country-specific local generation carbon intensities and fuel consumption. According to Tranberg et al. (2019), the Italian production intensity is slightly higher than the consumption intensity. Therefore, the analysis results in a slight overestimation of carbon emissions.

of different RES technologies in the context of the Italian power market.[15]

In the status-quo scenario, RES are part of the supply curve, together with conventional fossil fueled power plants. The alternative scenario is the counterfactual situation in which the RES are artificially (intentionally) removed from the supply curve, thus leading to a different equilibrium situation. The comparison of the two equilibrium outcomes allows the conventional fossil fuel plants that were crowded-out in the equilibrium with RES to be identified, because of the dispatching of less costly RES electricity. Moreover, the calculation of the quantity of fossil-fueled electricity crowded out by RES plants leads to the calculation of the amount of saved carbon emissions due to RES penetration in the day-ahead market mechanisms, as well as the value of replacing more costly conventional thermal plants with RES plants.

A crucial element is the amount of energy not dispatched because of RES supply. It is possible that in a given hour there is insufficient supply to replace the energy produced by RES. Whenever this occurs, we assume that the residual part of the load that cannot be served is shed. Theoretically, this would mean that the price reaches the opportunity cost of not being served by the power, i.e. the *Value of Lost Load* (VOLL, see Cretì and Fontini, 2019), set at 3000 $€/MWh$ in Italy. Note, however, that such a price spike has never been observed in the Italian market, even when the system was under tight conditions. This is due to the reserve margin maintained by the Italian SO (System Operator) and to the emergency measures[16] activated when the system falls short of reserves. Therefore, in the simulations, whenever load shedding occurs this is coupled with a price spike that corresponds to the highest price observed in each zone, i.e., P_z^{max}. In year 2018, this amounted to 159.4 $€/MWh$ for all zones but Sicily, which experienced a spike of 196 $€/MWh$.

The model runs as follows:

1. Firstly, the supply curve is replicated each hour and for each zone of the Italian day-ahead market by means of the supply bids that were effectively submitted to the market, at unit level. The supply is constructed on the basis of the merit order provided by the actual bids presented to the market in a given zone ($p_{i,h}$) where i denotes the unit and h the hour. Each quantity submitted to the market, at unit level, is ranked on the basis of the asking price from the lowest to the highest. When two bids presented by distinct operators have the same price, they are assumed to have the same merit order (i.e. the relative ranking on the supply curve).

2. The load is assumed to be rigid and set at the level given by the effective market clearing quantity realized at each given hour and in each zone.[17] The highest willingness to pay corresponds to the maximum price for that zone in year 2018.

3. The market equilibrium is calculated. The *Market Clearing Price* (MCP) and the equilibrium quantity are retrieved. Moreover, the marginal supplier is also identified (i.e., the offer corresponding to the last unit called). When the equilibrium quantity corresponds to several

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[15] The Italian MGP is a zonal market, split up in six physical market zones: North, Center North, Center South, South, Sicily and Sardinia. Each market zone generates its own supply and demand curves for each hour of the day. Producers receive the zonal market clearing price, while consumers pay the weighted average of zonal prices, called PUN (Prezzo Unico Nazionale - *Single National Price*). Each zone is characterised by heterogenous electricity generation mix, specific demand centres and distribution systems. On top of that, the zonal structure of the Italian market allows to analyse interesting scenarios linked to the effects of congestion events in the transmission system.

[16] In Italy there is a voluntary load shedding scheme for eligible large customers, who receive ex-ante a yearly premium in exchange for their willingness to be shed in case of shortage.

[17] Note however, that demand bids actually submitted between the system marginal price and the maximum observed price for that zone and year are considered for the calculation of the market equilibrium.

offers with the same merit order (i.e. with the same price), the marginal unit is identified on the basis of a second-order ranking given by the size of the offers.[18] The procedure replicates the task of the independent Market Operator (*Gestore del Mercato Elettrico*, from now on, the *GME*) which, at middays, collects the offers of market participants for the 24 hours of the following day.

4. For each hour and day, the quantity scheduled by each plant is translated into CO_2 emitted, using the procedure discussed in the section below. CO_2 emissions data for each unit are added up, obtaining total emission for each hour and in each zone.

5. Finally, the alternative scenario is the one in which the supply of RES is removed, and the procedure set out in points 1-4 above is repeated. In this case too, when several offers beyond the marginal one of case 3 above could be accepted at the margin in the new equilibrium, the most marginal offer is selected following the procedure specified above. Several specific sub-scenarios are also calculated in which only some types of RES are selectively removed, on the basis of the classification presented further on.[19]

Henceforth, we use the superscript $*$ to express the result of the methodological procedure described above using data for the actual quantities dispatched including RES, i.e. the status-quo approach. In addition, superscript S is used to express the result of the equilibrium calculation for alternative scenarios, in which all RES or only a subset are selectively removed. The methodology described here is applied to each zone. Note that we omit the subscript z denoting a given zone whenever not needed.

Note that two crucial assumptions are implicitly adopted in this framework. The first is that we take the bids placed in the market as given, assuming no strategic bidding when creating the alternative scenarios without RES, either by means of physical capacity withholding, or economic capacity withholding (namely bidding at high price in order not to be dispatched). As a consequence, the plants that were not accepted in the status-quo scenario are assumed to be available to produce in the counterfactual ones. We are aware of this limitation shared, however, by all simulation studies that consider alternative counterfactual scenarios. The second refers to the zonal structure of the Italian Market. We take instances of zonal congestion as given, irrespective of the market configuration (see Würzburg et al. (2013) for a comparative assessment of the literature). Clearly, this is a false assumption; in reality inter-zonal transmission lines constraints (which are communicated by the TSO to the market before bids are presented) are not independent of the market configuration, including supply. However, we cannot replicate the topology of the Italian grid, and therefore cannot endogenise network constraints and therefore take them as given.

We encode generating units on the basis of the technology available. A generating unit can be encoded either as an RES or as a thermal power plant. This broad division is further disaggregated,

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[18] Assuming there are n offers with the same price, we first select, from among all the possible permutations, the $n-1$ offers that minimize the difference between the residual load and the sum of those $n-1$ supplies; then, the marginal unit is chosen, i.e. the unit with the largest quantity from among the units not yet selected, from the previous $n-1$ units, given the convexity cost assumption (see Section 3.2 below). Note that in real-world dispatching, the Market Operator can rely on the information provided by other constraints on top of bid costs, such as ramp-up constraints or minimum technical requirements, that allows to rank units which present the same bids. Because of the lack of this information, we cannot apply the same procedure and therefore use the methodology described here.

[19] In our approach the focus is on the effect of RES on the equilibrium quantity. This allows indirectly to derive the influence of RES on electricity prices. For a comparison of the RES price effect evaluated by means of a different approach see Bigerna et al. (2017).

for RES power plants, into: Wind, Solar (PV), Hydro, Biomass, Geothermal, Non-relevant RES (NRRES), Waste. The classification is self-explanatory except for the last two groups. For the former, the definition depends on the specific Italian encoding of plants and RES subsidy rules. Small-scale renewables, i.e. renewables size smaller than 10 MW (mostly connected at distribution level) receive subsidies by means of a purpose-built public company, called GSE (*Gestore del Sistema Energetico*, in Italian - Energy System Manager). The individual supply of these sources, which are called *non-relevant RES*, is collected by the GSE and placed all together on the market at zero price. This category includes various small-scale RES plants. Depending on the zone, the majority of these plants are either small PV or run hydro. However, there are also other types, such as small-scale wind, or small old co-generation plants (even non renewables).[20] Further disaggregation is not possible and therefore they are classified as a single category within the RES. The Waste category refers to plants that use Municipal Solid Wastes (MSW) for energy recovery. Even if MSW cannot be termed as RES according to the European Waste Incineration Directive 200/76/EC, they received incentives in Italy as *sources similar* to RES. Hence, this category is intentionally separated from the others. Note, however, that its relevance is quite limited, totaling only 4.8% of all RES produced in year 2018.

Thermal power plants are grouped on the basis of the fuel which feeds them as coal, natural gas and oil plants. This allows us using average emission factors for each fuel (coal, natural gas or oil). However, in each category, the units can be further disaggregated on the basis of their thermal efficiency, and this information can be used to calculate fuel consumption at plant-level.

Figure 1 below displays the market equilibrium, by comparing the status-quo and counterfactual scenarios. Note that two outcomes could arise. On one hand, RES can displace several thermal units, and therefore when the counterfactual scenario is created, there are sufficient units (out-of-the market in the status-quo scenario) to the right of the marginal plant that can be called to supply energy. However, it is also possible that the supply offers that were not called in the status-quo scenario are limited, and therefore when RES are removed, the supply of the thermal power units that were crowded out is insufficient to serve the load. In this case, the equilibrium quantity is reduced, resulting in load shedding. Panels (a) and (b) of Figure 1 illustrate the two cases.
Load shedding occurrences depend on the overall supply and load in a given zone and hour. As a reference, it is possible to measure the security margin by calculating the ratio of the highest producible energy over the peak load, for both the case of full production and the residual thermal production, i.e., by removing production from RES. This gives an indication of the necessity of RES to cover the load in a given zone. Data are reported in Table 1 below. Moreover, in the Appendix we report the calculations of the percentage of hours in which load shedding might occur in each zone and under different assumed counterfactual scenarios.

3.2 Calculating CO_2 emission savings at unit level

In order to calculate CO_2 emissions at unit level, we start by defining the (inverse of) the function of technical efficiency for a fossil fuel power plant. We assume a convex function for which the hourly fuel consumption (expressed in $Gcal/h$) is expressed as a function of the electricity power supplied (MWh), given the plant-level fuel (or fuel mix). The fuel consumption function is given

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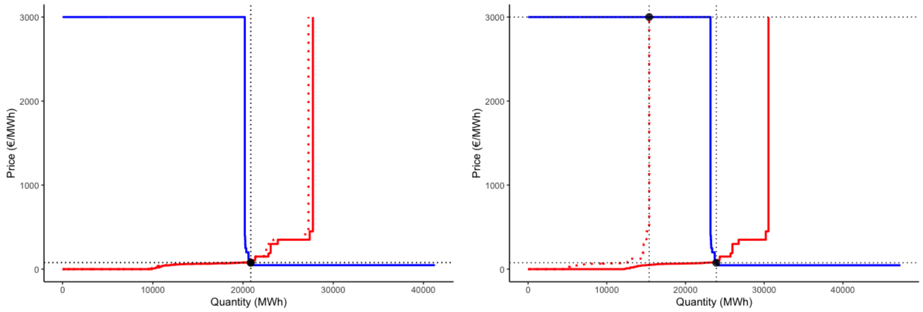
[20] In particular, plants that received incentives for heat recovery under an old incentive scheme, called CIP6. The amount of energy produced by these plants used to be considerable but is now negligible.



(a) No load shedding

(b) Load shedding

Figure 1: *Simulated impact of the removal of a specific basket of RES offers from the supply curve in the Italian day-ahead market: hour 8 (panel a); hour 12 (panel b). Physical zone: North. Day: 5 September 2018. Legend: actual supply curve (red), actual demand curve (blue) and counterfactual supply curve (dotted red).*

by the following equation:[21]

$$g_i^f(Q_{i,h}) = \sum \alpha_i^f (c_{2,i}^f Q_{i,h}^2 + c_{1,i}^f Q_{i,h} + c_{0,i}^f) \qquad (1)$$

where the uppercase f stands for the fuel type (natural gas, oil, coal) and $Q_{i,h}$ is the hourly accepted electricity generation; for the sake of simplicity, we have omitted the subscript z indicating a given zone. We allow for the case of multi-fuel power generators (two at most). In this specific case, we compute the amount of savings in carbon emissions separately for each fuel type and then aggregate the results.[22] The parameters used to calculate the fuel consumption function per relevant thermoelectric unit are:

- minimum and maximum power capacity available for each thermal group;
- percentage mix - expressed by the parameter α - of the utilized fuels (set in our case to a maximum number of two fuels available per unit);
- three non-negative coefficients for the hourly consumption quadratic curves (c_2^f, c_1^f, c_0^f), which are specifically related to the fuel used in the mix of production.

Equation (1) allows the quantities accepted for power supply under each scenario to be transformed into the required fuel consumption. Then, the hourly consumption of fuel (converted into TJ/h with a standard conversion factor λ) is further transformed into the hourly carbon emission at plant-level using emission intensity factors which depend on the technology type f. Emission

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[21] The quadratic cost functions are frequently assumed in the literature, see for example Cretì and Fontini (2019, p. 29). They have been used also by Marcantonini and Valero (2017), who share with us the methodology for the calculation of the hourly fuel consumption of conventional power plants. This model is based on the application of ELFO++, a cost-based deterministic model designed by the energy consulting company REF-4E, which is kindly acknowledged by the authors.

[22] Due to the lack of data, we are not able to calculate the extra-efficiency that multifuel plants have by taking advantage of the joint usage of different fuels. Nevertheless, please consider that this issue refers only to three power plants. For this reason, we believe that the bias in the calculation of emissions can be neglected.

factors are derived from average national carbon intensities, which depend on the fuel type only. Summarizing, unit-level total emissions are given by:

$$E^f_{i,h} = \varepsilon^f \cdot \lambda \cdot g^f_i(Q_{i,h}) \tag{2}$$

In Equation (2), the source of variability of hourly CO_2 emissions is the hourly accepted electricity generation $Q_{i,h}$, the average plant-specific technical efficiency parameter $\lambda \cdot g^f_i$, the average fuel-dependent carbon emission factor (carbon intensity parameter) ε^f.

The total CO_2 emitted in the status-quo scenario, in each z, is

$$E^* = \sum_{h=1}^{T} \sum_{i=1}^{n^*} E^f_{i,h} \tag{3}$$

where T is the total number of hourly auctions ($T = 8760$ in 2018) and n^* the number of units dispatched in the equilibrium with RES. The CO_2 emitted in each counterfactual scenario is

$$E^S = \sum_{h=1}^{T} \sum_{1=1}^{m^S} E^f_{i,h} \tag{4}$$

where m^S now denotes the number of units dispatched in each alternative scenario S. The CO_2 saved is each zone is thus simply the difference

$$\Delta E^S = E^S - E^* \tag{5}$$

The calculation of the saved CO_2 is not independent of the removal order of the RES sources replaced by the displaced thermal capacity in each counterfactual scenario. In other words, since RES sources are disaggregated into different RES types, the individual contribution of each RES to the saving of CO_2 is not independent of each other RES contribution to the energy supply. As a consequence, the calculation of each RES contribution to CO_2 savings differs from the calculation of the whole RES contribution to CO_2; moreover, it is not independent of the RES merit order in the supply curve. This can be shown as follows: let RES_i be the $i-$th renewable source, with $i = 1, 2, \ldots, r$, where r is the total number of RES types, such as "Solar", "Wind", etc. Henceforth, we set $r = 5$ for all zones but Center North, grouping Biomasses and Waste and neglecting Geothermal which is absent except for Center North where $r = 6$. $Plant_j$, with $j = a, b, \ldots$ denotes the RES-displaced plants, i.e. a power plant on the right of the equilibrium point in the status-quo scenario (when all RES are producing) with merit order j. ΔE^{RES_i} is the carbon emissions avoided due to the presence of RES_i in the supply function.

Two possible approaches can be followed to calculate the contribution of each RES to carbon saving, ΔE^{RES_i}, and the total RES contribution, call it $\Delta E^{RES_{tot}} = \sum_{i=1}^{r} \Delta E^{RES_i}$: independent and cumulative.

Independent approach. In this case, the counterfactual equilibrium is obtained by removing each RES at a time from the supply function, leaving all other RES in the supply curve. Call RES_1 the first RES removed (for instance, "Solar"); the supply curve moves to the left creating a quantity "gap", called gap_{RES_1} which is covered by the quantity offered by the displaced plants, i.e., those plants which were on the right of the equilibrium quantity before the RES was removed. For the sake of simplicity, assume that all displaced plants have the same capacity, but have different efficiencies (or possibly burn different fuels) and, consequently, different emissions. Let the emission of the first plant in the merit order j be lower than the second, and so on. The plants covering the gap are selected according to their merit order, starting from the lowest. Assume $Plant_a$, $Plant_b$ and $Plant_c$ are included to affset the gap created by RES_1. The carbon emissions avoided by RES_1, that is, ΔE^{RES_1} are obtained according to the type of fuel and efficiency of $Plant_j$, $j = a, b, c$. Once ΔE^{RES_1} has been estimated, RES_1 is re-introduced in the supply function and RES_2 is omitted. The gap created on the supply curve by the omission of RES_2 is usually different from the gap created by RES_1. Without loss of generality, assume that $gap_{RES_2} < gap_{RES_1}$ and that just $Plant_a$ and $Plant_b$ are sufficient to cover gap_{RES_2}.[23] As a consequence, $Plant_a$ and $Plant_b$ will be considered to compute both ΔE^{RES_1} and ΔE^{RES_2}. The same procedure is repeated with all remaining RES_i, with $i = 3, \ldots, r$. In the computation of $\Delta E^{RES_{tot}}$ the emissions of the displaced plants with the lowest merit orders are included many times. This implies that the calculation of the overall saved emissions will be always higher than the figures obtained applying the cumulative approach described below.

Cumulative approach. The first step of the cumulative procedure is the same as in the independent approach. At the second step, RES_1 is not re-introduced in the supply function. Thus, the removal of RES_2 is added to that of RES_1 creating a cumulative gap equal to $gap_{RES_1} + gap_{RES_2}$ which is offset by the introduction in the supply curve of $Plant_a$, $Plant_b$, $Plant_c$ (to offset $gap(RES_1)$) and $Plant_d$, $Plant_e$ (to offset $gap(RES_2)$). When the removal of all other RES_i is aggregated, additional Plants are introduced ($Plant_f$, $Plant_g$, $\ldots$) until all removed RES capacity is offset. Remember that not all the omitted capacity could be compensated by available non-RES plants, that is, load shedding may occur. Thus, the cumulative approach provides a calculation of the overall saved CO_2 which is not dependent on the order of removal of each RES_i, since it measures the emissions of the entire available displaced thermal capacity. However, the calculation of the contribution of each RES depends on the order with which each RES contribution is calculated. To give an idea of this issue, assume first withdrawing RES_2 and then RES_1, instead of following the order RES_1, RES_2 described above. In this case, we obtain an estimation of the contribution of RES_2 to avoid emission, call it $\widetilde{\Delta} E^{RES_2}$ which derives from the emissions of $Plant_a$ and $Plant_b$, i.e. the first plants on the right of the equilibrium. Of course $\widetilde{\Delta} E^{RES_2}$ differs from ΔE^{RES_2}, which was obtained by considering the emissions of $Plant_d$ and $Plant_e$ when RES_2 was the second RES to be removed.

In our study, following the cumulative approach, there are 5! permutations of RES categories in each zone (6! in Center North). For instance, in the supply curve, the contribution of each RES calculated by the cumulative approach on the basis of the following order: Solar-Wind-Biomass and Waste-Geothermal-NRRES-Hydro gives estimates for each RES that differ from those obtained following the inverse order: Hydro-NRRES-Geothermal-Biomass and Waste-Wind-Solar (or any other possible permutation of RES_i). Each combination yields a different estimate of ΔE^{RES_i}, yet they all provide the same figure for $\Delta E^{RES_{tot}}$.

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[23] If $gap(RES_2) > gap(RES_1)$, $Plant_a$, $Plant_b$ and $Plant_c$ are not sufficient and other plants (for instance $Plant_d$ and $Plant_e$) have to be introduced in the supply curve to ensure equilibrium. If no further plants are available, load-shedding occurs.

We follow the independent approach calculating the contribution of each RES to CO_2 savings and the cumulative approach when showing the overall savings, choosing one of the possible permutations of the RES merit order.

3.3 Calculating the economic impact of RES

The presence of renewables increases the supply of energy to the market and, by displacing some more expensive thermal power plant, lowers the equilibrium price of electricity.[24] Let $\hat{p}_{i,h}$ denote the system marginal price in each scenario. That is to say, $\hat{p}_{n^*,h}$ is the system marginal price under the status quo scenario given by the bid of the marginal plant n^*, $\hat{p}_{m^S,h}$ is the system marginal price under the alternative scenario S in which RES are removed i.e. the offer bid of the marginal m^S-th plant. Q_h^* is the total quantity dispatched in the status quo scenario in a given hour (and zone): $Q_h^* = \sum_{i=1}^{n^*} Q_{i,h}$; similarly, Q_h^S is the total quantity dispatched in the counterfactual scenario S: $Q_h^S = \sum_{i=1}^{m^S} Q_{i,h}$. Note that because of RES supply, $\hat{p}_{n^*,h} \leq \hat{p}_{m^S,h}$ and $Q_h^* \geq Q_h^S$. The two prices coincide when the supply of RES, in that hour and zone, is extremely limited and there are enough plants displaced by RES bidding at the same price as the system marginal price. On the contrary, whenever the removal of RES involves calling plants that are bidding at higher prices, the system marginal price rises. In the latter case, it can be that $Q_h^* > Q_h^S$, or $Q_h^* = Q_h^S$. When the two quantities coincide, there is no load shedding since there are sufficient units beyond the n^*-th that were displaced by RES and can be called to serve the load. When $Q_h^* > Q_h^S$, the difference $Q_h^* - Q_h^S$ measures the amount of load that would have been shed had the RES not been present at that hour; as a consequence, the price goes to P^{max}. The change in price is the *price effect* of RES. The extra load served thanks to RES is a *quantity effect*.

Under the simplifying assumption that the load is rigid, the calculation of the average price in the status quo scenario and in each alternative scenario allows us to compute the total expenditure consumers face when buying electricity at the wholesale level, given by:

$$Exp^* = \hat{p}^* \sum_{h=1}^{T} Q_h^* \tag{6}$$

where $\hat{p}^* = \frac{\sum_{h=1}^{T} \hat{p}_{n^*,h} Q_h^*}{\sum_{h=1}^{T} Q_h^*}$ is the weighted average system marginal price in the status quo scenario, and compare it with the total expenditure consumers would have faced had RES not been present:

$$Exp^S = \hat{p}^S \sum_{h=1}^{T} Q_h^S \tag{7}$$

where $\hat{p}^S = \frac{\sum_{h=1}^{T} \hat{p}_{m^S,h} Q_h^S}{\sum_{h=1}^{T} Q_h^S}$ is the weighted average system marginal price under scenario S. Note that the use of weighted average system marginal prices in the status quo and counterfactual scenarios enables the potential differences arising from peak and off-peak hours to be harmonized.

The comparison of the total welfare in the status-quo scenario and in alternative scenarios leads to the measurement of the change in welfare due to RES.[25] The welfare associated with the status-quo in any one zone is given by:

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[24] It should be recalled that we do not consider here any strategic bidder behavior.

[25] We reiterate that our welfare function only takes into account direct positive effects of avoided carbon emissions, without including other indirect positive effects due to the reduction of the externalities.

$$W^* = \sum_{h=1}^{T} [P_z^{max} Q_h^* - \sum_{i=1}^{n^*} p_{i,h} Q_{i,h}] \tag{8}$$

Similarly, the welfare of the alternative scenario S is:

$$W^S = \sum_{h=1}^{T} [P_z^{max} Q_h^S - \sum_{i=1}^{m^S} p_{i,h} Q_{i,h}] \tag{9}$$

Therefore the economic impact of RES in each counterfactual scenario S is given by:

$$\Delta W^S = W^* - W^S = \sum_{h=1}^{T} \Big[P_z^{max} (Q_h^* - Q_h^S) + \Big(\sum_{i=1}^{m^S} p_{i,h} Q_{i,h} - \sum_{i=1}^{n^*} p_{i,h} Q_{i,h} \Big) \Big] \tag{10}$$

where clearly the term $P_z^{max}(Q_h^* - Q_h^S)$ disappears in the event of no load-shedding.

3.4 Avoided fuel costs

The production of electricity form RES allows saving the operating costs accruing from fuel combustion of those plants that would be necessary to produce power and that are displaced by the supply of electricity from RES. Using our notation, in the status quo scenario all plants that have bid at a price equal or above the system marginal price, i.e., that are at the right of the n^*-th one, are not called to produce. In each counterfactual scenario S, a subset of those plats are needed to replace the missing RES that are removed, namely, the plants from the n^* to the m^S-th one. Denote the quantity bid by those plants as $\tilde{Q}_h^S = \sum_{i=n^*}^{m^S} Q_{i,h}$. Note that $\tilde{Q}_h^S \subset Q_h^S$. Similarly, let $\tilde{p}_i^S, i = n^*, ..., m^S$ be the bid of each of those plants. Under the assumption that the bid price corresponds to each producer's marginal cost given by the fuel cost, we can calculate the value of the energy saved from conventional power plants thanks to RES production as $V = \sum_{i=n^*}^{m^S} \tilde{p}_i^S Q_{i,h}$. Note that such a calculation should not be confused with the one of the total welfare performed in the section above. From the total welfare point of view, there is a monetary transfer when energy is produced by conventional power plants, since that energy would be paid by power users, that remunerate producers which in turn buy their inputs, i.e., remunerate the suppliers of the conventional fuels that they use to produce power. When RES producers displace some of those fossil fuels, consumers save money since they do not have to pay (indirectly) for those conventional fuels, but they can be charged with indirect costs due to RES subsidies. Therefore, in Section 5.3, we calculate the value of the energy not produced from fossil fuels and compare it with the value of the subsidies to RES production.[26]

4 Data

The database collects information from several sources. In particular, we made use of data from GME and ENTSO-E *(European Network of Transmission System Operators - Electricity)* Additionally, as regards the efficiency coefficients of power plants, data were provided by the company REF-4E. Data sources are specified below.

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[26] We thank an anonymous reviewer for this suggestion.

1. Gestore del Mercato Elettrico (GME). We referred to GME public offers to obtain information about all the electricity supply and demand bids on the day-ahead market (MGP). The year covered is 2018, for which we have data with hourly frequency and zonal disaggregation. 2018 can be considered as a representative year of the previous 4 years and also of 2019 as evidenced by some key indicators (electricity consumption, generation level and fuel mix, and plant position in the merit-order) which are relevant to our analysis (Beltrami et al., 2021).[27] We deem the year 2020 not suitable for our analysis due to the structural but temporary change in generation and demand patterns caused by the pandemic. We expect a return to a "more normal" pattern of behavior after the end of this "unusual and unpredictable" event. Each bid is linked to a specific power unit. The integration of market data for the codification of power plants included consultation of the GME portal regarding real-time unavailabilities of production, consumption and transmission by the relevant Italian power plants. As included in the documentation of Terna (2016), a production unit is called "relevant" (UPR) when it is able to supply a power of at least 10 MVA.[28] This figure provides information about the size and therefore the installed capacity of the power plant. All plants not defined as "relevant" are classified as "non-relevant" (UPNR) units of production. Conversely, all the consumption units are classified as "non-relevant". These data allowed us to qualify nearly 1500 power units (both thermal and RES).

Table 1 below shows the data for the six Italian zones. They differ in load, units of production and electricity generated from RES. Zone North represents nearly 75% of total national load[29] and generates 58% of total national electricity. The largest share of RES production in this zone is from hydroelectric power plants (located in Trentino, Piedmont, Lombardy and the Aosta Valley) and non-relevant RES (particularly small PV plants). Center South is the second contributor in terms of load and electricity generation. The request for power is mostly met by wind turbines, non-relevant RES and hydro (several pump storage hydro plants). Center North strongly relies on geothermal power production plants (nearly 32% of total zonal power production). The residual renewable generation mix comprises non-relevant RES and hydro. South is similar to Center South, except that it has higher production from large-scale wind turbines, which - together with small-scale solar and wind units - provide nearly 73% of total zonal power generation. The amount of load and power generation in Sicily and Sardinia is relatively smaller than the other zones. Nevertheless, the power generation from large-scale wind farms and small-scale PV is significant and contributes in each zone to, respectively, 44% and 23% of total zonal power production. The security margins show that all zones are long in terms of capacity when including RES, except for Center North which highly rely on imports. When excluding RES, security margins reduce and are highly diversified across zones, reflecting the different RES penetration in each zone.

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[27] More precisely from ARERA (Autoritá di regolazione Energia Reti e Ambiente - Italian regulatory authority for energy, network and environment), yearly report 2019 e 2020, we highlight the following figures: electricity generation in 2018 is similar to 2015/16/19. In 2017 we observe an unusual increase in production (295 rather than about 290 GWh in other years mainly due to an increase in generation from thermoelectrical plants); in 2019 wind generation increased by 14% but overall generation from other sources is similar to 2018 (and previous years); the number of producers has been growing steadily from 2016; in 2019 we observe a (limited) +0.1% increase in transactions in the Day-Ahead market compared to 2018. Terna's (Italian transmission network operator) transparency report confirms the information listed above about total generation, generation mix and total load, revealing also a similar load shape for 2018 and 2019. Finally, we would like to add that the data extraction, manipulation and analysis beyond one year would require more time, due its labor-intensive nature, than it has been allowed for the submission of a revised version of the paper.

[28] This threshold figure can be approximated to 9.7 MW of installed power capacity and represents the so-called apparent capacity, or the size of the plant.

[29] Note that in Table 1 the data for the virtual production zones, the limited production poles and the interconnectors are not shown.

Table 1: *Zonal configuration of the Italian power market: yearly load, units of production and accepted generation per type of RES. Security margin (ratio of max observed production over max observed load) for both full supply and residual thermal production. Values of load and generation are in MWh and refer to 2018. The identification of units of production represents the status of active units at 31/12/2018. Source: our processing of GME data.*

	North	Center North	Center South	South	Sicily	Sardinia	Total
Yearly load	164,518,420	31,081,787	45,943,518	23,633,923	17,680,705	8,974,450	291,832,803
Number of UPs	588	172	238	290	129	77	1494
Of which: (1) Relevant UPs	434	100	167	221	98	53	1073
(2) Non-Relevant UPs	154	72	71	69	31	24	421
Yearly accepted generation	128,956,528	18,560,878	28,740,029	18,808,488	10,817,844	11,130,253	217,014,020
Of which: (1) Solar	417,426	23,105	420,040	246,598	28,647	84,537	1,220,353
(2) Wind	34,502	167,446	2,508,066	8,209,909	2,899,634	1,634,064	15,453,621
(3) Biomass	1,210,190	71,489	93,618	1,667,322	129,618	315,496	3,487,733
(4) Waste	2,832,667	103,038	1,421,965	971,108	-	-	5,328,778
(5) Geothermal	-	5,718,643	-	-	-	-	5,718,643
(6) Non-Relevant RES	26,987,673	4,044,144	4,594,367	5,712,600	2,079,473	952,958	44,371,215
(7) Hydro	27,081,187	2,318,525	3,147,286	1,423,159	68,198	300,481	34,338,836
Security margin - full prod.	1.4604	0.8754	1.1100	1.0790	1.3829	2.0215	1.3239
Security margin - residual thermal prod.	0.7959	0.3919	0.5933	0.0964	0.9908	1.4065	0.6944

2. REF-4E. With the support of the Italian company REF-4E, we identified the unit level technical efficiency parameters for the relevant ($>$10 MVA) thermoelectric power plants to which we apply the fuel consumption model discussed in the previous Section. Table 2 shows the average values of the efficiency parameters used for the analysis.

Table 2: *Average plant-level efficiency parameters by fuel type. Source: Our processing of REF-4E data.*

Fuel	c_2^f	c_1^f	c_0^f
Coal	0.000602	2.0575	67.325
Natural Gas	0.000488	1.55	61.4
Oil	0.00	3	0.00

3. ENTSO-E. The database was enriched by exploiting the information reported by each national TSO in Europe. This database provides information on power plants and especially their technologies. The information obtained was compared and integrated with data of public offers (in Italian: *Offerte Pubbliche*).

4. EEX database. The data for CO_2 prices[30] in 2018 are sourced from the EEX Emissions market database.[31] In order to cope with missing values, we interpolate figures for the weekend,

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[30] As stated by Siler-Evans et al. (2013), "displaced" emissions can be valued using allowance prices, which reflect the avoided abatement costs for generators in the system. Nevertheless, we are aware that this represents an underestimation of the aggregate social cost of carbon, which incorporates health, environmental and climate costs due to pollution.

[31] EEX stands for European Energy Exchange and collects data of the outcomes on the Primary Market Auction where emission allowances are exchanged in Europe under the Emission Trading Scheme (ETS) regulation.

constructing a full series of data of daily prices in 2018.

5. ISPRA. Average national fuel-dependent emissions factors (CO_2 intensity) for 2018 are derived from ISPRA.[32] Table 3 provides the values of the emission factors used for the analysis.

Table 3: *Average national emission factors from fuel consumption in 2018 (source: ISPRA, 2018).*

Fuel	CO_2 *intensity* $(t\,CO_2/TJ)$
Coal	95.124
Natural Gas	57.693
Oil	76.604
RES technologies	0.0

5 Results

The application of the methodology described allows the quantity of avoided emissions to be calculated, via Equation (5), the difference in expenditure by comparing Equations (6) and (7) and the economic impacts of RES using Equation (10), in the different scenarios under investigation.

5.1 Reduced carbon emissions

5.1.1 Cumulative contribution of RES

Table 4 illustrates the aggregated yearly reduced carbon emissions by physical zone of the Italian market, both in terms of tonnes of CO_2 and their economic value. The latter is calculated using the daily prices from ETS negotiations. Moreover, in order to provide an evaluation of the saved CO_2 that includes also the indirect social cost, we use two extreme estimates for the Social Cost of Carbon (SCC), derived from the literature.[33] Intermediate values for the SCC would obviously yield corresponding figures for the value of the saved CO_2.

It is noteworthy that North is the largest Italian zone in terms of carbon emissions savings, with roughly 68% of total national carbon reduction. Relevant contributions from other zones have been as follows: Sicily about 12%, Center North 8% and Sardinia around 6%. Figures for the remaining zones are smaller. Overall, the penetration of RES saved nearly 22 $MtCO_2$ in Italy. The economic benefit from CO_2 abatement equals almost €348 millions. This low resulting economic value can be explained by the low levels of ETS prices, that do not allow to fully internalise the damages from CO_2 leakage. Using the SCC for the evaluation, the economic benefit from CO_2 abatement

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[32] ISPRA (*Istituto Superiore per la Protezione e la Ricerca Ambientale*) is the Italian Institute for the Environmental Protection.

[33] Measuring SCC is a complex activity, based on simulating future paths starting form some integrated assessment model which dynamically replicates the structure of an economy. The results, depend, *ceteris paribus*, on assumptions about parameters' weighting, uncertainty, risk aversion and discount and time preferences. As a consequence, the results provide extremely different figures. Discussing all models and corresponding evaluations goes beyond the scope of this paper. For a compact review see Zhang et al. (2021). We just consider here two polar figures obtained from common approaches, namely, the DICE model by Nordhaus (2017), who provides an estimate of 33.87$ per ton of CO_2 for the year 2018, and the figure that can be derived from the Stern review by Stern (2007), which yields an estimate of 312$ per ton of CO_2 (for the business-as-usual scenario; see Stern and Taylor (2008)). Values have been converted in € by using the exchange rate euro/dollar at the 31st of December 2018.

rises, ranging from a lower €617 millions estimate up to roughly €6 billions. It is interesting to compare the values of the saved CO_2 with the cost of incentives to RES. According to GSE (2018), the total value of incentive schemes for RES in 2018 for the electricity sector amounted to €11.6 billions.[34] Thus, a simple back-of-the-envelope calculation shows that the implicit CO_2 price that would have broken even with the cost of incentives of RES is 527 $€/tCO_2$. Therefore, even the very high estimate of the SCC provided by Stern (2007) would provide an economic value of saved carbon emissions which is nearly the half of the cost of the incentives to obtain it.

Table 4: *Reduced CO_2 emissions and value of carbon reduction by zone in 2018.*

Zone	*Saved tCO_2*	*Value of CO_2 reduction*		
		Daily ETS prices (€)	Nordhaus (2017)	Stern (2007)
North	15,005,357.00	241,794,655	421,050,317	3,964,158,728
CNorth	508,297.48	6,973,213	14,262,827	134,283,502
CSouth	1,856,631.60	28,160,472	52,097,083	490,490,320
South	673,011.58	10,185,398	18,884,705	177,798,151
Sicily	2,651,977.00	40,691,509	74,414,475	700,606,975
Sardinia	1,290,136.00	19,820,540	36,201,216	340,831,870
Total	21,985,409.08	347,625,786	616,910,623	5,808,169,546

Figures 2, 3 and 4 plot the time series of zonal aggregate saved carbon emissions in 2018. Due to lack of space, we present here only the results for North, Center South and Sicily. The full zonal picture can be found in the Supplementary Material file (data in brief).

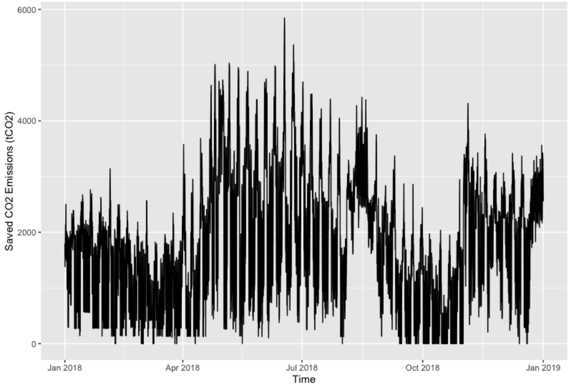

Figure 2: *Amount of reduced carbon emissions in 2018, North zone.*

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[34] The value refers to the cost of incentives for sales of electricity and includes €1.1 billions of hydro support costs.

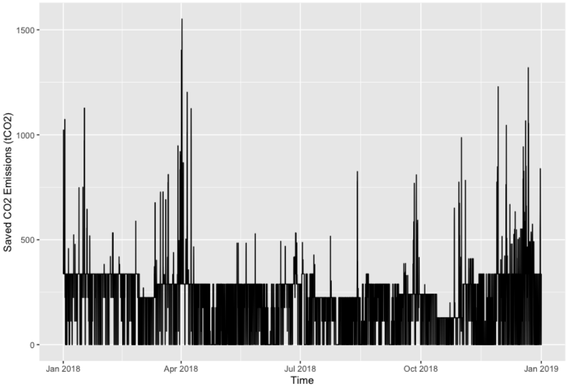

Figure 3: *Amount of reduced carbon emissions in 2018, Center South zone.*

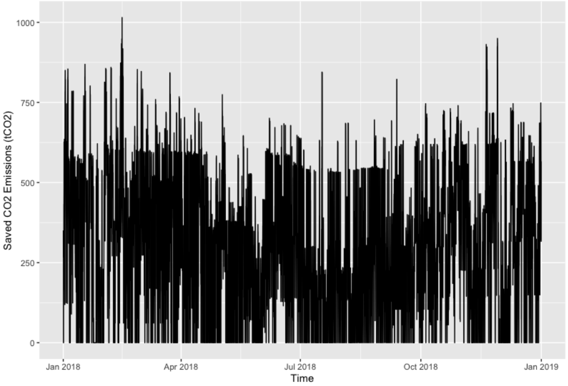

Figure 4: *Amount of reduced carbon emissions in 2018, Sicily zone.*

In order to better distinguish how the contribution from RES depends on the hour when energy is produced, we further disaggregate the analysis distinguishing between peak and off-peak hours.

Figures 5, 6, 7 display the amount of reduced carbon emissions in a cold and a hot month, January and June (panel a and b, respectively), in the three zones North, Center South and Sicily, distinguishing between peak and off-peak hours and interpolating a non-parametric local polynomial smoothing curve.[35] We choose to keep different scales across the panels to emphasize the differences between the two smoothing curves in each time span.

The analysis shows that the impact of RES on peak vs. off-peak carbon savings depends on the zone. In North, the curve for the average carbon savings in off-peak hours is higher than the curve for peak hours. This suggests that the wider fluctuations of reduced carbon emissions during peak-hours eventually cause a corresponding shift of the smoothing curve downwards. This is due to the intermittent nature of RES technologies which mostly contribute during peak-hours. The results for Center South do not show a relevant difference between peak and off-peak hours. On the

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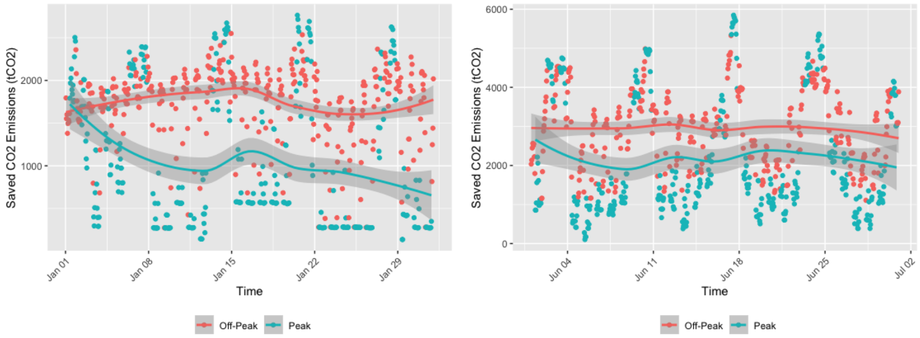
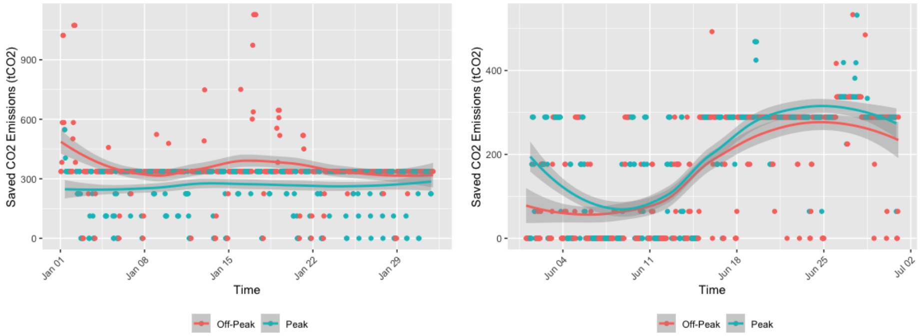
[35] The interpolating trend has been estimated by the R function `loess`, using a quadratic local polynomial fitted by OLS and a smoothing parameter equal to 0.75.

contrary, Sicily has an opposite trend to North. The figure clearly highlights that reduced carbon emissions are higher both in absolute and average terms at peak hours. This is true regardless of the month considered. The outcome is reasonable given the strong dependence of Sicily's power generation mix on intermittent technologies (wind and PV).



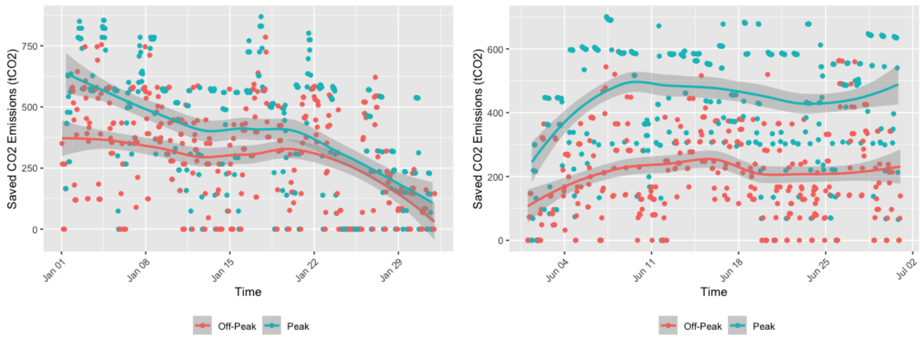
(a) January (b) June

Figure 5: *Reduced carbon emissions, peak and off-peak hours, North zone, January (panel a) and June (panel b) 2018.*



(a) January (b) June

Figure 6: *Reduced carbon emissions, peak and off-peak hours, Center South zone, January (panel a) and June (panel b) 2018.*



(a) January

(b) June

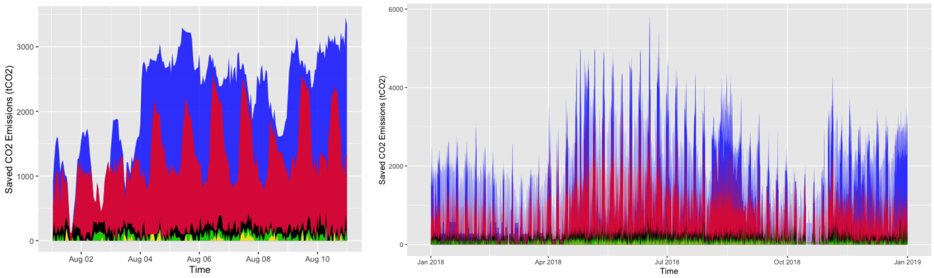
Figure 7: *Reduced carbon emissions, peak and off-peak hours, Sicily zone, January (panel a) and June (panel b) 2018.*

We now calculate how the whole contribution of RES changes over time for each type of RES. We follow the cumulative approach in order to have a picture coherent with the overall amount obtained in 4.

Figures 8, 9 and 10 show the results for the progressive removal of RES, according to the chosen criterion. As previously, we set out here the results for the three zones North, Center South and Sicily. For a clear view of the patterns, we show both the result for a given week (first week of August) in panel (a), and for the whole year 2018 in panel (b).

For North, the figure clearly shows that the major contribution to carbon emissions abatement is due both to NRRES power plants (the red area) and hydroelectric power plants (the blue area). This is consistent with the structure provided in Table 1. The amount of reduced carbon emissions strongly depends on seasonal patterns and shows relevant differences between weekdays and weekends. Moreover, the magnitude of reduced carbon emissions is larger during summer months, due to the high contribution of small-scale PV generation (in the NRRES category) especially at peak hours.

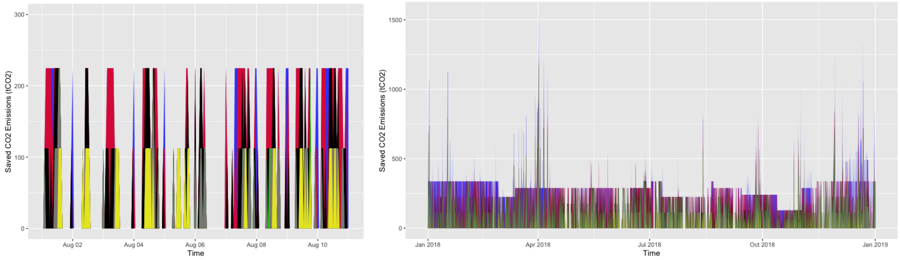
Conversely, for Southern zones - such as Center South and Sicily - the role of Wind (the grey area) becomes prominent. In Sicily, the spread of large wind farms contributes to about one half of all carbon emissions savings from wind in Italy. In both zones, savings from wind are coupled with a significant contribution of NRRES. Note that in both zones the reduced CO_2 emissions have a less volatile hourly pattern compared to North, due to the stable contribution of wind (in Sicily) and small scale solar (in both zones). The share of hydro is also considerable in Center South. Looking at the yearly pattern, the seasonal shape is not as evident as in North, again due to the larger share of small scale RES, coupled with more sunlight in southern Italian regions compared to North.



(a) First week of August

(b) Whole year

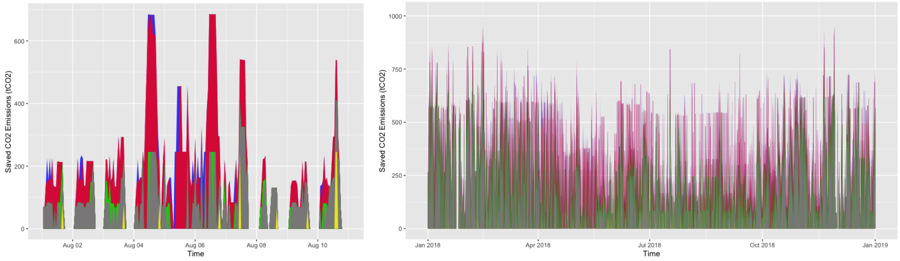
Figure 8: *Saved carbon emissions by RES technology in North zone in a given week (panel a) and for the whole year (panel b). Legend: Solar (yellow); Wind (grey); Biomass (green); Waste (black); NRRES (red); Hydro (blue).*



(a) First week of August

(b) Whole year

Figure 9: *Saved carbon emissions by RES technology in Center South zone in a given week (panel a) and for the whole year (panel b). Legend: Solar (yellow); Wind (grey); Biomass (green); Waste (black); NRRES (red); Hydro (blue).*



(a) First week of August

(b) Whole year

Figure 10: *Saved carbon emissions by RES technology in Sicily zone in a given week (panel a) and for the whole year (panel b). Legend: Solar (yellow); Wind (grey); Biomass (green); Waste (black); NRRES (red); Hydro (blue).*

5.1.2 Independent contribution of RES

In order to shed further light on the impact of each RES on CO_2 savings, we calculate for each hour the carbon emissions reduced by each RES following the independent contribution approach, then aggregated over time and per zone. Table 5 shows the results for the contribution of the individual removal of RES technologies to carbon reduction, disaggregated by zone for 2018. As pointed out in section 5, the total by zone obtained with the independent approach is greater than the total obtained in Table 4 where the cumulative approach is applied. The analysis performed here refers to each single RES, since their sum overestimates the total RES contribution.

Table 5: *CO_2 emissions reduced by technology and zone in 2018, considering each RES technology as independent of the others (independent approach).*

	Solar	Wind	Biomass & Waste	Geothermal	NRRES	Hydro	Total
North	153,995	11,829	1,416,377	-	7,750,818	10,983,288	20,316,307
CNorth	2,937	21,880	21,425	439,824	351,625	297,480	1,135,172
CSouth	67,840	494,033	230,730	-	745,920	1,694,791	3,165,476
South	12,598	533,252	135,265	-	341,764	248,722	1,271,602
Sicily	16,643	1,460,489	64,477	-	1,111,923	31,967	2,685,500
Sardinia	8,918	317,878	59,723	-	213,628	61,742	661,890
Total	262,931	2,839,361	1,928,000	439,825	10,515,680	13,317,991	29,303,789

Hydro is the RES source that contributes most to the overall CO_2 reduction, closely followed by non relevant RES, whose contribution is more than three times that of wind. Biomass (and waste) closely follows wind, while solar has a very limited impact.

According to the disaggregated data for each zone, hydro is the largest contributor in North and Center South. Worth noting is the considerable impact of wind in Sicily and the large share of NNRES in Sicily and Center South confirms our previous analysis. Finally, note that in zones South, Sardinia (and Sicily) wind contribution to the reduction of CO_2 outweighs the contribution of small-scale non relevant RES.

5.2 Economic value of RES

In this sub-section we estimate the economic value of RES in various scenarios, starting with the general scenario $S_1 = RES$ that measures the economic value of all RES. This is followed by the case $S_2 = RES - hydro$ in which all RES but hydro are removed, and then by a focus on scenario $S_3 = PV + NRRES + wind$, in which only the contribution from large and small-scale wind and solar technologies is considered.

Table 6 shows the price effect, displaying the weighted average values of the actual equilibrium price and the simulation-built counterfactual prices in scenarios S_1 and S_2 in each zone in 2018.

Table 6: *Weighted average price in year 2018 with, without all RES and without RES (but hydro) by zone. Values in €/MWh.*

Zone	$\hat{p}^*$	$\hat{p}^{S_1}$	$\hat{p}^{S_2}$
North	62.6077	104.6638	70.7061
CNorth	62.9077	148.4691	136.0541
CSouth	62.3616	116.2735	99.4925
South	60.6759	159.4	159.4
Sicily	72.4247	85.9291	79.5305
Sardinia	61.8147	74.825	73.8652

In the scenario in which all RES are excluded, in each zone the average price without RES is significantly higher, spiking up to roughly 148€ in the zone Center North. Moreover, volatility also increases, except for South. In the latter, without RES the price rises to P^{max} in all hours.[36] Such a paradoxical result depends on the specific market configuration of zone South. In that zone, the thermal capacity is mostly in three specific geographical locations in regions that belong to zone South but are not accounted for in the market zone, namely, Rossano in Calabria and Foggia and Brindisi in Apulia. These places are characterized by transmission constraints and limited load; they are considered *limited production poles* and not included in the data for South.[37] This explains why the limited thermal capacity of zone South is never able to replace the large share of RES in that Zone. In scenario S_2 in which hydro supply is not excluded, there is a less marked effect of RES in North, as expected given the large share of hydro in that zone. Prices are still quite high in Center North, due to the large share of geothermal, and in South, for the reasons explained above. There is still a positive impact of RES in the other zones, but more moderate, except for Sardinia, where hydro is almost absent.

Figures 11, 12 and 13 show the hourly price effect and the quantity effect for scenario S_1. They include the hourly price differentials $\hat{p}^S_{i,h} - \hat{p}^*_{i,h}$ in the selected zone, on the left y-axis. The scale on the right y-axis indicates the quantity of load (in MWh) that would have to be shed without all RES, i.e. the quantity effect. As before, we include only the figures for two selected months, one cold (January) and one hot (June) and for the three selected zones. The graphs for the remaining zones can be found in the Supplementary Material file (data in brief).

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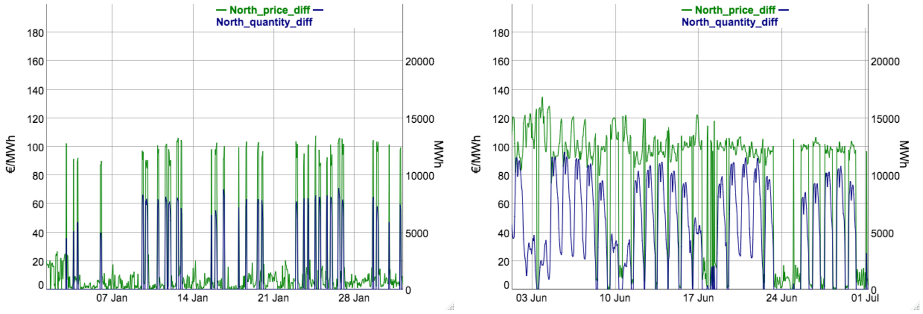
[36] As all prices are equal, the variability is absent, thus, its standard deviation is zero.

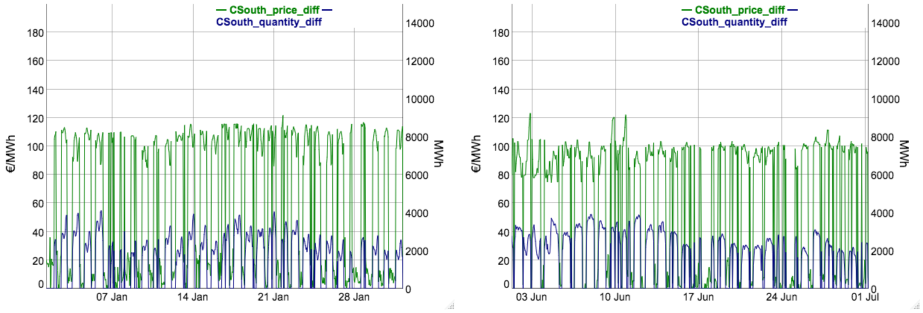
[37] The TSO is undertaking a transmission capacity expansion which eventually allow for the merging of the limited production poles in South zone. In year 2019, the poles of Brindisi and Foggia were eliminated and the corresponding thermal capacity included in the zone South.



(a) January

(b) June

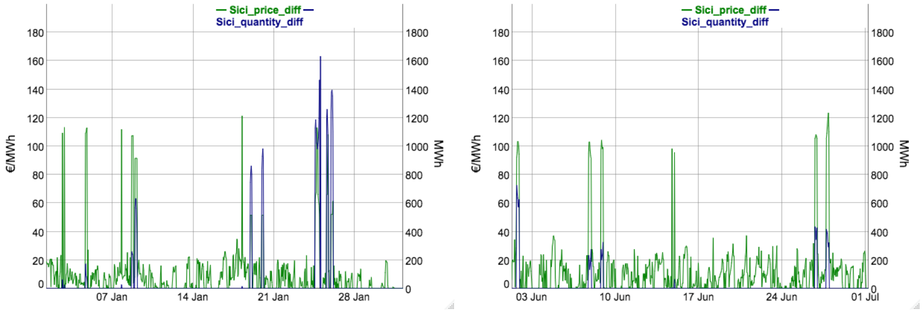
Figure 11: *Price and quantity differential for North zone in January (panel a) and June (panel b) 2018.*



(a) January

(b) June

Figure 12: *Price and quantity differential for Center South zone in January (panel a) and June (panel b) 2018.*



(a) January

(b) June

Figure 13: *Price and quantity differential for Sicily zone in January (panel a) and June (panel b) 2018.*

Crucially, the price effect is enhanced when is coupled with a quantity effect, as expected. For

North, the price effect is higher in the summer, probably due to the impact of small scale RES. For Center South, seems to be no seasonal effect, since the figures for January and June are very similar. For Sicily, the quantity effect is more limited, and this explains the lower impact of RES on the price dynamics, characterized nonetheless by high price jumps.

Table 7 sets out descriptive statistics for the hourly price differential by zone for scenario S_1, distinguishing between peak and off-peak hours.

Table 7: *Descriptive statistics of the hourly price differential (€/MWh) by zone in 2018, peak and off-peak hours, considering* S_1 *as the alternative scenario.*

Zone	Mean	Std. deviation
North	45.84	44.96
peak	62.41	42.43
off-peak	29.26	41.15
CNorth	92.18	25.72
peak	94.17	17.63
off-peak	90.19	31.69
CSouth	61.83	43.86
peak	81.98	33.37
off-peak	41.69	43.85
South	100.03	14.03
peak	99.08	14.61
off-peak	100.97	13.37
Sicily	14.36	21.13
peak	18.15	26.16
off-peak	10.56	13.42
Sardinia	12.87	16.17
peak	13.46	19.04
off-peak	12.28	12.64

As before, there is no common trend, since the relative impact depends on the specific structure of the zone. In North, the price effect of peak and off-peak hours is equivalent. For the other zones, there is a higher impact on off-peak hours in Center North and a similar yet more limited impact for Center South. The opposite is true for the remaining zones. In Sicily, in particular, the price impact in peak hours is twice the impact for off-peak.

Table 8 describes total expenditure[38] calculated by means of Equation 6 and compares them to the expenditure consumers would have faced in scenarios S_1 and S_2, respectively, computed through Equation (7).

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[38] Recall that consumers in Italy do not pay the zonal price, but a weighted national average price, the PUN. Therefore, these figures do not measure savings, only revenues for producers, and the virtual reduction of the cross subsidisation for the PUN.

Table 8: *Total expenditure with RES, without any RES and with only hydro by zone in 2018. Values in millions of euros.*

Zone	Exp^*	Exp^{S_1}	Exp^{S_2}
North	10,300.418	14,307.073	11,594.111
CNorth	1,955.303	1,925.685	2,497.251
CSouth	2,865.128	3,818.724	4,253.708
South	1,434.027	365.504	1,198.674
Sicily	1,280.531	1,507.412	1,396.120
Sardinia	554.755	670.796	662.838
Total	18,390.162	22,595.194	21,602.702

Note that, as is obvious, the *price effect* increases expenditure without RES, while the *quantity effect* reduces expenditure. Nevertheless, the rigidity of demand means that total expenditure increases without RES in scenarios S_1 and S_2. The only exception is South, because of its specific market configuration, with almost no thermal capacity. Hence, quantity dominates the price effect. The highest reduction in total expenditure occurs in zone North, because of the large share of Hydro. Savings in the other zones are more evenly distributed, except in zone Center South, where they are higher, and Sardinia, where the effect of RES is almost negligible.

Finally, Table 9 illustrates the outcome of the welfare increase due to RES, calculated through Equation (10) both for S_1 and S_2 scenarios. Clearly the North, the largest zone, is also the largest contributor to the economic welfare accruing from RES availability. As before, the comparison of the two columns sheds light on the role of hydroelectric generation. The dispatch of electricity from hydro power plants is the main contributor to the economic benefits of RES for the whole Italian market, contributing to half of its overall effect. Without hydro, South zone is the largest contributor to economic savings provided by RES, ahead of the North, the largest zone.

Table 9: *Net economic surplus from the removal of all RES (S_1) and the removal of all RES except hydro (S_2). Values in millions of euros.*

	ΔW^{S_1}	ΔW^{S_2}
North	20,943.520	6,531.363
CNorth	7,088.341	5,992.978
CSouth	6,742.093	3,800.115
South	7,596.692	7,291.772
Sicily	1,299.471	1,208.222
Sardinia	131.557	83.140
Total	43,801.674	24,907.59

Table 10 shows the welfare increase due to wind and solar generation in Italy for 2018, amounting to nearly 19.5 billion euros. The time dimension shows a rather stable contribution of RES to total welfare, with similar figures in all months, with limited variation. Of all the zones, South is the main contributor to the economic benefit from combined wind and solar penetration, due to the large amount of wind power capacity installed, in particular in Apulia. The economic benefit from the South zone represents nearly 31% of the total, followed by North (28%) and a similar share by Center North and Center South (18% and 16%, respectively).

Table 10: *Net economic surplus from the removal of PV, Wind and NRRES (ΔW^{S_3}). Values in millions of euros.*

ΔW^{S_3}	NORTH	CNORTH	CSOUTH	SOUTH	SICI	SARD	Total
Jan	395.423	218.943	207.566	499.963	101.098	6.504	1,429.497
Feb	418.509	382.235	224.902	697.820	110.271	4.718	1,838.455
Mar	555.224	225.898	284.805	549.910	132.464	5.968	1,754.269
Apr	514.773	185.949	255.338	405.336	58.675	13.101	1,433.172
May	554.365	223.227	247.693	432.040	52.557	4.446	1,514.328
Jun	553.090	296.241	304.333	516.446	77.999	5.041	1,753.150
Jul	542.163	341.001	275.100	589.035	102.173	6.516	1,855.988
Aug	346.685	311.139	263.799	572.046	102.593	11.299	1,607.561
Sept	502.654	365.404	242.482	503.985	78.882	6.287	1,699.694
Oct	543.518	423.727	223.535	480.805	87.776	0.263	2,022.361
Nov	308.530	299.986	251.317	463.520	118.902	0.470	1,912.255
Dec	280.466	233.333	335.093	474.886	136.168	6.021	1,465.967
Total	5,515.406	3,507.088	3,115.969	6,185.797	1,159.563	70.638	19,554.461

Table 11 relates the welfare effect due to RES in each scenario to the estimate of total economic welfare (at the wholesale level) calculated by means of Equation (8). The results show that the positive welfare effect due to RES on average in Italy amounts to roughly 42% of total welfare accruing from electricity production. The share of welfare due to RES in each scenario reflects the different relative availability of each RES technology in each zone. Apart from zone South, due to its specific design, the largest benefit from RES occurs in the central mainland zones of Italy. In North, albeit the zone with the largest overall amount of welfare savings due to RES, its overall dimension (in terms of energy production) from thermal capacity means that the contribution of RES to total welfare is below the national average and drops to roughly 10% without hydro (and even less excluding wastes and biomass). In the two islands savings are below average and are almost negligible in Sardinia.

Table 11: *Comparison of the total computed actual economic surplus with selected scenarios. Values in the second column are expressed in millions of euros.*

Zone	W^*	$\Delta W^{S_1}/W^*$ (%)	$\Delta W^{S_2}/W^*$ (%)	$\Delta W^{S_3}/W^*$ (%)
North	61,622.766	33.98	10.59	8.95
CNorth	10,818.750	65.51	55.39	32.41
CSouth	14,368.770	46.92	26.44	21.68
South	8,522.241	89.13	85.56	72.58
Sicily	6,166.832	21.07	19.59	18.80
Sardinia	3,257.826	4.03	2.55	2.16
Total	104,757.185	41.81	23.77	18.66

5.3 Value of avoided energy from fossil fuels

Table 12 reports the value of the avoided energy that should have been produced from thermal power plants burning fossil fuels had RES not been present, by zone. The highest amount of energy saved in 2018 occurs in the zone North, as expected, being the largest Italian market zone. In the other zones, the quantity of energy saved depends on the different structure of power supply. For instance, in zone South the savings are the lowest, due to the limited overall supply from thermal power plants (recall that zone South does not include the thermal supply from power plants included in the limited production poles of Foggia, Brindisi and Rossano).

As concerns the magnitude of the results, this depends on the quantities and on the bidded prices. The overall amount of energy savings from fossil fuel power plants is roughly €11 billion. This figure is almost equivalent to the overall amount of incentives for electricity production from RES (€11.6 billion). Therefore, in 2018 consumers did pay to incentivise production from RES an amount which is roughly equivalent to what they have benefit from them in terms of saving exhaustible resources. The zonal investigation shows that the total amount of energy saved comes from the zone North for roughly 60%. For the other zones, the amount depends on their relative size, with the notable exception of South for which the saving is higher than the one from Sicily and Sardinia, although the quantity is smaller. This might signal that the plants in South are less efficient, and therefore have a higher marginal cost, or that there is some potential market power which might be exploited in that zone, favored by the limited supply of thermal power plants.

Table 12: *Avoided energy (MWh) and economic value (€) of avoided generation from fossil plants in the Italian day-ahead market in 2018 by zone. Values are in MWh and millions of €, respectively.*

	Avoided energy from fossil fuels	Value of avoided energy
North	45,644,800	6,691.554
CNorth	6,127,451	1,042.089
CSouth	8,304,808	1,836.576
South	1,758,261	704.107
Sicily	3,389,574	403.187
Sardinia	2,231,691	323.702
Italy	67,456,585	11,001.215

6 Conclusions

This paper estimates the economic and environmental impact of RES generation within the Italian wholesale power market in 2018.

Starting from available market data about bids submitted by market participants, we simulate the effect of RES supply by defining counterfactual scenarios based on the hypothesis of zero electricity generation from RES. This allows us to compare the ex-post observed market equilibrium and the alternative condition that would have occurred had RES generation not been present. We calculate both the amount of avoided carbon emissions due to RES and the net economic welfare caused by the increase of power supply provided by the RES, together with the resulting price reduction.

To do this, we identify the crowded-out units and apply a fuel consumption model based on technical efficiency parameters, collected by the energy consulting company REF-4E, of conventional power units of generation. This allows to identify the estimated amount of plant-level displaced CO_2 emissions through the use of national fuel-dependent carbon emission factors. Moreover, the comparative analysis also allows us to calculate the System Marginal Price (SMP) that would have occurred without RES generation under a range of counterfactual scenarios, together with the amount of energy that would have not been served. Finally, we calculate the expenditure and the welfare of overall energy provision under the actual and the counterfactual scenario without RES supply.

The results from our empirical simulation approach are the following: in terms of CO_2 reduction, there is a strong contribution by both hydroelectric and small-scale RES power plants to CO_2 abatement. This is particularly true in zone North. During both hot and cold months, there are wider variations of reduced CO_2 emissions at peak-hours due to the penetration of solar generation into the market, although the average amount of reduced carbon emissions at off-peak hours turns out to be larger. Hydroelectric generation is the main contributor to the expenditure savings and to net economic welfare in the Italian power market.

For southern zones, especially Sicily and South, the large contribution to the reduction of carbon emissions is due to wind and small-scale RES generation. In particular, nearly 50% of reduced CO_2 emissions in 2018 in Sicily are due to large-scale wind farms. The analysis for Sicily also suggests some stability (regardless of the time of year) in carbon reduction at peak hours both in absolute and average terms. Very importantly, the South is the zone that mostly benefits in terms of welfare from the combined effect of large and small-scale wind and solar power plants, which amounts to nearly 72% of the total actual economic welfare in the status-quo situation in that zone. Indeed, zone South would have seen a constant price rise up to the highest observed level, had the generation from RES not been present.[39]

The results for Center North, Center South and Sardinia are more heterogeneous. The former is strongly dependent on production from the geothermal source, which displaces nearly 38% of CO_2 emissions itself. Center South provides some mixed evidence, explained by the very diversified mix in electricity generation. Lastly, for zone Sardinia we found significantly low values for the impact of RES on the market. This is because the structure of Sardinia's power generation mix still relies strongly on conventional thermoelectric power generators, with a relatively low penetration of RES.

The contribution of photovoltaic energy to CO_2 savings is negligible everywhere. Interestingly, in absolute terms its contribution in zone North amounts to almost 60% of the overall PV contribution, even though the North has the least solar irradiation in Italy.

The calculation of the economic value of CO_2 reduction amounts to nearly 348 million euros, mostly obtained from the contribution of the North (nearly 69%). Despite the encouraging results in national carbon savings (roughly 22 Mt in 2018), we argue that the resulting economic value of carbon abatement is not sufficiently backed up by the price of CO_2 arising from ETS negotiations, which signals a slow process of supporting firms to incorporate environmental costs in their budget constraints. Indeed, a simple calculation shows that a much higher price for CO_2 is needed to align the cost of incentives to the gain.

We also calculate how much RES generation contributes to the reduction of the SMP and how much it saves in terms of consumer expenditure to purchase power in the day-ahead market. The price effect of RES is quite large. In each mainland zone of Italy, the weighted average price of energy would have been more than doubled had RES not been present. In North zone, hydro plays a very important role in balancing the demand for load from the market, since its presence after

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[39] Note that this result is mainly due to the specific configuration of the South market adopted by the TSO.

removing all the other RES involves only a 13% increase in the weighted average price. We show that this price effect is much larger in Center North, Center South and South, whereas in Sicily and Sardinia it is almost negligible. Without RES, consumers would have spent roughly 4.2 billion euros more to purchase power, or 3.2 billion if Hydro is not included. Clearly, North is the zone that benefit most from the reduction in expenditure. When Hydro is not included, the savings in North and Center South zones are almost equivalent. In southern Italian zones the savings from RES are quite small, even though these are the zones with the highest potential in terms of the availability of renewable primary energy sources.

Regarding the contribution to total welfare, RES amount to roughly 40% when including Hydro, dropping to 23% of total welfare when Hydro is removed and 18% if only PV, Wind and small-scale RES are considered. Across zones, the highest relative impact of RES in terms of welfare occurs in central mainland zones and in South, even though these are not the zones with the highest share of RES (except for South). It is worth pointing out that the impact of PV, Wind and small-scale RES on total welfare in zone North (9%) is relatively limited, even though this is the zone with the highest absolute amount of RES energy supplied from these sources.

Focusing on the value of saving energy produced from fossil fuels, we see that nationwide it roughly corresponds to the value of incentives to RES production (€11 billion vs. €11.6 billions). Therefore, from an ecological economics point of view, it seems that Italian power consumers in year 2018 have paid in terms of incentives an amount of money that is roughly equivalent to the value of the replacement of energy producible from exhaustible primary energy sources with energy produced form renewable ones.

We are aware of some limitations in this research.

The first regards the chosen methodology. We provide a short-term analysis by assuming no investments in power plants that may modify their capacity and accordingly meet the residual load. Moreover, in this paper we calculate the social benefits from the penetration of RES without taking into account the costs for the integration of RES into the system. These might include balancing, grid-related and adequacy costs which are linked to the location of RES installation, the type of variable energy source and the overall flexibility of the power system. Secondly, we took network transmission constraints as exogenous. This issue is linked to the role of network congestions in the grid. Indeed, the implementation of our simulation algorithm for the calculation of counterfactual scenarios assumes that the market conditions, namely the configuration of congestions among market zones and the occurrence of specific market splitting situations, are fixed. However, the network constraints are in fact endogenous in the system. For example, the theoretical removal of some RES capacity might change the grid congestion, inducing market splitting. Moreover, prices and quantities of the neighbouring zones might change accordingly, together with a variation of the resulting marginal technology and ultimately of the avoided carbon emissions. This is also true for international interconnections, that are considered as given, and for which carbon emissions are not included in our simulation since the lack of data that does not allow us to properly estimate them.

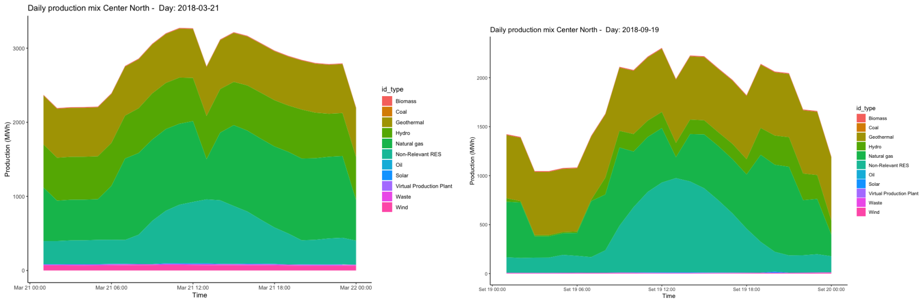
Thirdly, our simulation approach is based on the assumption that the artificial removal of RES supplies in the market does not lead market operators to withhold capacity and then affect the determination of the SMP. Hence, we assumed that the merit-order ranking was not affected by strategic bidding of market operators. Intuitively, market operators may adapt their bidding behaviour to the available RES power capacity in the market. Yet, the potential absence of intermittent generation in the market may be deliberately exploited by market operators to maximise their profits.

Nevertheless, we provide an initial carachterisation of the value of the savings of carbon emissions due to the economic effect of RES supply in the Italian wholesale power market. Overall, the analysis shows that the limited economic effect of CO_2 emissions savings is counterbalanced by the considerable economic effect of power supply in terms of price reduction and welfare increase for power users. As such, the amount of money spent to support RES capacity seems to have acted more as a capacity remuneration scheme by enhancing power supply rather than as environmental expenditure aimed at reducing carbon emissions in the atmosphere. Assessing whether this is an efficient allocation of resources is outside the scope of this paper, but could be of interest in future research.

Acknowledgements. The first author wishes to thank Monica Giulietti and the participants to the seminar at the School of Business and Economics at Loughborough University. The first author is grateful to Fany Nan (European Commission, JRC), Virginia Canazza and Guido Gatti of REF-4E, whose data and insights represent the value added of this study. The authors are thankful to the C.I.D.E. of the University of Verona for the compact database of market data, which simplified data collection. We wish to thank Anna Creti and Paolo Falbo and all the participants to the workshop "Energy Transition and Decarbonization" organised by the Italian Association of Environmental and Resource Economists held at the University of Brescia, Italy on 6-7 February 2020 and the participants to the conference "Energy Finance Italia" held at University of Roma Tre, Italy, on 10 - 11 February, 2020. Their comments and suggestions helped to improve the preliminary version of the manuscript. The first author wishes to thank also Silvia Concettini and Matteo Di Castelnuovo for their useful comments and the anonymous external reviewers for their useful comments to improve the final version of this paper. The usual disclaimer applies.

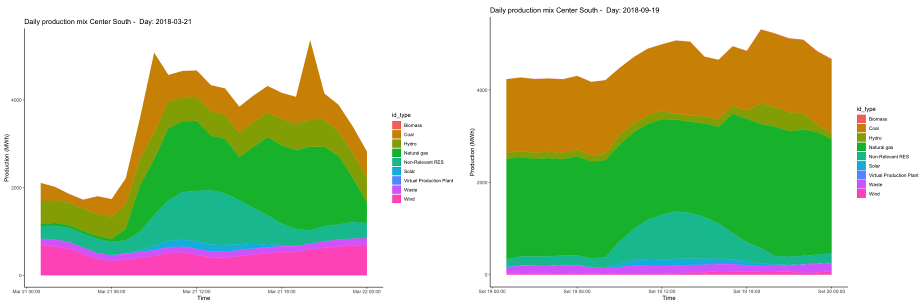
A Appendix

In this Appendix we report the daily supply mix for two reference days (in spring and fall) in each zone, to show the relevance of RES in each zone. We confirm the differences in the supply of each zone already highlighted in Table 1. Note that RES supply is more sensitive to seasonal variation, and this affects more those zones where it has the largest share, as it is for zones South and Sicily.



(a) March 21 (b) September 19

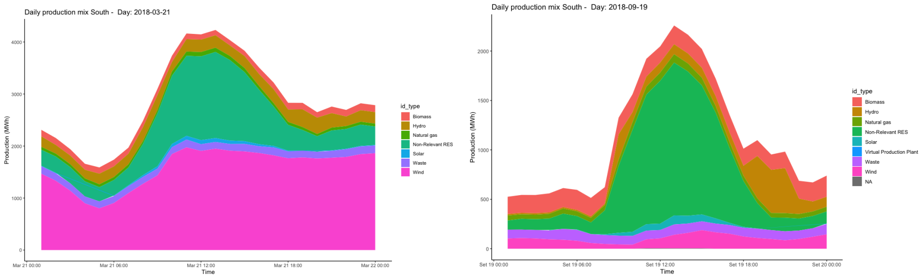
Figure A.1: *Daily mix supply Center North.*



(a) March 21 (b) September 19

Figure A.2: *Daily mix supply Center South.*

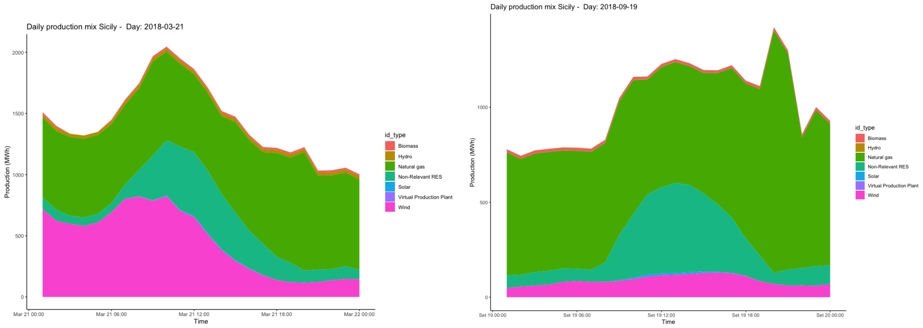
We calculate also the percentage of hours in each zone in which there is load shedding, i.e., the LOLP (Loss of Load Probability), under different scenarios. It should be noted, however, that such a calculation depends on specific assumption about transmission capacity. In an effective situation of supply shortage the inter zonal transfer would not coincide with the observed in the market when the system was not short of supply. Indeed, in our simulation under a given scenario some or all RES are removed in a zone, independently of what occurs in the other zones. In real settings, if this was the situation the inter-zonal transfer would differ form the one we consider here since the scarcity situation in that zone would induce the TSO to maximize the imports from neighbouring zones. This problem is worsened for the zone South by the permanent congestions of the thermal power plants which are not accounted for in zone South in the Italian market design but are included in the limited production poles of Brindisi, Foggia and Rossano, even though



(a) March 21

(b) September 19

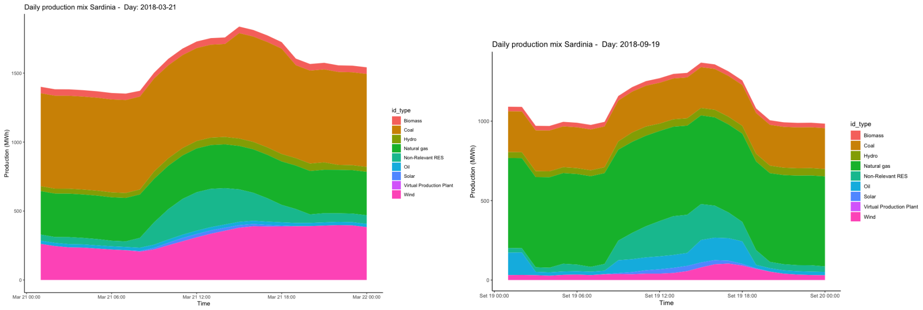
Figure A.3: *Daily mix supply South.*



(a) March 21

(b) September 19

Figure A.4: *Daily mix supply Sicily.*



(a) March 21

(b) September 19

Figure A.5: *Daily mix supply Sardinia.*

they are physically located in the regions that belong to zone South. Similarly for the limited production pole of Priolo in Sicily. It is plausible that in a situation of shortage of RES supply, the TSO would maximize the supply of thermal capacity from the limited production poles. We cannot replicate the optimal power flow in the grid and therefore are forced to keep imports and exports fixed in the simulations. We do so under two possible assumptions. In the first case, we perform the simulations using the effective import and exports observed in each zone and hour; in the second case, we use the maximum observed imports from all neighbouring zones (including foreign and limited production poles, when relevant) when performing the counterfactual scenarios. Note that under the first assumption, the LOLP is overestimated, since in the reality we would observe a higher import in the zone that is falling short of supply; in the second assumption, the LOLP is underestimated since there is no guarantee that whenever the zone is short of capacity the zone that is short of it would benefit from an import equivalent to the highest level observed in year 2018 from all neighbouring zones. Moreover, we perform the calculations for scenario S_1^a, in which all RES are removed, and S_2^a, in which only PV and wind power is removed. Table A.1 reports the data.

Table A.1: *LOLP in 2018 by zone. Hypothesis:* H_1 *= observed imports;* H_2 *= import equal to maximum capacity importable from neighbouring zones, foreign and limited production poles for South and Sicily.* S_1^a*: simultaneous removal of all RES;* S_2^a*: simultaneous removal of all RES except hydro and geothermal.*

	H_1: observed import		H_2: maximum import	
	LOLP (%) $-S_1^a$	LOLP (%) $-S_2^a$	LOLP (%) $-S_1^a$	LOLP (%) $-S_2^a$
North	46.49	3.95	0.012	0.00
CNorth	93.96	31.58	0.00	0.00
CSouth	62.23	35.25	0.00	0.00
South	99.98	99.98	0.00	0.00
Sicily	3.22	2.99	0.00	0.00
Sardinia	2.93	1.57	0.023	0.00

We see that there are striking differences between hypothesis H_1 and H_2. It should be noted that a simultaneous removal of all RES including Hydro is a purely theoretical exercise, and this explain the extremely high figures of the result of the simulation H_1, S_1^a. Central continental zones depend very much on inter-zonal transfers, and this explains the high figures of the simulation H_1, S_2^a. Zone South depends crucially of the thermal supply of limited production poles. Under simulations H_2, S_1^a, we obtain more plausible figures, which correspond to one hour an two hours of load shedding in zone North and Sardinia, respectively. Recall however that assumption H_2 overestimates the contribution of transmission lines; this explains the null figures of simulation H_2, S_2^a.

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