Economic and environmental impact of photovoltaic and wind energy high penetration towards the achievement of the Italian 20-20-20 targets

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***Abstract*—The paper presents an analysis of the operating parameters of the Combined Cycle Gas Turbine (CCGT) systems in Italy in the years from 2006 to 2013, studying the environmental and economic impact of renewable energy sources spread on CCGT. Variable Renewable Energy (VRE) sources development, electricity demand reduction and CCGT overcapacity have affected the CCGT systems that have had to operate at partial load, experiencing several rump-up/down cycles in a day. The consequent increase of CO_2 emission and costs have to be considered in a RES high penetration future scenario. The paper aims to evaluate the net avoided emissions by RES and the cost that Italy have incurred to avoid to emit a tonne of CO_2. To reach the high penetration of RES targets the attention is switching from the problem of adding more renewable energy installations to the problem of managing the whole "green" electricity production in a smarter way. Considering all the indirect effects caused by RES on the electricity system is essential for everyone who wants to analyse future scenarios.**

Keywords — photovoltaic; wind; economic and environmental impact; RES high penetration; VRE; 20-20-20 targets; Combined Cycle Gas Turbine; CO_2 emissions; CoE.

I. INTRODUCTION

The Italian electricity market is a free market since 1999. Since then, it has been dynamic and characterized by important changes. In 2006 Europe defined its 20-20-20 objectives calling for 20% renewables in 2020. The resulting increase of installation of variable renewable energy (VRE) in Italy has increased the volatility into the grid. It is necessary to balance the electricity production to match the demand instantaneously, to ensure a stable electricity network. Storage systems are, at the moment, not so widespread (except for pumped hydro systems) because of high cost, leading to power modulation by traditional sources. Therefore, the power plants used for power modulation are the newest and most flexible power plants based on the technology of Combined Cycle Gas Turbine (CCGT). The older fossil fuel power plants have a lower marginal cost (cost of producing an additional unit) than CCGT power plants and are slower in load change, so work at constant and maximum load. The CCGT have adapted to face the increase in electricity production by variable RES, also characterized by priority dispatch and to face the decrease of the electricity demand. To achieve this task the CCGT power plants work at partial load and experience several rump-up/down cycles in a day. These bring about lower efficiency, higher specific emission of carbon dioxide and therefore higher consumption of fuel compared to full load operation. In such a complex and ever changing context, there is a need to consider the environmental and economic impact to support the planning and design of a future energy policy [1]. This paper focus on the Italian situation with a preliminary analysis of the impact of Variable Renewable Energy (VRE) on CCGT plants where the two main variable renewable energy sources are photovoltaic and wind power. Their joined annual electricity production share is the 11.5% (Photovoltaic 6,8%, Wind power 4,7%) of the Italian total annual electricity consumption in 2013. Installed power of VRE in Italy is 18,4 GW of photovoltaic and 8,6 GW of wind power.

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This paper presents a preliminary economic and environmental assessment of the indirect consequences due to the development of photovoltaic and wind power technology on CCGT power plants. It highlights an effect that is not always considered within the RES high penetration future scenario studies.

II. EFFECTS ON CCGT POWER PLANTS

In the last few years, Italian electricity market have undergone deep changes. Two main reasons have influenced the CCGT electricity demand on the market: decrease of electricity demand and increase of RES electricity production.

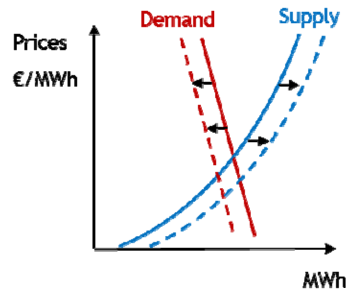

Fig. 1: Shift of equilibrium price on Italian electricity market due to decrease of demand and increase of RES production.

Fig 1 shows the consequences of these two effects on the Italian electricity market. The decrease of the electricity demand has produced a shift to the left of the demand curve and the increase of RES electricity production has produced a shift of the supply curve to the right. Both these two effects have affected and reduced the CCGT electricity production. The supply curve is composed by the ordering of the different offers based on quantity and price of the different technologies [2]. These offers are directly connected with the marginal costs of each technology. For this reason the supply curve is called the "merit order curve" and goes from the least expensive to the most expensive units (Fig. 2). Because of the very low marginal costs of RES technologies and their priority dispatch, their bids enter near the bottom of the supply curve and choose a price taking strategy.

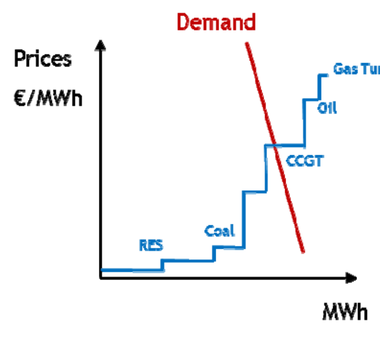

Fig. 2: Merit order curve on the Italian electricity market [2].

CCGT systems are the main technology for defining the electricity equilibrium price [3]. CCGT is the most marginal technology. For this reason, the electricity demand that can be covered by CCGT is strongly affected by the shifts of the two curves. Both the shift of the demand curve on the left and the shift of the supply curve on the right bring the equilibrium price to a lower value reducing the share of electricity that can be covered by CCGT.

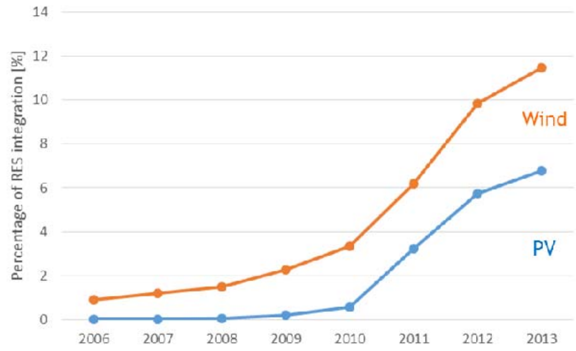

Fig. 3: increase of the percentage of the integration of RES in Italy [4].

Fig 3 shows the increase of RES electricity production and integration in Italy from 2006 to 2013. Not programmable renewable energy production has increased from 3 TWh in 2006 to 36,5 TWh in 2013 moving from about 0,9 to 11,4% of the annual electricity demand.

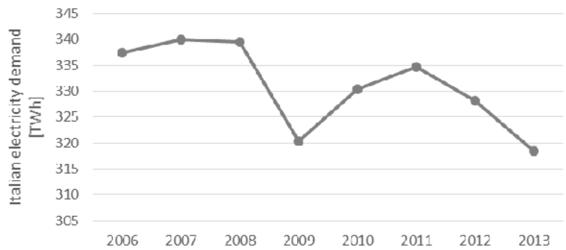

Fig. 4: Decrease of the total annual electricity demand [4].

Fig 4 shows the decrease of electricity demand in Italy from 2006 to 2013. The reduction between 2006 and 2013 is 19 TWh (equal to 5,6% of total electricity demand).

The increase of RES affects the CCGT production not only on average during the year but mostly on the time of the day. If there is plenty of photovoltaic power at midday the supply curve is widely shifted on the right and the CCGT available production is largely reduced. For this reason CCGT work at partial load with several rump-up/down cycles in a day. Furthermore the number of starts and their connected O&M costs and the increased quantity of fuel increase their marginal cost [5].

The described market is the mode of operation of the MGP (Mercato del Giorno Prima) that is the market in which the owners of the electrical plants present the bids and the programs of production for each hour of the considered day. The lifetime of this market go from nine days before the considered day to one day before. CCGT systems cover always less share of electricity in this market for the two described effects of the shifting curves. CCGT systems attention is focusing on the MSD (Mercato dei Servizi di Dispacciamento) where they offer back-up capacity to cover the unrealized programs of the MGP market. For this reason their way to recover investments costs is shifting from constant loads and offer on the MGP (2006) to variable loads, fast responses to the grid demand and back-up capacity on the MSD market (2013).

It is necessary to underline that the intense collapse of the CCGT production is also caused by the overcapacity of combined cycle installed power. In 2006 there has already been enough installed power to cover an appropriate back-up load. However new CCGT power plants have been installed in the last few years. This has increased competition between them, shifting their interests toward flexibility and quick responses to the grid demand.

A. The sample of italian CCGT power plants

A representative sample of Italian CCGT power plants has been considered in order to study the variation of the outputs of the operating systems. The reference year is 2006 with the assumption that the CCGT were not affected by RES (see fig. 3). The values of this reference year have been compared with 2011, 2012 and 2013 where the effect of the influence by RES has been significant (fig 3).

The Sample is composed by eight CCGT power plants: Cassano d'Adda (A2A) 995 MW of installed capacity [6], Mincio (A2A) 380 MW [7], Chiavasso (Edipower) 1150 MW [8], Piacenza (Edipower) 840 MW [9], Sermide (Edipower) 1140 MW [10], Porto Corsini (Enel) 760 MW [11], La Casella (Enel) 1484 MW [12] and Ostiglia (Eon) 1152 MW [13]. They are big power plants and are all placed in the north of Italy.

The years 2011, 2012 and 2013 in Italy have been characterized by an unprecedented amount of photovoltaic installation. For this reason, the evolution of the representative sample parameters should be investigated. The data of 2006, 2011, 2012 are taken from the EMAS environmental declaration (Eco-Management and Audit Scheme is an attestation, recognized to European level, of the excellence in best managing of the interaction with the environment and a recognition of the appointment to the continuous improvement) published by the company owners of the plants. Since 2013 data are not yet available, they were thus estimated. The relationship between the percentage penetration of RES on the total Italian electricity consumption and the equivalent hours was selected for the preliminary estimation of the sample values in 2013 where the penetration of photovoltaic and wind power is known (Fig. 5).

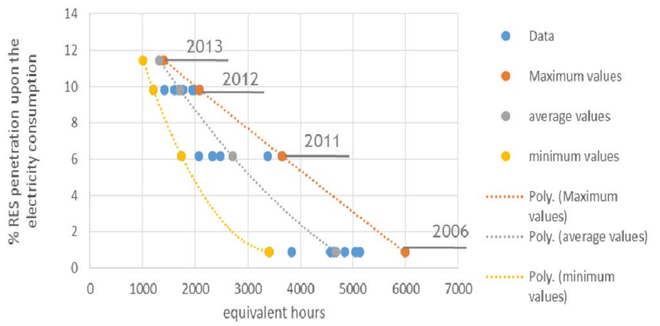

Fig. 5: Relationship between the percentage penetration of RES on the total Italian electricity consumption and the equivalent hours of the CCGT power plants sample.

The parameters of the representative sample of CCGT power plants were used to draw a regression curve for estimating the relationship between equivalent operating hours and specific emissions. Hence establishing a connection between their operation and environmental parameters. Operating hours can be seen as representative of the average load, while specific emissions of the efficiency and of the fuel consumption (fig. 6).

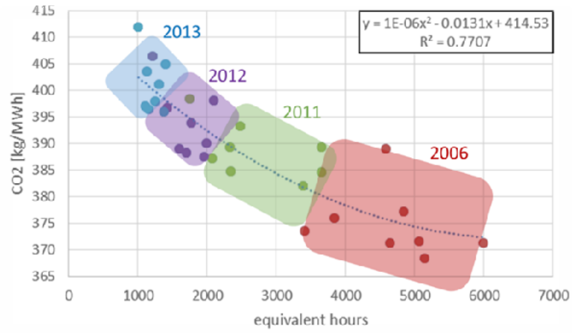

Fig. 6: Specific emissions depending on equivalent hours. 2006, 2011, 2012 and estimated 2013 values of the considered sample.

Fig 6 depicts the cloud values divided for each considered year and the regression line. These values are the annual average values and for this reason consider all the power plants turning on and switching off.

The relationship between specific emissions and load is not linear (fig. 6). Gulen and Joseph [14] have discussed in detail the relationship between efficiency and load into the CCGT systems, highlighting how the efficiency drops more than linearly as the load decreases.

B. Analysis of the sample

The sample is composed by those CCGT power plants that have been installed before 2006 and have not undergone interventions of upgrading through capacity increasing or CO2 capture system implementation during the last few years. It represents the 26% of the total electricity produced by Italian CCGT systems (9,6 TWh of 37 TWh of the Italian CCGT production) and the 30% of the total installed capacity. For simplicity this paper takes into account the whole Italian CCGT systems that produce only electricity and doesn't consider the cogeneration from CCGT.

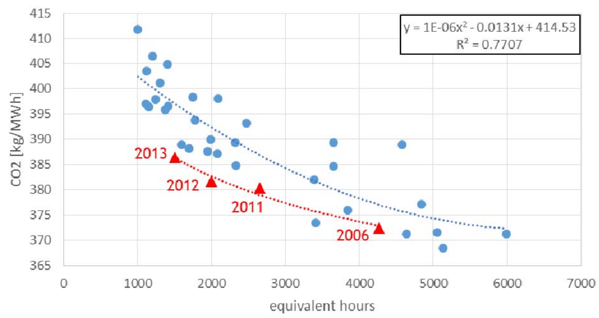

Fig. 7: Specific emissions depending on equivalent hours. Comparison between sample values and Italian CCGT overall values [3]. The years 2006, 2011, 2012

and 2013 highlighted on the map identify the average Italian values for CCGT operating.

The Sample is composed by power plants with a large installed capacity. They are all placed in the north of Italy and this fact can explain why the values of the parameters are above the Italian average (Fig. 7). The Italian electricity market is divided in different areas identified by power transmission constraints. During periods with high photovoltaic generation, there may be congestion in power transmission and a even greater competition between CCGT power plants. North of Italy is characterized by two features that affects the CCGT electricity operation: CCGT overcapacity and VRE electricity production. The installed power of CCGT in the north of Italy is the 67% of the total Italian CCGT installed power [15]. Hence the problem of CCGT overcapacity would already cause an increase of competition between CCGT power plants, the VRE spread has further affected competition and CCGT electricity production. These affects the sample that shows values of the parameters above the Italian average (Fig. 7). Fig. 7 shows, however, that the parameters of the average Italian power plants have a similar trend of the sample. Fig 8 shows how, effectively, a great share of electricity from photovoltaic is produced in the north of Italy. The 38% of the electricity production from photovoltaic systems in Italy is produced in the north.

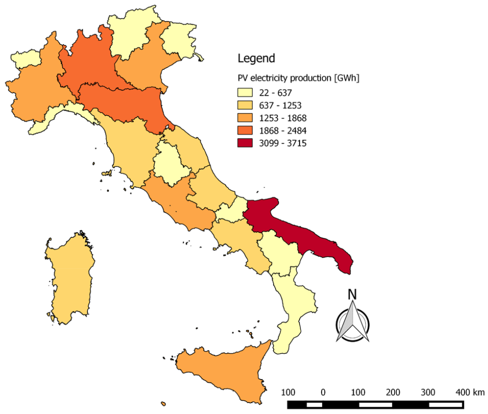

Fig. 8 Electricity production from photovoltaic per region in Italy [16] [17].

The south of Italy is characterized by a great amount of VRE electricity production (southern photovoltaic plants are responsible for the 43% of the total Italian electricity production from photovoltaic) and by a lower share of CCGT installed power (equal to 20% of the total CCGT installed power). For these reasons the effects on CCGT operation are less pronounced than in the north of Italy.

Fig 7 shows two slightly divergent curves. While the sample has remained the same from 2006 to 2013, the overall Italian CCGT capacity has increased during these years. New installations have a higher efficiency that permit to reduce specific emissions of CO_2.

For further considerations the average Italian values [4] of CCGT systems will be taken into account. The representative sample has been useful to highlight the trend and to underline that the effect can be even stronger in some areas due to transmission line constraints.

III. RESULTS

The analysis presented so far allows for the evaluation of the annual emissions of CO_2 induced into the whole Italian CCGT systems by efficiency decrease caused by increasing penetration of photovoltaic and wind energy and electricity demand decrease. The related CO_2 emissions are calculated as difference between the total annual emissions of 2011, 2012, 2013 and those that there would have been if the CCGT had worked with the specific emissions of 2006. In this way it is possible to obtain the value of the emissions caused by this effect for the years 2011, 2012 and 2013.

When considering the total annual emissions reduction thanks to production from RES over traditional fossil fuel sources, this effect has to be taken into consideration.

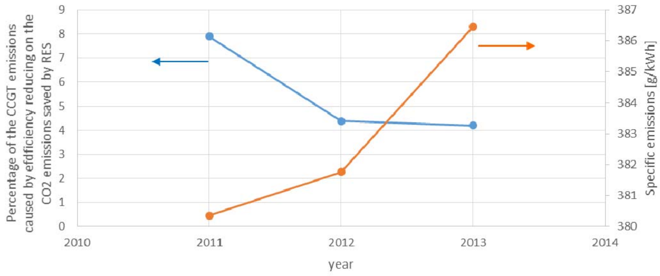

Fig. 9: Percentage of the CCGT emissions caused by efficiency reduction on the CO2 emissions saved by RES and the increase of specific emissions in the years 2011, 2012 and 2013.

The value of the total annual emission released by CCGT caused by efficiency reduction is the 7,9% of the quantity saved by RES in 2011. 4,4% in 2012 and 4,2% in 2013 (Fig. 9). It is a relevant share that has to be taken into account during this transition phase towards 100% penetration levels where future CO_2 emissions scenarios should consider higher amount of fuel/gas due to lower efficiency of CCGT plants working at partial load. This percentage is decreasing due to the increase of electricity by RES and the decrease of the production by CCGT systems. Thus the absolute value of the emissions caused by CCGT efficiency reduction is decreasing but the relative value of CCGT emissions is increasing (see fig 9).

A. *Economic evaluation*

The estimation of induced CO_2 emissions can be used to better calculate the average cost incurred by Italy to avoid the emission of a tonne of CO_2 during the period 2006-2013 by evaluating the avoided CO_2 cost parameter (1).

$$avoided\ CO_2\ cost = \frac{COE_{ccpt} - COE_{ref}}{emissions_{ref} - emissions_{ccpt}} \tag{1}$$

The *cost of electricity* is defined as the total lifetime cost of an investment divided by the cumulated generated energy of this investment. The CoE, therefore, is the price at which the electricity is to be sold in order to achieve a zero Net Present Value (NPV is the sum of the present cash flow over a period of time). The average CoE (cost of electricity) of the years from 2006 to 2013 for photovoltaic [18] [19] [20] and wind power [21] [22] technology and the relative net emissions of the considered renewable energy technology permit to evaluate this value. The parameters used to calculate the CoE are shown in tab 1. All the costs have been actualized to the year 2013.

TABLE I. PARAMETERS FOR ESTIMATING COST OF ELECTRICITY FOR PHOTOVOLTAIC AND WIND POWER TECHNOLOGY [20] [21].

PV		Wind	
CAPEX [€/kW]		CAPEX [€/kW]	
2006	6500	2006	2550
2007	5660	2007	2400
2008	4820	2008	2300
2009	3980	2009	2200
2010	3140	2010	2100
2011	2500	2011	2000
2012	2300	2012	2000
2013	2000	2013	2000
OPEX	1.5% CAPEX	OPEX	1% CAPEX
Lifetime	20 years	Lifetime	25 years
Discount rate	4%	Discount rate	4%
Inflation rate	2%	Inflation rate	2%
Degradation rate	1%		
Performance Ratio	0.76		
Irradiation [kWh/m2]	1677		

CoE_{capt} is the cost of electricity of the technology that permits an abatement of CO_2 emissions. In this case photovoltaic and wind power. CoE_{ref} is the *cost of electricity* of the reference technology. In this case it is taken equal to the PUN (Prezzo Unico Nazionale) that is the weighted average of the zone prices developing on the MGP market. All the future costs are actualized at 2013. $Emissions_{ref}$ and $emissions_{capt}$ are the specific CO_2 emissions of the CCGT systems in Italy and photovoltaic or wind power respectively. Hence $emissions_{capt}$ are the additional emissions produced by CCGT due to efficiency penalties related to photovoltaic and wind power. Performance ratio and yearly insolation are calculated through a weighted average of the regional values on the electricity produced by each region of Italy [16] [17].

The results show that for wind power the related costs to avoid a tonne of CO_2 is equal to 71 €/t in relation to the lower cost of electricity (96 €/MWh). Photovoltaic technology has an average cost of electricity (for the period 2006-2013) of 174 €/MWh and a cost per tonne of CO_2 avoided of 291 €/t. For Photovoltaic this value is going to decrease further in the future as the CoE is continuously decreasing. For example if the same parameters are calculated in 2013 for photovoltaic the results are: CoE equal to 135 €/MWh and a cost per tonne of CO_2 avoided of 181 €/t.

TABLE II. RESULTS FOR PHOTOVOLTAIC AND WIND POWER DIVIDED IN THE TWO EXTREME CASES. "CONSIDERING THE EFFECT ON CCGT" MEANS THAT VRE DEVELOPMENT IS THE ONLY RESPONSIBLE FOR CCGT EFFICIENCY REDUCTION. "NOT CONSIDERING THE EFFECT ON CCGT" IS THE OTHER EXTREME CASE THAT CONSIDER NO RELATION BETWEEN VRE DEVELOPMENT AND CCGT OPERATION.

	PHOTOVOLTAIC		WIND POWER	
	Considering the effect on CCGT	Not considering the effect on CCGT	Considering the effect on CCGT	Not considering the effect on CCGT
COE_capt [€/MWh]	173.83	173.83	96.62	96.62
COE_ref [€/MWh]	71.33	71.33	71.33	71.33
emissions _ref [kg/MWh]	372.36	372.36	372.36	372.36
emissions _capt [kg/MWh]	20.62	0	20.62	0
Avoided CO2 cost [€/t]	291.39	275.25	71.90	67.91

Tab 2 shows the results of the indicator avoided CO_2 cost. It permits a comparison between two extreme cases. "Considering the effect on CCGT" is the case in which VRE development is the only responsible for CCGT efficiency reduction. It means that electricity demand reduction, CCGT efficiency increase in new plants, and CCGT overcapacity are not taken into consideration. "Not considering the effect on CCGT" is the other extreme case that consider no relation between VRE development and CCGT operation. For this reason $emissions_{capt}$ are equal to zero. "Not considering the effect on CCGT" shows a reduction of the avoided CO_2 cost of 5,8%. This means that not considering this effect can bring to an underestimation of the avoided CO_2 cost. On the other hand, CCGT efficiency reduction indeed occurs, as it has been analyzed in this paper, due to several concurrent causes.

IV. CONCLUSION

The growing capacity of renewable energy sources has increased the variability in electricity production. As other solutions are at the moment not cost-effective (e.g. electric storage systems, power to gas, etc), a reserve generating capacity is required in order to balance the consumer demand. CCGT power plants are the only traditional thermal plants that can cover this role. To support further deployment of variable renewable energy sources, it is important to quantify the real impact those have on the energy system in terms of indirect environmental impact and extra cost connected to the balancing power generation that can be related to variable renewable energy technology as cause of this imbalance [23]. Bass et. al. [24] discussed the impact of variable demand upon the performance of an English CCGT power plant.

In this paper, a preliminary analysis of the impact of variable renewable energies (VRE) on CCGT in Italy from 2006 to 2013 was presented together with concurrent factors such as CCGT overcapacity and electricity demand reduction. At this stage of the analysis, it is not possible to quantify the weight of each factor on CCGT efficiency reduction. To this extend, it is in fact important to analyze not only annual balance but also daily profile of generation and demand.

The results show that, considering the performance parameters of Italian CCGT power plants during this period of time, a not negligible share of CO_2 emissions is produced due to efficiency reduction due to operation at partial load. If we compare this share with the emissions avoided thanks to electricity production by RES, we obtain the results of fig. 9 that shows a value equal to 4,2% in 2013. It is important to consider this indirect effect and these results in a future RES high penetration scenario to better evaluate the alternative solutions for power modulation such as storage systems [25] or expansion and enforcement of distribution and transmission grids [26]. The examined data of the CCGT operation are average data and consider all the starting and switching off. Comparing photovoltaic and wind electricity production is possible to observe that wind power has a more stable power production during the seasons and also during the day. Hence photovoltaic has a bigger responsibility on CCGT emissions from efficiency decreasing, starting and switching off.

The average cost incurred by Italy to avoid to emit a tonne of CO_2 during the period 2006-2013 with RES technologies has been evaluated (1) in order to understand, considering the net avoided emissions by RES, the weight of the two technology, photovoltaic and wind energy, in a CO_2 save perspective.

This is a preliminary study that aims to underline the indirect effect of VRE on CCGT systems. Further studies could be analyzed in order to evaluate the impact of a flexibility payment on the energy supply system. How it would incentivize the spread of storage systems that would become direct competitors of the CCGT systems or how it would incentivize de-carbonization, making CCGT systems more competitive in relation to coal power plants.

To reach the high penetration of RES targets the attention is switching from the problem of adding more renewable energy installations to the problem of managing the whole "green" electricity production in a smarter way.

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