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Electrify Italy: The Role of Renewable Energy

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Abstract— In this paper, we evaluate the current status and future outlook (i.e. for 2022, 2030, 2050) for renewable electricity sources (RES) in Italy, considering the present challenges and solutions for relevant dimensions such as technology advancement and environmental impacts. We provide quantitative projections for future RES penetration levels in Italy, based on a cost-based analysis of future generation expansion. The economic expansion analysis indicates that by 2050, more than 80% of the electricity will be provided by RES even in the absence of a CO_2 price. This share can even go above 90% with CO_2 emission reduction measures such as a CO_2 price. These high penetrations of RES will lead to a substantial reduction of the CO_2 emissions from the electricity sector in Italy.

Keywords— Renewable Energy Sources, energy storage, capacity expansion analysis, CO_2 emission reduction

I. Introduction

Transition to renewable energy sources (RES) and reducing greenhouse gas (GHG) emissions is at the center of attention in recent years in the public, among politicians, and in the research community [1] due to the serious environmental issues caused by human energy consumption in recent decades [2]. Deployment of renewable resources in electricity and heat production and energy systems in general can mitigate the GHG emission from this sector which accounts for 35% of overall GHG emissions [3]. Moreover, [4] reported that GHG emission reductions coincided with economic growth in the United States in 2008 to 2015 period. Not limited to the U.S., renewable energy consumption has a significant positive impact on the economic output for 57% of the top 38 renewable energy consuming countries, according to [5].

Renewable electricity costs have fallen significantly in recent years, leading to increased interest in a large-scale RES expansion in power systems. From 2008 to 2015, the cost of electricity fell 41% for wind, 54% for rooftop solar photovoltaic (PV) installations, and 64% for utility-scale PV [6]. These reductions in renewable technology costs has motivated researchers to explore the possibility of 100% renewable power system and related challenges. [7] and [8] address high-level technical and economic challenges of 100% renewable power system in US and UK. [9], [10] present the requirements for 100% renewable energy system in Europe and conclude that extra 90% more generation and 240% more transmission capacities are needed to achieve this goal by 2050. They emphasize that bio-electricity including biomass and biogas units are necessary for flexibility purposes. In [11] and [12], two detailed technical issues of 100% renewable energy systems are explored for European power system as a whole in 2050. The authors of [11] focused on the different energy storage system requirements including long term hydro storage of northern Europe and [12] reviews the flexibility requirements for high RES systems.

These studies address questions about 100% renewable electricity system realization at the European and worldwide scales. However, two important issues are remaining. First, aggregated system results for large regions give limited information about individual counties challenges and requirements. For policy making and security purposes, each individual country needs to know what the optimum solution is for its customized power system and available energy resources. Second, available studies either consider highly subsidized renewable energy or force 100% RES penetration and explore the requirements for its realization. However, there is limited study on the future configuration of power systems without renewable subsidies and based only on technology cost evolution.

To address the shortcomings outlined above, in this paper we select Italy as a candidate power system and perform economic capacity expansion analysis for the future years of 2022, 2030 and 2050. We consider the current configuration of the power system and evaluate a least-cost system configuration in future years in a scenario without subsidies for renewables where investments are driven by projected future technology costs. We also examine scenarios with CO_2 prices to explore its impact on the RES penetration. We provide quantitative projections for future generation from different generation resources in Italy, accompanied with illustrative examples of more detailed projected daily and weekly dispatch results. The rest of the paper is structured as follows: section II explains the simulation method and input data, section III presents and discusses the results and conclusions are provided in section IV.

II. Methodology

In order to take into account technology development and economic factors of RES growth in Italy's future electricity generation and provide an economically optimal solution for the expansion of the power system, we used "GenX", a tool developed for generation expansion planning (GEP). GenX is an optimization model that determines the optimal mix of electricity generation and energy storage capacity and their generation dispatch to meet the electricity load in a future planning year at lowest cost subject to a variety of power system operational constraints and specified policy considerations, such as CO_2 emissions, and natural resources limits [13]. The GenX model does a simultaneous co-optimization of multiple decision layers in the power system, including capacity expansion, unit commitment and dispatch, and operating reserves, transmission and distribution power flows. Depending on the problem, it is possible to run the GenX model for all or some of these decision layers. The model structure to solve the multi-layer optimization problem is as follows:

$$\min \sum \mathit{Investment\ costs} + \mathit{Operational\ costs}$$

Subject to:

- Generation units' investment constraints
- Hourly energy balance constraints
- Thermal, RES and storage units' operational constraints
- Unit commitment constraints
- Reserves and regulations constraints
- RES limits and CO_2 emission constraints

Similar to many other GEP models, GenX uses hourly load time series as the input and optimizes the total annual capital and operating cost of generation across different generation technologies (traditional fossil fuel plants and renewable resources). Fuel costs, different generation technologies' capital and O&M costs and availability factors, which consist of hourly time series for variable RES, are other inputs to GenX. The model also considers the possibility of investing in energy storage. The main outputs are the installed capacity of different technologies and hourly generation of each technology to meet the load requirement. The total cost of the electricity generation as well as GHG emissions are other outputs of the model. Policies like carbon costs and RES requirements can also be represented in the model. Next, we summarize the main input data sources used for the Italian power system and other assumptions used in this expansion analysis.

A. Generation units

Italy's current generation system is a combination of conventional thermal power plants (Gas, Coal and Oil) and renewables (hydro, solar, wind, geothermal and bioenergy). The same generation technologies, as shown in Table I, are used as candidate generation technologies for the capacity expansion model. Also, two types of energy storage systems (8-hour pumped hydro and 3-hour battery storage) contribute to reserves and support RES integration if needed. Technology cost and performance characteristics, as shown in Table I and Table II, are used as input to the capacity expansion analysis.

Table I. Technology cost projections [14]

	Capital cost (E/kW)			Fixed O&M cost (E/kW-yr)			Variable cost (E/MWh)		
	2022	2030	2050	2022	2030	2050	2022	2030	2050
Wind: onshore	1268	1161	943	14	14	12	0.18	0.18	0.18
Wind: offshore	2632	2048	1891	39.8	31	28	0.39	0.39	0.39
Hydro: reservoir	3000	3000	3000	25.5	25.5	25.5	0.32	0.32	0.32
Hydro: run of river	2440	2400	2300	8.76	8.2	8.1	0	0	0
Hydro: pumped 8-hour	3500	3500	3500	30	30	30	0.4	0.4	0.4
Solar PV	700.6	663	454	12.24	10.8	9.2	0	0	0
Battery 3-hour	1000	570	405	11	6.3	5.5	0	0	0
Geothermal	3760	3198	2613	91	95	105	0.32	0.32	0.32
Bioenergy	1290	1250	1050	27.9	24.3	23.3	2.56	2.56	2.56
Gas combined cycle	714	690	640	15	15	15	2.31	2.31	2.31
Gas open cycle	403.2	403.2	403.2	15	15	15	3.5	3.5	3.5
Coal	2380	2300	2150	46.42	44.9	41.9	5.12	4.96	4.6
Other non-RES (Oil)	1200	1200	1200	20.7	20.7	20.7	2.76	2.76	2.76

Table II. Generation technologies in Italy

Unit	Type	Fuel	Efficiency	unit commitment (UC) and reserves (R)	Average availability factor		
					2022	**2030**	**2050**
Gas combined cycle	Thermal	Gas	0.517	UC, R	1	1	1
Gas open cycle	Thermal	Gas	0.341	UC, R	1	1	1
Coal	Thermal	Coal	0.331	UC, R	1	1	1
Other non-RES (Oil)	Thermal	Oil	0.348	UC, R	1	1	1
Wind: onshore	VRE	-	NA	-	0.209	0.229	0.249
Wind: offshore	VRE	-	NA	-	0.325	0.354	0.506
Hydro: reservoir	Hydro	-	NA	UC, R	1	1	1
Hydro: run of river	VRE	-	NA	-	0.445	0.445	0.445
Hydro: pumped 8-hour	Storage	-	NA	R	1	1	1
Solar PV	VRE	-	NA	-	0.145	0.153	0.173
Battery 3-hour	Storage	-	NA	R	1	1	1
Geothermal	VRE	-	NA	-	0.8	0.8	0.8
Bio: Electricity only	Thermal	Biofuel	0.341	UC, R	1	1	1
Bio: Cogeneration	VRE	-	NA	-	0.54	0.54	0.54

For thermal units, the fuel price in the candidate years must be provided, and also the fuel's CO_2 content to calculate the CO_2 emissions and cost, in scenarios with a CO_2 price. Fuel price projections were collected from the European Commission report on energy, transport and GHG emissions trends to 2050 [15]. The CO_2 contents of each fuel type was obtained from the U.S. EPA [16]. Table III summarizes the fuel prices in the projection years and their CO_2 content. For the units that have unit commitment decisions and participate in providing operating reserves, the minimum output power is set, which is 40% for the oil and coal plants, 30% and 20% for the combined cycle and open cycle gas plants,10% for the hydro reservoir units, and 20% for bioenergy (i.e. for the electricity only category, similar to open cycle gas turbine). Note that for computational reasons, power plants are aggregated and clustered into groups, where plants in each group have identical characteristics, as described in [13]. There is no constraint on retirement or expansion for gas and oil power plants, but coal power plants are assumed to be retired by 2025 due to the expected coal phase-out in Italy.

Regarding RES, a cap on expansion of onshore and offshore wind in Italy of 20GW and 1GW in 2050 were imposed on the model. No constraint was imposed on the expansion of solar. The model keeps the installed capacity of hydro power constant. Reservoir hydro is optimized over the course of the year based on historical inflows and reservoir limits, whereas run of river hydro has a constant availability for all hours. Additional input data for reservoir hydro include the initial water level in the reservoir, inflow data, power to energy ratio of the reservoirs, and maximum and minimum reservoir levels. The water level at the end of year is limited to be within a 10 % deviation from its value in the beginning of year [17]. The reservoir hydro inputs were calibrated based on historical hydro data for 2015. Installed capacity for geothermal energy is considered to remain constant with no expansion potential. Also, two different types of bioenergy are modelled. First, cogeneration units that are considered as variable renewable energy without expansion potential. Second, electricity-only production units assumed to have expansion potential. The electricity-only units are assumed to have similar characteristics as thermal units with unit commitment and contributing reserves.

The model finds the optimal expansion for a given year. In order to simulate the gradual development of the system, the current installed capacity of each technology is considered as existing capacity when the model calculates the optimal generation mix for 2022. Next, the optimal output capacity of the model for 2022 is used as input capacity for 2030. From 2030 to 2050, given the long time horizon, the model optimizes the generation portfolio without considering existing capacity, except hydro, geothermal, and bio-cogeneration, which are assumed to have fixed capacities.

Table III. Fuel price projections and CO_2 content [15], [16]

Input data for thermal units				
Fuel	**Price (Euro/boe)**			**CO_2 content**
	2022	**2030**	**2050**	**(tons/ MMBtu)**
Oil	79	94	111	0.07
Coal	16	21	26	0.1
Natural gas	51	60	68	0.053
Biofuel	108	108	108	0

B. Availability factors

Another important input to the model is hourly availability factors of different technologies. This factor defines how much energy can be harvested from each technology in each hour. These data for thermal, reservoir hydro, and storage units are set to 1, their nominal power capacity is always available (i.e. we do not consider outages). However, for variable renewables the availability varies on hourly, daily and seasonal basis. The resource availability data for wind and solar is collected from [18], [19] which is a database with historical resource database for these technologies. For future years, projected future average capacity factors [20] for these technologies, reflecting expected technology improvements, are used to scale up the hourly availability factors. For hydro, the weekly production and inflow in 2015 are collected from ENTSO-E and kept constant for all simulated years.

C. Load data

To obtain the hourly forecast of load data for future years, the estimated future total energy consumption is used to calculate the total load. To estimate the other sectors' future demand, the average growth rate of industry, buildings and transportation sectors were considered. After calculating the total electricity demand, the percentage losses of transportation and distribution systems in Italy (assumed constant at 7%) was added to the load and the projected import of electricity was also deducted. The resulting load is the total TWh electricity that should be supplied by the generation system in Italy. We assumed that the imports will be kept constant through 2030, i.e. equal to 35TWh, but then reduced to zero by 2050. Having estimated the total annual demand from the Italian generation system, hourly load forecasts from ENTSO-E for 2020, 2030, and 2040 [21] were scaled up to calculate the total load in 2022, 2030 and 2050 respectively. These calculations led to an electricity demand of 326, 356 and 402 TWh in 2022, 2030 and 2050, respectively.

D. Energy storage

This analysis considers two types of energy storage systems; existing 8-hour pumped hydro storage and battery storage which is considered to have 3 hours of storage. The roundtrip efficiency of pumped hydro and battery storages are considered 80% and 85%, respectively. Both technologies are providing operating reserves. Note that the total installed capacity of pumped hydro in Italy is 7.4 GW, which is combination of pure and mixed (with reservoir) pumped hydro. In this study, the mixed hydro plants are modelled as reservoir plants and their storage capacity is not considered in the pumped hydro category.

E. CO_2 price

The 2017 World Energy Outlook from the International Energy Agency (IEA) [22] projects European CO_2 prices for three different decarbonization scenarios (current policies, new policies, sustainable development from low to high) in 2025 and 2040 (Table IV). Based on these projections, we have used the "current policies" and "sustainable development" scenarios' CO_2 prices for our target years as input to the generation expansion model, in addition to a case with no CO_2 price, in order to analyze the impact of CO_2 prices on RES investments.

Table IV. CO_2 price projections [22]

CO_2 price (\$/ton)			
Scenario	**2022**	**2030**	**2050**
Current policies	18.4	28	52
New policies	20.4	32.6	63.3
Sustainable development	47.6	88.6	191.3

III. GENERATION EXPANSION RESULTS

Using the input data and assumptions outlined in previous section, the GenX optimization model is run for three cases of CO_2 prices, i.e. zero CO_2 price, "current policies" (CP) and "sustainable development" (SD) pricing scenarios of CO_2 (Table IV). For the case of zero CO_2 price, the power plants are selected based purely on their cost characteristics. The shares of new RES and non-RES installed capacity in this scenario in candidate years are shown in Fig. 1. This result shows that even without a CO_2 price, the majority of future capacity installation consist of RES technologies, illustrating an expected competitive advantage for these technologies even in the absence of a carbon price, i.e. based on minimizing total system generation costs.

The breakdown of the total installed capacity of all generation technologies across the three CO_2 price scenarios are presented in Fig. 2, along with the historical installed capacity from 2015, which was used as the initial capacity for the model. According to the capacity expansion model results, in 2022 due to the substantially lower fuel cost of coal power plants compared to gas power plants (Table II), the economic optimum is to retire a substantial share of the gas-fired power plants, including all the open cycle gas turbines, while maintaining the coal capacity. The economically optimal solution also retires the existing oil-fired power plants due to the higher price of oil compared to gas and coal. Note that the Italian government in its national energy strategy from 2017 aimed at phasing out coal plants by 2025. Therefore, in 2030 and 2050, there is no contribution from coal and natural gas is the only fossil fuel power plant technology. In the cases with carbon emissions prices, the model tends to increase the capacity of solar while decreasing the gas-fired power plants.

Energy storage can address the variability and uncertainty in RES. The total installed storage capacity of pumped storage hydro and batteries are shown in Fig. 3. Interestingly, the economic optimum does not include battery storage until 2030, where some investments in battery storage occurs under the high emissions price scenario. However, in 2050, when the cost of battery storage is assumed to be substantially lower, the model finds it economically beneficial to install large amounts of battery storage, particularly in scenarios with CO_2 prices.

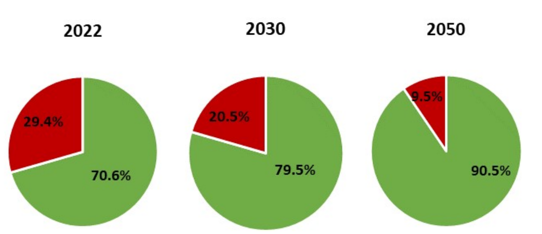

Fig. 1. Shares of total new capacity expansion with zero CO_2 price (RES: Green, Non-RES: Red)

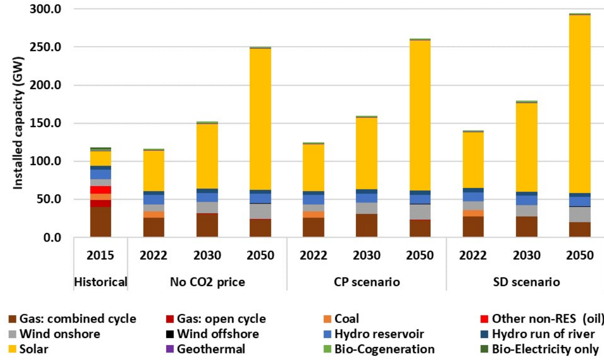

Fig. 2. Current and future installed capacity in different scenarios

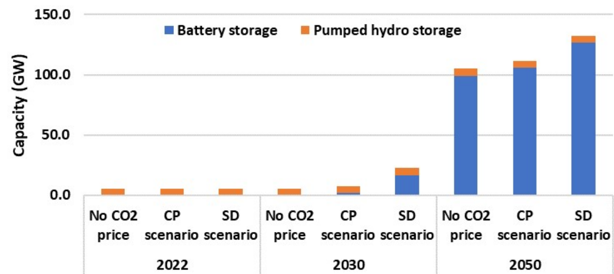

Fig. 3. Installed energy storage capacity

Higher installed capacities of RES increase their contribution to the total electricity consumption. Exploring the electricity harvested from each technology, Fig. 4 shows that in 2022 gas and coal power plants combined will still have the highest dispatch contribution in all three scenarios. Increased CO_2 price decreases the generation of fossil fired power plants and replaces it over time with solar. In fact, by 2050 solar energy will be the dominant generation technology in all scenarios.

Hydro power plants will have close to constant total generation in all years since its installed capacity is constant, however it uses the water with slightly different profiles in different years and different scenarios. Note that the water level in reservoirs is assumed limited to operate within 40% and 70% of the total reservoir capacity, based on historical aggregated reservoir levels. Wind energy generation increases from 2022 to 2050, but the growth is limited by the imposed caps on installed capacity. Table V presents the detailed TWh generation from each technology in different scenarios and years from Fig. 4.

CO_2 prices not only limits the generation from thermal units, but also increases the share of RES in general. To illustrate the effect of CO_2 price on the RES percentage share, Fig. 5 shows the total RES share under different CO_2 price scenarios for three candidate years. Based on these results, RES shares of 45-53% in 2022, 56-65% in 2030 and 84-90% are achieved with increasing CO_2 prices. The results underscore that high RES shares are likely to unfold under the assumptions made in this capacity expansion model, mainly due to the expected cost reduction of solar. Moreover, climate emissions reductions policies such as carbon prices make a substantial impact on the capacity expansion results and contribute to even higher RES penetration levels.

Table V. Historical and future generation results

	Historical	No CO_2 price			CP scenario			SD scenario		
(TWh)	2015	2022	2030	2050	2022	2030	2050	2022	2030	2050
Gas	108.1	104	157	68.2	96.7	149	60.5	92.3	127	41.8
Coal	59.3	74.3	0	0	72.4	0	0	60.0	0	0
Oil	4.3	0	0	0	0	0	0	0	0	0
Wind onshore	14.8	16.8	28.7	38.5	16.7	28.2	37.2	19.7	27.5	34.3
Wind offshore	0.0	0	0	3.8	0	0	3.6	0	0	3.0
Hydro reservoir	24.6	25.5	25.5	25.3	25.5	25.5	24.7	25.5	25.5	22.1
Hydro run of river	20.9	20.7	20.2	20.8	20.6	20.6	20.8	20.8	20.6	20.8
Solar	22.9	66.8	112	250	77.7	121	262	91.2	147	292
Geothermal	6.2	6.0	5.8	5.3	6.0	5.6	5.1	5.8	5.5	4.5
Bio-Cogeneration	9.6	9.5	8.9	7.8	9.3	8.8	6.9	9.0	8.5	5.6
Bio-Electricity only	9.8	0	0	0	0	0	0	0	0	0

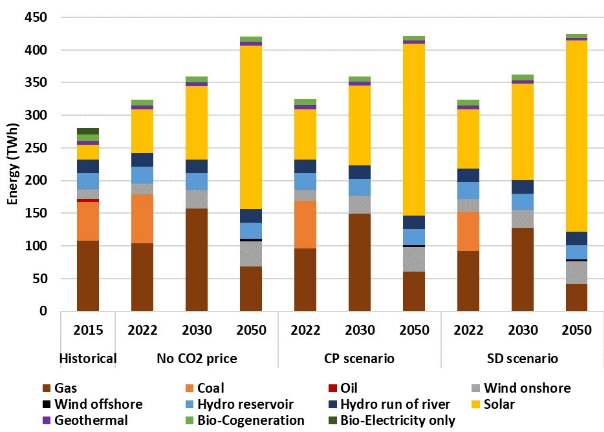

Fig. 4. Historical and future electricity generation by technology

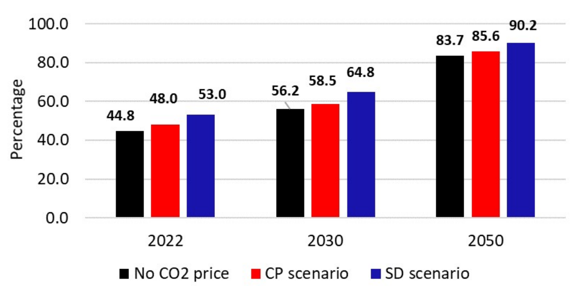

Fig. 5. Percentage share of RES in total electricity generation for different scenarios

To provide insights into the hourly loads and how the units are dispatched to supply that demand, the dispatching result for the first week of January in 2050 is shown in Fig. 6(a). The figure illustrates that solar has a high peak with generation far exceeding the demand during day hours. This extra generation is stored in energy storage units for later use. The resulting aggregate charging and discharging of the storage systems (i.e. pumped storage hydro and batteries) is shown in Fig. 6(b) for the same week. As illustrated in this figure, the peak of charging and discharging of storage units coincides with the mid-day solar extra generation and evening peak loads.

The main contribution of gas-fired units is to support load during evening hours when there is no solar energy available. Fig. 6 clearly illustrate that the gas units' dispatch is dependent on each day's solar generation, with less gas power dispatch in days with high solar generation. Wind generation has the same impact as solar generation on the contribution of gas units in the daily dispatch.

To further explore the contribution of each technology on proving the hourly demand, Fig. 7 shows one day dispatching result for CP scenario in different years. This result illustrates how the demand for electricity in a selected day in 2050 is mostly supplied by renewable generation (especially solar) along with a substantial contribution from battery storage. In contrast, in 2022 and 2030 thermal units still provide the majority of the electricity supply under the CP scenario. From 2022 to 2030, the generation from coal power plants is largely replaced by gas and solar power. By 2050, the combination of solar and energy storage has reduced the need for conventional thermal units. While wind resources have limited diurnal variation, the surplus generated by solar during the day is stored in the batteries and is used to meet demand during evening peak and night hours.

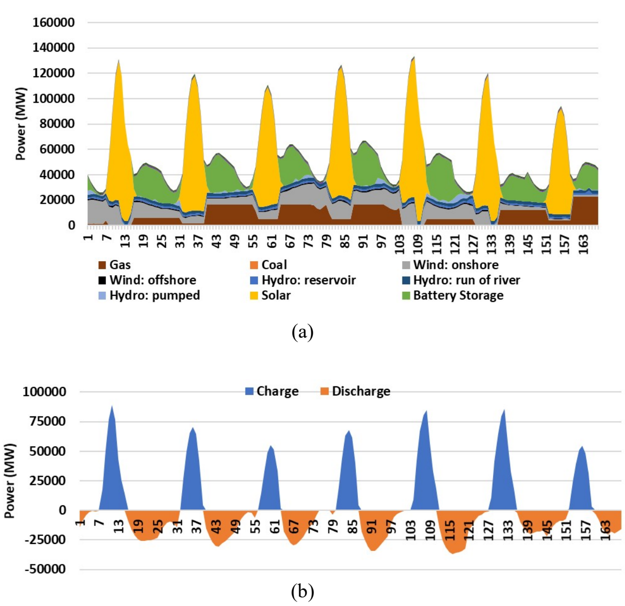

Fig. 6. (a) hourly dispatch result and (b) charge/discharge of storage systems in CP scenario for first week of January in 2050

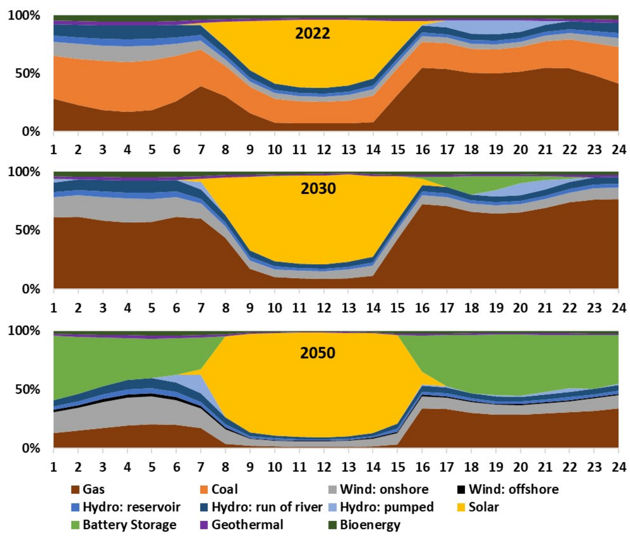

Fig. 7. Dispatching result of CP scenario for January 2nd in different years

IV. Conclusions

In this paper, we estimated the RES penetration levels in the future power system in Italy based on capacity expansion optimization and concluded that Italy's electricity supply is likely to be shaped by RES in the future. The least-cost expansion analysis indicates that by 2050, more than 80% of the electricity can be harvested from RES even without environmental policies such as a CO_2 price. This share can even go above 90% if CO_2 prices are applied. The large RES penetrations are driven by projections of substantial cost reductions in these technologies. In 2050, the most dominant generation technology based on the results is solar energy with 60-70% of the total generated electricity under different CO_2 price scenarios, with gas and wind contributing 10-16% and 10-11% of the total generation. Grid scale batteries may not be economically viable until 2030 unless there are scenarios with high CO_2 prices, while in 2050, due to projections of substantially lower costs for batteries, they will become economically viable. However, it is important to note that these results are obtained under a set of assumptions that are highly uncertain over such a long planning horizon. For instance, there is no constraint applied for the expansion of solar power, which may be limited by both technical constraints and societal preferences. Moreover, the future cost assumptions for different energy technologies used in the study, which include substantial reductions in RES costs, may not follow the projections.

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