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Assessment of the Impacts of Climate Change on Power Systems: The Italian Case Study

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Abstract: Climate change due to the greenhouse effect will affect meteorological variables, which in turn will affect the demand for electrical energy and its generation in coming years. These impacts will become increasingly important in accordance with the increasing penetration of renewable, non-programmable energy sources (e.g., wind and solar). Specifically, the speed and amplitude of power system transformation will be different from one country to another according to many endogenous and exogenous factors. Based on a literature review, this paper focuses on the impact of climate change on the current, and future, Italian power system. The paper shows a wide range of results, due not just to the adopted climate change models used, but also to the models used to assess the impact of meteorological variables on electricity generation and demand. Analyzing and interpreting the reasons for such differences in the model results is crucial to perform more detailed numerical analyses on the adequacy and reliability of power systems. Concerning Italian future scenarios, the double impact of uncertainties in national policies and changes in power plant productivity and demand, has been considered and addressed.

Keywords: climate change; power systems; wind; solar PV; thermo; hydro; electricity demand; future scenarios

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1. Introduction

The world is facing enormous environmental issues. The rate of energy consumption that we are accustomed to has begun to stress the Earth's resources and its ability to sustain our current lifestyle. In this context of threatened sustainability, the urgency to deploy solutions to contrast climate change is compounded by parallel and equally daunting issues, such as the depletion of conventional energy supplies and the safety and political stability of several energy-producing countries.

According to the World Meteorological Organization (WMO), climate is defined as an average weather. The climate system is an interactive system with five components: the atmosphere, the hydrosphere, the cryosphere, the biosphere and the land surface; and these five components are affected by external inputs such as the Sun and human activities [1]. The climate is the state of the climate system, which is a measure of relevant meteorological variables over a given period of time—which the WMO sets at 30 years [2]. Therefore, climate change is defined as a statistically significant variation from its mean state, or in its variability. The most recent (August 2021) AR6 of the IPCC WG I [3] reported the influence of human activities on climate change as an "unequivocal" cause. In addition, five new illustrative emissions scenarios were included in AR6, compared with AR5.

One of the most concerning human activities responsible for altering the climate system is power production. In 2021 the global energy-related CO_2 emissions were equal to 33.0 Gt [4].

Despite these figures, the world continues to electrify, with an all-time high request for power supply. However, according to the "Evolving Transaction" scenario, i.e., a scenario in which government policies, technology, and societal preferences continue to evolve in a manner and at a rate that has been observed in the recent past [5], a slowing down of forecast rates is predicted. From the point of view of the "Evolving Transaction" scenario, the following remarks are of greatest relevance [5]:

- About three-quarters of the total primary energy growth will be used for electricity generation, with about half of the total primary energy absorbed by the electricity sector by 2040;
- Almost all of the growth in electricity demand comes from developing economies, led by China and India, if compared with OECD countries, reflecting both slower economic growth and the weaker responsiveness of electricity demand to economic growth in more mature, developed economies;
- The mix of fuels in global electricity generation is shifting significantly, with renewable energy sources (RES) gaining share at the expense of coal, nuclear and hydro. The share of natural gas remains largely unchanged at around 20%. In the future, two-thirds of the increase in electricity generation will come from RES, with their share of the global electricity sector rising to about 30%. In contrast, the share of coal is declining/will decline significantly, and by 2040 it will be overtaken by renewables as the main energy source in the global power sector.

The worldwide electricity generation from renewable energy sources, over the last twenty years, is characterized by (data available in 2021, referring to 2019): hydropower generation equal to 4321 GWh; wind power generation of 1412 GWh (one third of hydropower); PV generation equal to 693 GWh. These data are justified by the high-capacity factor of hydroelectric plants (3653 h per year (h/y) on average), photovoltaic (1241 h/y in 2019) and wind (2199 h/y) [6]. The hydroelectric sector still dominates the RES industry, however, with an increasing presence of wind and PV in the power generation mix.

Looking at RES generation capacity worldwide, in 2020 hydropower capacity was equal to 1331.9 GW (of which 222.5 GW in Europe), wind power capacity amounted to 733.3 GW (207.8 GW in Europe) and solar power capacity was equal to 714 GW (163.5 GW in Europe) [7]. It is worth noticing how the latter two capacities combined (viz. photovoltaic and wind power) were greater than hydropower capacity. Moreover, the worldwide RES capacity has experienced a net increase if compared with the previous year. While hydropower capacity grew by just 2%, the wind and solar energy power sectors witnessed a much greater growth (18% and 21%, respectively).

Most renewable energy sources are non-programmable and intermittent sources, which means they are characterized by a limited capacity to adapt production to the growth of electricity consumption, and by strong, short term fluctuations.

Climate change is certainly one of the main drivers of both the extent and the speed of changes happening in the power system. Climate change, responsible for fluctuations in environmental variables, will also have a quantitative and qualitative impact on future demand and generation (conventional and renewable). For instance, a recent report showed how a +2 °C rise in temperature will impact Europe's future electricity generation and demand, more significantly than a +1.5 °C increase [8]. However, these changes will not be uniform throughout the globe: northern countries will experience a greater climate difference. In support of this evidence, unevenness of climate change impact can also be forecast at a more local level. For instance, Mediterranean regions will be the most affected by climate change, with an increase in temperature 20% greater than the global average increase, and precipitation will be drastically reduced. At a more granular and local level, precipitation will be reduced unevenly through Italy, with the central and southern part being most affected during summer; while the northern regions will experience an increase in precipitation during winter. It is important to point out that precipitation levels projections and scenarios vary greatly depending on the RCP scenario selected [9].

With the scenario mentioned above in mind, power systems must evolve, and the transformation must be driven by cost reductions, energy security, reliability, resilience goals, and both local and global environmental concerns about greenhouse gas (GHG) emissions. Indeed, electricity grids are called upon to reduce greenhouse gases emissions.

Power systems are in “adaptation” mode, being able to accommodate incremental changes in demand growth, technological change, and consumer preferences [10]. The gradual substitution of conventional programmable energy sources (mainly thermoelectric power plants) by non-programmable sources (photovoltaic and wind power) calls upon the need to face and overcome important challenges in power system adequacy and security management. In particular, a power system can be adequate only if it can ensure sufficient generation capacity to meet the electricity demand in each hour and market zone of a country. Uncertainty about the availability of RES generation poses a challenge to the adequacy of the power system.

Climate change will likely increase the frequency, severity and persistence of extreme weather events which are already impacting the resilience and reliability of electric power systems [11].

Climate change will likely cause an increase in average temperature worldwide. This in turn will compromise power systems operations, because several components are sensitive to variation of the ambient air temperature. Moreover, the impact of climate change on renewable energy sources changes depending on the considered technology. Transformers are bound to a maximum operating temperature; therefore, global warming could strikingly compromise their nominal operations. Increased temperatures also affect the efficiency and power output of thermoelectric power plants. A higher frequency and severity of droughts (also caused by long heat waves) affect water availability, which in turn affects hydropower and thermoelectric energy generations. High temperatures also affect the efficiency of PV modules. Finally, global warming will likely cause changes in electricity demand and load patterns, which will be exacerbated by migrations from areas more affected by climate change to other regions [11].

Among the various factors which might influence electricity demand, ambient temperature is certainly the most relevant. Demand changes seasonally, and the widespread use of electric heating and cooling have a significant impact on electricity demand. Moreover, temperature varies from year to year, resulting in fluctuating demand. In sum, extreme events have a major impact on electricity demand (and supply).

Climate change will impact the heating and cooling needs of buildings, which will translate into changes in the magnitude and timing of electricity demand. In order to quantify such impact, researchers have used both top-down and bottom-up approaches. While the former regresses historical load against variables such as temperature or degree-days to estimate economy-wide demand, the latter inputs similar variables into building energy models to estimate demand for specific sectors or building classes. Merging top-down and bottom-up approaches would complement detailed thermodynamic building models by taking into account data that are usually omitted in either of the approaches [12].

In order to understand whether and what actions need to be taken to maintain an economic, resilient and reliable future for electricity supply, it is of crucial importance to collect the impacts and interactions of climate change on the electricity system and link them to planning and operations. This should be conducted within the framework of uncertainty, as of the nature of future climate change and its impacts on power systems. This uncertainty is the combination of uncertainty in climate models, in future emission pathways, and in intrinsic climate dynamics. In addition, the impact of climate change varies between countries and depends on many factors, most notably the mix of the electricity generation park.

The aim of this work is to study the impact of climate change on the Italian power system, while considering electricity generation and demand. Two issues are addressed in this paper: first, to interpret, align, and utilize data related to the impact of climate change on the Italian electric power system; the second issue concerns the way in which it is possible to utilize these data and information to enhance the development plans released by the Italian government. Therefore, a review of the pertinent literature along with an alignment of methods, climate and generation/demand models have been performed. Papers were selected based on the kind of generation technology (wind, PV, hydro and thermoelectric power), and if electricity demand was considered. From these papers which dealt with power generation and demand in present-day European power systems, information about Italy has been extrapolated. For thermoelectric generation technology, a reference about present-day thermoelectric generation in the USA has been considered for completeness. Together with the present-day power systems, some references also referred to future energy systems scenarios.

In this work, particular attention was paid to the models and forcing scenario used in the references analyzed, in addition to the magnitude and sign of the scatter between models, looking closely at the uncertainties within each model. Such an analysis allows insights into the possible changes that the Italian electric power system (characterized by a high share of wind and PV capacity) needs to conduct, in order to maintain the power system adequately.

The medium and long term evolution of a national electricity system is determined by the adopted energy policy. In this context, the last part of this paper analyses the future energy systems scenarios for Europe and Italy. For the Italian future energy scenarios, priority has been given to the most recent literature sources (2019–2021). For Europe, the double contribution of the uncertainty of climate model projections and future energy systems scenarios have been analyzed. For Italy, the double impact of the uncertainties of the national policy, and the changes linked to the productivity and demand of power plants in future scenarios, has been considered.

The paper is structured as follows. Section 2 analyzes the methodologies and models used in the reference papers regarding present-day power systems, for electricity demand and each generation technology; Section 3 presents the status of the Italian electricity generation mix until 2020; Section 4 reports the results given in the selected references with considerations and comparisons; Section 5 presents Italian future power systems scenarios with related results and comparisons. Finally, conclusions are drawn in Section 6.

2. Climate Change Impact on Present-Day Power Systems: Reference Methodologies and Generation/Demand Models

2.1. Reference Methodologies

This section discusses the two main papers [13,14], from which the methodologies for assessing the impacts of climate change on power systems are drawn. These papers deal with the impacts at the European level, from which information was extracted for the impacts on the Italian electricity grid.

In [13], the climate change impacts on PV, wind, hydro, and thermo power generation for 28 European Union countries were evaluated.

Five RCM (regional climate model) simulations taken from the EURO-CORDEX initiative [15] were used. This ensemble of simulations comes from a model simulation selection methodology, necessary to gain a cheaper computational cost. The five selected RCM model experiments were based on a combination of three GCMs (general circulation model) and three RCMs. Climate models need to be forced by an emission scenario, so in [13], four out of five simulations were forced with an RCP (representative concentration pathways) 8.5 radiation forcing scenario, whereas the remaining model was forced with an RCP 4.5 scenario.

Referring to IMPACT2C project studies [16], Tobin et al. used 1971–2000 as the reference climate period to compare future changes in power generation.

The assessment focusses on three global warming levels, i.e., 1.5 °C, 2 °C and 3 °C (with respect to the pre-industrial period 1881–1910), which will be reached, according to the five simulations above, in time periods spanning 2004–2043, 2016–2059, and 2037–2084, respectively.

Three-hourly data was used for wind and PV power analyses, whereas daily time-series were used for hydro and thermoelectric power.

A 0.11° in latitude and longitude (almost 12 km) was the spatial resolution of the simulations, over the European region.

In [14], the impact of climate change on surface climate indicators (2 m temperature, 10 m wind speed, surface irradiance) and power systems components (sensitive to weather), within a chosen power system scenario, was analyzed. In this way, two types of uncertainty were considered: power system scenario and climate change projection. Moreover, the impacts of climate change and uncertainty were investigated considering the differences between technologies (amount of wind and PV installed generation) and geographic locations. Finally, Bloomfield et al. studied whether the operation of different European energy policy scenarios was impacted by climate change. The Copernicus Climate Change Service (C3S) European Climate Energy Mixes (ECEM) project was used as the data source for meteorological variables, electricity demand, onshore wind and PV generation, for each climate model and emissions scenario. Hydropower generation was excluded as it was considered to be of high operational complexity.

These data were derived from two sources of climate data: a bias-adjusted reanalysis of the period 1979–2016, and a regionally downscaled climate model projection spanning the period 2006–2100.

Six EURO-CORDEX global-RCM couples forced with RCP 8.5 and RCP 4.5 were considered. These models were selected to give a likely representation of current European climate, whereas the inter-model range was considered to give a range of the likely climate change responses of the 11-member EURO-CORDEX set.

The climate change impact on electricity demand and generation was evaluated considering the 2015 power system scenario, taking the difference between the 2045–2065 mean and the 1980–2000 mean, for Europe and four case study countries (Sweden, Romania, Italy and Germany), on an annual mean and seasonal mean basis.

2.2. Generation and Demand Models

This section presents the models of generation systems and demand found in the literature for the specific assessment of the impact of climate change, and thus of temperature (due to global warming), on different generation technologies and demand. Given the two main papers [13,14], the analyses of models have been joined to other references, to gain greater clarity and completeness.

2.2.1. Photovoltaic Power

For solar energy, variations in cloud cover are one of the causes that dramatically impact the surface downwelling solar radiation. Specifically, in PV systems there is almost a linear relation between the power and the irradiance when the system works at the maximum power point (MPP) [17]. Other meteorological variables, such as wind and ambient temperature, affect the efficiency (and then the power output) of PV systems [18]. In particular, the output power is affected by cell temperature, T_{cell}, whose dependence is quantitatively defined by the coefficient α_{PV}, that is the power temperature coefficient, whose value depends on the PV cell technology considered. For example, in monocrystalline silicon solar panels, it can range mainly between -0.5 and $-0.4\%/{}^{\circ}\mathrm{C}^{-1}$ (e.g., in [13] $\alpha_{\mathrm{PV}} = -0.5$). In turn, the cell temperature depends on the ambient variables (e.g., irradiance, temperature and wind speed). In [13], T_{cell} was modelled, considering the effects of the near-surface temperature (T_a), the 10-m wind speed (v_{10}), and the surface downwelling solar radiation, G [$\mathrm{W/m^2}$] as the following:

$$T_{cell}(t) = c_1 + c_2 T_a(t) + c_3 \mathrm{G}(t) + c_4 \mathrm{v}_{10}(t) \tag{1}$$

where $c_1 = 4.3\ {}^{\circ}\mathrm{C}$, $c_2 = 0.943$, $c_3 = 0.028\ {}^{\circ}\mathrm{C\ m^2 W^{-1}}$ and $c_4 = -1.528\ {}^{\circ}\mathrm{C\ s\ m^{-1}}$ are coefficients stated empirically.

Considering now the PV module efficiency, and its variation with respect to reference conditions STC (G_{STC} = 1000 ($\mathrm{W/m^2}$), T_{cell} = 25 °C, AM = 1.5), it can be expressed by an equation in which the dependency on G and T_{cell} is expressed. In this case the effect of other losses (IAM optical losses, and the Joule losses) are neglected [19].

$$\eta_{\mathrm{el,PV}} = \gamma_{PV} \cdot \eta_{PV,STC} \cdot (1 + \alpha_{PV} \cdot (T_{cell} - T_{STC})) \cdot \left(1 + \beta_{PV}^{II} \cdot (G - G_{STC})\right) = \gamma_{PV} \cdot \eta_{PV,STC} \cdot P_R \tag{2}$$

where:

$\eta_{\mathrm{el,PV}}$ is the electrical efficiency of the PV module (1);

γ_{PV} is the degradation rate (1), i.e., considers the reduction of the rated power during the designed life of the PV module;

$\eta_{PV,STC}$ is the electrical efficiency in STC (1);

α_{PV} is the power temperature coefficient (1/°C);

T_{cell} is the cell temperature (°C);

T_{STC} is the temperature in standard test conditions (°C);

β_{PV}^{II} is the solar radiation coefficient of the power at maximum power point (MPP) ($1/\mathrm{W/m^2}$);

G is the surface downwelling solar radiation ($\mathrm{W/m^2}$);

G_{STC} is the surface downwelling solar radiation at standard test conditions ($\mathrm{W/m^2}$);

P_R is the performance ratio (1).

Another aspect that modifies the solar radiation is the concentration of aerosols in the atmosphere. Indeed, aerosols scatter and absorb solar radiation, modifying the shortwave radiation that reaches the PV modules [18]. Moreover, concentrations of aerosols could have a relation with climate change [20]. Therefore, climate change will also affect the absorption of solar radiation from the atmosphere, so it is worth citing another efficiency expression where the air mass (AM) is considered [19]:

$$\eta_{\mathrm{el,PV}} = p \cdot \left(q \cdot \frac{G}{G_{STC}} + \left(\frac{G}{G_{STC}}\right)^m\right) \cdot \left(1 + r \cdot \frac{T_{cell}}{T_{STC}} + s \cdot \frac{AM}{AM_{STC}} + \left(\frac{AM}{AM_{STC}}\right)^u\right). \tag{3}$$

where:

p, q, m, r, s and u are parameters that must be determined for each type of module from a specific set of outdoor measurements;

AM is the air mass (1);

AM_{STC} is the air mass at STC (1).

In climate change studies, future variations in PV electricity production are calculated as a function of installed capacity. In particular, given the performance ratio P_R and knowing the variations of irradiance and installed power, it is possible to obtain the produced power by means of photovoltaics power potential PVpot, that is a dimensionless number [13]:

$$\mathrm{PVpot(t)} = \mathrm{P_R(t)} \frac{\mathrm{G(t)}}{\mathrm{G_{STC}}} \tag{4}$$

Once PVpot has been calculated at the grid cell level, the PV power production is obtained (according to the power installed capacity) for each grid cell, considering non-tilted PV panels. Finally, PV production is aggregated over regions of PV plants of each country, in this way obtaining PV production at national scale.

In [14], PV production on a grid cell basis, using a physical model of capacity factor, was evaluated. The meteorological inputs of the model (surface irradiance, 2 m temperature, and solar zenith angles) were put in an empirical solar power curve to obtain a resultant solar power capacity factor at each grid box. Then, these capacity factors were aggregated to national scale considering a homogeneous distribution of solar PV production in each country. This assumption was also used for future scenarios with increased solar PV capacity. The national capacity factors then were scaled by country level installed capacity. Characteristics of the PV modules were estimated using statistical techniques.

2.2.2. Wind Power

Among the RES power capacities worldwide, wind power capacity was the second in quantity [7]. Therefore, it is important to understand the ways in which climate change could impact wind energy generation.

Wind speed is the most important influencing factor of wind energy. Specifically, the expression of input wind turbine power, under the assumption of dry air at pressure of 1 atmosphere is [21]:

$$P_w = \frac{1}{2}\rho(T_a, p)\cdot A\cdot \mathrm{v_H}^3 = \frac{1}{2}\frac{353.05}{273.15 + T_a}\cdot A\cdot \mathrm{v_H}^3 \quad (5)$$

where:

P_w is the power in the wind (W);
ρ is the air density (kg/m^3) function of temperature T_a and pressure p;
A is the cross-sectional area through which the wind passes (m^2);
and $\mathrm{v_H}$ is the windspeed at the hub turbine height and orthogonal to A and at the hub turbine height (m/s).

The cubic relation in (5) suggests that even little variations in mean wind speed and wind patterns can drastically change the wind energetic potential. Climate change may modify atmospheric dynamics with impacts on both wind speed and wind patterns [22]. In light of this, many studies have addressed the forecast of long term wind patterns and average wind speed, for different regions of the world.

Finally, in addition to mean wind speed and wind patterns, other factors affect wind energy production such as air density (which in turn depends on the air temperature), but less research has been conducted on this aspect.

Focusing on the two main papers of this work, [13,14], the procedure followed in [13] took the wind input data, that is, wind speed at 10 m ($\mathrm{v_{10}}$), then extrapolated it to the turbine hub height (H), for example using the power law found by Elliot [23]:

$$\mathrm{v_H} = \mathrm{v_{10}}^{\frac{1}{7}} \quad (6)$$

Once the wind speed at hub height was obtained, this value was entered in a standard turbine power curve to obtain the electric power generated by the turbine.

Specifically, the wind turbine characteristic showed further no linearities when the wind speed was either lower than the cut-in wind speed or when it exceeded the cut-out wind speed, where in both situations the output power was zero [21].

The wind farm distribution existing in the year of paper was considered to evaluate future relative changes in wind power potential.

In [14], the wind power capacity factor was calculated at each reanalysis grid box, with the extrapolation of near-surface winds to a constant hub-height of 100 m. Taking these values by means of a turbine standard curve, these speeds gave the value of power generated. The capacity factor was aggregated to country level, and then it was multiplied by the national installed capacity (scaled) to obtain the country level wind generation. Only onshore wind farms were considered. The grid resolution used was 0.5°, being not so fine a resolution that makes it difficult to state where wind power farms will be installed between grid points, inside a country. This motivates the assumption of a homogeneous distribution of wind farms for future scenarios assessment.

2.2.3. Thermoelectric Power Modelling

Several studies have demonstrated that droughts and hotter water and air temperatures caused by climate warming will reduce thermoelectric plant efficiency by 0.12−0.45% for each 1 °C of warming [24]. The reasons of this strong impact are several, and change depending on the cooling system technology selected. Figure 1 shows two main cooling system technologies of power plants: the once-through system and the recirculating system. Both simple steam Rankine cycle and the combined Rankine/Brayton cycles of steam cycle can have either type of cooling system.

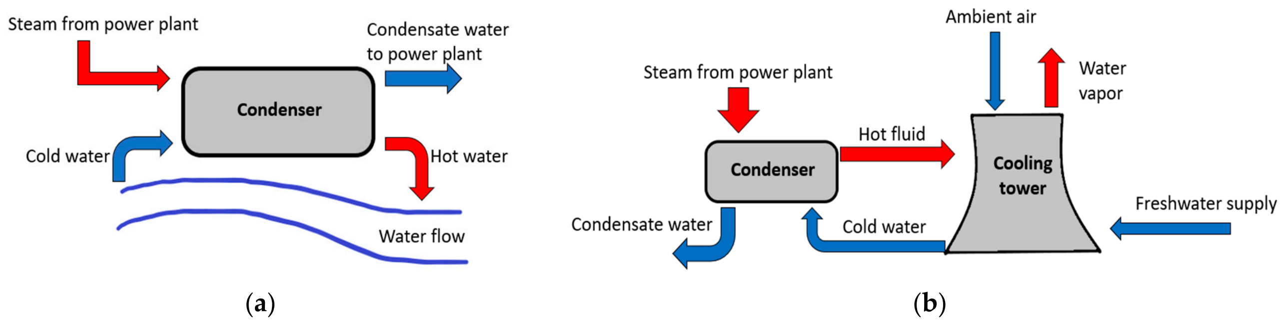


Figure 1. Cooling system technology of power plants: (**a**) the once-through cooling system, (**b**) the recirculating cooling system. Either type of steam cycle can have either type of cooling system. Blue arrows indicate cold fluid flow and red hot/warm fluid flow.

The efficiency and useful power output of gas turbines depend on the ambient temperature. Considering that average air temperatures are expected to increase due to global warming, it is reasonable to consider the effects of air temperature on efficiency and useful power output of the gas turbine. The International Standards Organization (ISO) sets the reference conditions for air temperature and pressure at 15 °C and 1.013 bar. Considering the efficiency of the gas turbine at ISO conditions $\eta_{GT,X}$ and the useful power of the gas turbine at ISO conditions $P_{GT,X}$, two empirical relationships can be given [25]:

$$\eta_{GT} = \eta_{GT,X} - (0.1)\Delta T_a \tag{7}$$

where:

η_{GT} is the predicted efficiency of the gas turbine at an ambient temperature that differs from the ISO conditions by ΔT_a (1);

$\eta_{GT,X}$ is the efficiency of the gas turbine at ISO conditions (1);

ΔT_a indicates the temperature difference from the ISO condition of 15 °C (°C).

$$P_{GT} = P_{GT,X} - (1.47)\Delta T_a \tag{8}$$

where:

P_{GT} is the predicted power output of the gas turbine at an ambient temperature that differs by ΔT_a from the condition ISO (W);

$P_{GT,X}$ is the useful power of the gas turbine at ISO conditions (W).

Considering these equations, it can be said that for every 1 °C increase in ambient temperature from the temperature specified in the standards of ISO, the gas turbine efficiency decreased by 0.1%, while the useful power output decreased by 1.47 MW [25].

To evaluate the impact of climate change on steam gas turbine, a model of the power plant efficiency as a function of ambient variables must be used.

In [24], a least squares model (GLS), based on numerical regression, for the hourly efficiency was used where the variables were: hourly plant capacity factor C_f (%), ramp rate ΔC_f (%), and either water temperature T_w (°C) and dry-bulb air temperature T_{db} (°C) for once-through plants, or simply wet-bulb air temperature T_{wb} (°C) for recirculating plants. Air temperature was included too, due to the potential impacts from ambient air drawn into the boiler. The error term ε contained the autocorrelation and white noise error of the model.

For open-loop thermoelectric plants, the increase in temperature due to global warming will lead to a reduction of cooling water availability and an increase in coolant temperatures. The latter effect impacts the open-loop power plant efficiencies because hotter waters remove less heat from the plants' steam cycle. Wet-bulb air temperature has not been included in the open-loop model because research suggests that the effect of humidity on boiler efficiency is minimal [26].

The hourly efficiency of a once-through plant is expressed as:

$$\eta_{\text{open}} = a + b\left(C_f\right)^{\text{f}} + c\Delta C_f + dT_w + eT_{db} + \varepsilon \tag{9}$$

where a [%], b [%], c [h], d [%/°C], e [%/°C], f (unitless) are constant coefficients.

For closed-loop thermoelectric plants, the efficiency is more impacted by elevated ambient air temperature and humidity (characterized both by wet-bulb temperature). Both effects, indeed, reduce the condensation in cooling towers and thus the system's cooling capacity.

The hourly efficiency of closed-loop plant is expressed as:

$$\eta_{\text{closed}} = m + n\left(C_f\right)^{\text{q}} + o\Delta C_f + pT_{\text{wb}} + \varepsilon \tag{10}$$

where m [%]: n [%], o [h], p [%/°C], q (unitless) are constant coefficients.

For closed-loop (or recirculating) plants, the temperature of the coolant is determined principally by the cooling tower, whose performance is a function of both humidity and dry-bulb air temperature. For this reason, the authors used T_{wb} for this kind of plants. Moreover, the boiler of these plants can be affected by T_{wb}.

Equations (9) and (10) depend on capacity factor C_f; in turn, the capacity factor is proportional to the usable capacity. Therefore, another crucial model expresses the P_{usable} as not only a function of the T_W but also of the water availability Q (kg/m^3), the latter depending on the actual environment and climate conditions.

In [27], in order to represent the actual conditions, a cooling water scarcity factor φ was assumed to be the ratio of Q and q, where q is the amount of cooling water required (m^3/h). As T_w is the inlet cooling water temperature, two temperature thresholds T_{health} and T_{shut_down} have been defined. If $T_w < T_{health}$, the usable capacity P_{usable} would be determined only by φ:

$$P_{usable} = \min(\varphi,\ 1),\ T_W \leq T_{health} \tag{11}$$

This means that Q dominates the impact on the usable capacity, until T_w reaches T_{health}. When $T_w > T_{shut\_down}$ the P_{usable} is zero.

$$P_{usable} = 0,\ T_{shut-down} \leq T_W \tag{12}$$

When $T_{health} < T_w < T_{shut\_down}$, both Q and T_w have an impact on usable capacity.

When $T_{outlet\_max} - T_w > \Delta T_{max}$ (where ΔT_{max} is the allowance of the maximum temperature difference between the inlet and outlet cooling water (°C)), q is constant. In this way, P_{usable} depends on the relation between Q and q. In order to evaluate the decrease in the usable capacity with the increase of T_w, a linear function was proposed with a coefficient λ_D, as shown below:

$$P_{usable} = \min(\varphi, 1)\cdot(1 - \lambda_D(T_W - T_{health})),\ T_{health} \leq T_W \leq T_{outlet\_max} - \Delta T_{max} \tag{13}$$

The impact of Q was considered by introducing the coefficient min(φ,1) in the previous equation. If T_w continued to increase, $T_{outlet\_max} - T_w$ would become less than ΔT_{max}, causing a significant increase of q. In this situation it is assumed that P_{usable} would be affected only by an increase of q. For this reason, a de-rating factor is introduced in the following equation:

$$P_{usable} = \frac{T_{outlet\_max} - T_W}{\Delta T_{max}}\cdot\min(\varphi, 1)\cdot(1 - \lambda_D(T_{outlet\_max} - \Delta T_{max} - T_{health})),\\ T_{outlet\_max} - \Delta T_{max} \leq T_W \leq T_{shut-down} \tag{14}$$

For open-loop cooling systems, the models in (11) and (14) are more appropriate because they properly consider the inlet cooling water temperature and water availability.

For closed-loop/hybrid cooling systems, since the cooling water circulates in a closed loop, the loss of this water is about 2–4% of the inlet cooling water used in the open-loop cooling systems. In this sense, the water availability has negligible effect on closed-loop/hybrid cooling systems. Due to these considerations, it is possible to say that the models in (11) and (13) can be used to represent closed-loop cooling systems, assuming $\varphi = 1$, and a very high T_{outlet_max}.

In [13], VIC (variable infiltration capacity) hydrological model and RBM (river basin model) water temperature models (modified by the authors) have been used to produce streamflow and water temperature projections on a daily time step, with a spatial resolution for Europe of $0.5^\circ \times 0.5^\circ$. In order to simulate streamflow and water temperature under future climate, the VIC-RBM framework (validated for river basins in Europe and worldwide) was forced with the RCM outputs of minimum and maximum temperature, precipitation and wind speed. The impacts of variation in streamflow and water temperature on thermoelectric production were evaluated with a model that simulated, in a first step, the water demanded for cooling, and in a second step, the usable power plant capacity [13]. Thermoelectric power plants were divided into once-through cooling and recirculation cooling plants, and were selected according to the cooling system type, available information on installed capacity and river water as the source for cooling. Finally, the climate change impact on river flow and water temperature was evaluated for each thermal power plant, and then the results were aggregated at the national scale.

The works [13,24,27] are connected to each other, so it is worth underlining the alignments between them. In [13], Equation (4a,b) (for once-through cooling systems) and Equation (5a,b) (for recirculation (wet tower) cooling systems) have been used. Moreover, in [13] the climate change impacts on thermoelectric generation were evaluated considering environmental regulations and variations in future cooling water availability such as in [28]. In [13], plants using river water for cooling were considered. In [27], starting from Equation (4a,b) in [13], a simplified model was proposed. In this way, Wang et al. created a practical model for the cooling system, without specifying the kind of water source considered in the model (river flow or sea water). Both [13,27] analyzed the impact of climate change (changing water temperature and availability) and environmental regulations on the useable plant capacity.

On the contrary, [24] proposed a different approach based on plant efficiencies (by means of regression analyses) instead of useable plant capacity such as in [13,27]. Moreover, in Henry's and Pratson's models, the future cooling water availability and the environmental regulations were ignored. This led to results in thermoelectric power plants efficiencies that were much less sensitive to climate change impacts. Finally, in [24], open-loop and closed-loop plants, with rivers as water source, were considered.

2.2.4. Hydropower

Periods and patterns of precipitations, temperatures and evaporation are the main influencing factor of stream flow and reservoir levels. Climate change will affect these environmental variables, also in this way impacting hydropower generation. In particular, precipitation levels will change depending on the season and geographical area; evaporation will likely rise due to higher temperatures caused by global warming. Both precipitation and evaporation variations will likely change the discharge regimes of rivers [29].

The authors in [29] tried to evaluate climate change impacts on hydropower generation in the European Union. Evaporative water loss from the reservoir surfaces was neglected. Indeed, quantifying evaporation is a difficult task due to measurement difficulties (evaporation depends on factors such as temperature increase, wind speeds, humidity and solar radiation, that have regional dependence), very few direct measurements of evaporation are present, and different equations are required to calculate evaporation, which give different estimates of absolute evaporation rates. For future climate change impacts on hydroelectric production, the authors have taken available information about changing hydropower potentials from the literature. To carry out simulations, the authors used the prospective outlook for long term energy systems (POLES) model. This model is a market-oriented partial equilibrium model (balance of supply and demand obtained through the market equilibrium prices) with year-by-year (from the current year of the paper to 2100) dynamic simulation processes, for each type of energy. POLES can simulate international markets and energy systems in 57 countries and regions; for the purpose of [29], 27 member states of the EU were selected.

In [13], gross hydropower potential in each country (i.e., the annual energy available if all natural runoff is gained) at each "river grid cell" was considered. Daily streamflow projections were obtained by means of the VIC hydrological model, [30,31], considering a $0.5^\circ \times 0.5^\circ$ spatial resolution for Europe. Climate output variables taken from CORDEX simulations were daily values of precipitation, minimum and maximum temperature, incoming fluxes of short and long-wave radiation (all bias-corrected), humidity and wind speed. These variables were used as input for the VIC model.

2.2.5. Demand Model

In [32] a MAF (mid term adequacy forecast) assessment was conducted by ENTSO-E. The temperature dependency between heating and cooling devices and electrical energy use is shown in the following figure.

Figure 2 shows that in colder days the power demand increases due to heating request (heating zone). Around 20 °C, neither heating nor cooling are requested by the users (comfort zone). At higher temperatures, the demand increases with temperature in an almost linear way (cooling zone).

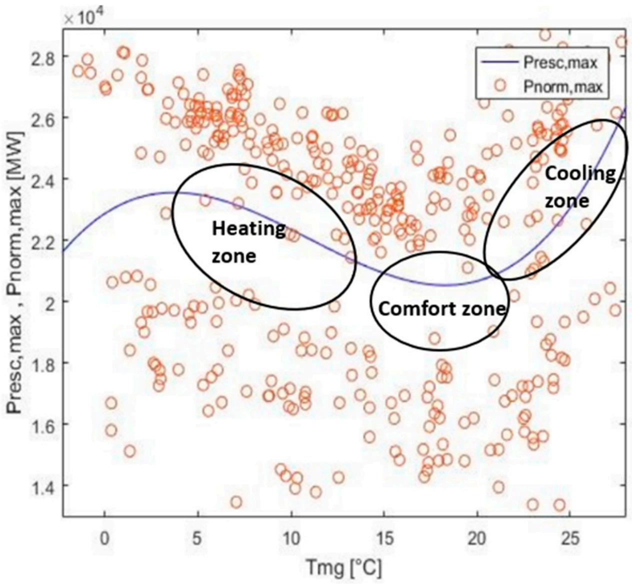


Figure 2. Temperature dependency of consumed energy. Each dot is a combination of consumption and daily average temperature for one day; the curve is the interpolating line [33].

In MAF, by means of a demand–temperature sensitivity, mathematical correlations between the ambient temperature in an area and its consumption were calculated.

Specifically, a cubical polynomial approximation was used as the basis for creating synthetic hourly demand profiles for each area.

In [32] the cubical polynomial approximation was applied to the measured demand profile of 2015. The daily average temperature was calculated from a data set which included 34 years of meteorological data. In this way an hourly demand profile was obtained that represented the demand of the market zones.

Finally, summing up every hour of this normalized demand profile, the total electrical demand of 2015 of each zone was obtained.

To obtain a specified synthetic hourly demand profile for a target year, it is necessary to up- or downscale the above procedure by means of the following formula:

$$\frac{(P_{norm} - P_{norm\_min})}{(P_{norm\_max} - P_{norm\_min})} = \frac{(P_{resc} - P_{resc\_min})}{(P_{resc\_max} - P_{resc\_min})} \quad (15)$$

In Figure 3 shows, as an example, the final result of the procedure described.

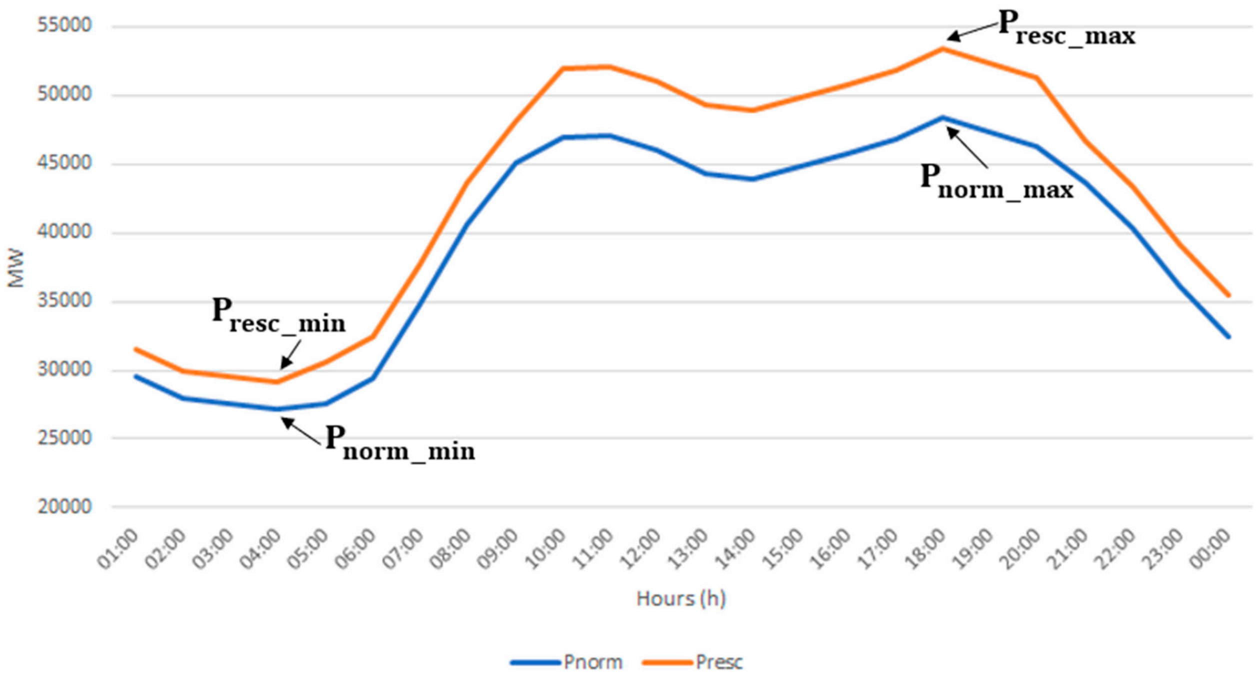


Figure 3. Stretch rescaling of a daily demand profile.

In [34], the load power hourly referment profile in 2018 was considered along with the temperature profile in 2018. With these two inputs, the coefficients of the two cubic functions were evaluated. From the temperature profile estimated from the model, it was possible to obtain the daily average temperature profile. If this profile was given as an input to the previous cubic functions, the daily minimum and maximum power values could be obtained. Given these values, it was possible to rescale the referment profile, by means of a proportionality relation, and in this way obtaining the simulated load power.

In [14], the countries' individual daily electricity demand was modelled by means of a GAM (generalized additive model) approach, re-combining two different contributions: the first considered the long term changes in demand, the second considered the daily weather-dependent residuals (both modelled separately). To model the latter, meteorological variables such as near-surface temperature, surface solar irradiation, wind speed and relative humidity were considered. Moreover, fixed demand data (i.e., independent on the physical changes in climate) taken from the ECEM Demonstrator, were used. Furthermore, in their study, Bloomfield et al. considered both the impact of climate change and the impact of policy decisions on European power systems, comparing them through demand data modelled by means of five contrasting e-Highway 2050 evolving scenarios that were named as: "Small and Local", "Big & Market", "100% RES", "Large and Scale Renewables" and "Fossil and Nuclear" [35].

3. The Present Italian Power System

The energetic mix of sources that contribute to Italian electricity production has strongly changed in recent years. In 2005, RES covered almost 16% of net production (due mostly to hydropower plants); in recent years this percentage has more than doubled.

Indeed, in 2020, renewable sources covered almost 42% of national production (114 TWh of the total 273 TWh); this percentage increased compared with 2019 (40%). Consequently, the amount of production from non-renewable plants as a proportion of overall Italian production reduced from 84% in 2005 to 58% in 2020. In absolute terms, the value of thermoelectric generation decreased from 236 TWh in 2005 to 157 TWh in 2020 (almost −33%).

In Italy, in December 2020, the installed wind capacity was almost equal to 10,918 MW. A large part of the installed wind capacity is concentrated in southern Italy, due to more availability of wind in that part of the country. The installed PV capacity, in the same month and year, was equal to about 21,629 MW. Specifically, in 2020, the installed PV capacity increased by about 729 MW compared with 2019, whereas the wind source increased by about 160 MW compared with 2019 [36]. Figure 4 shows the evolution of the Italian production from 2011 to 2020. Figure 5 shows the historical demand profile from 2011 to 2020.

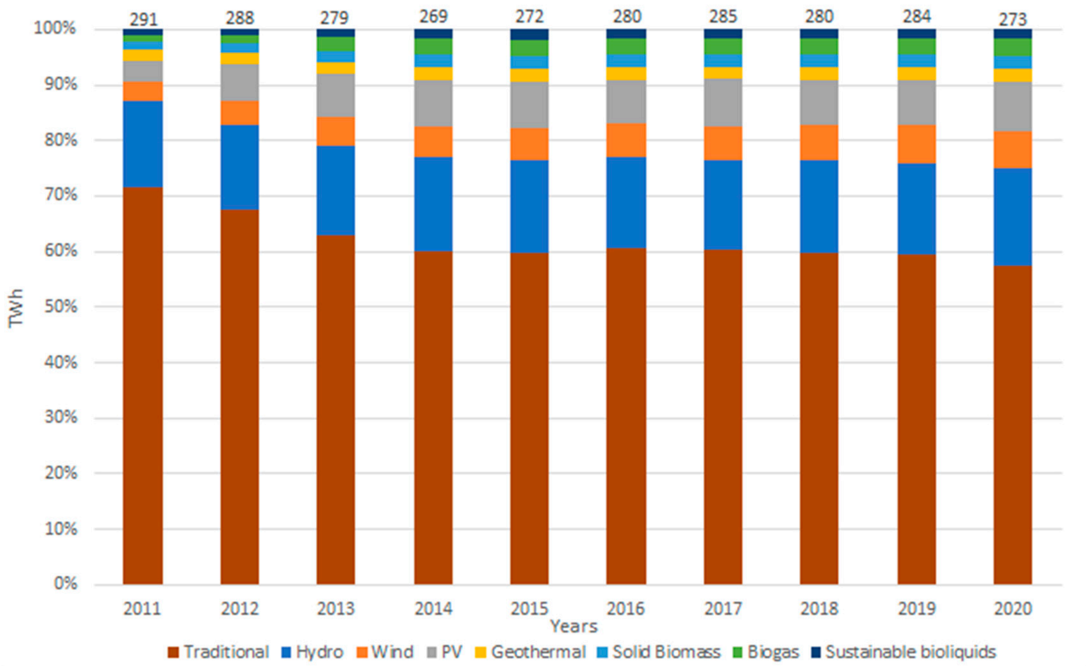


Figure 4. Evolution of the net Italian production by color. The top of the columns shows the yearly energy production values in TWh.

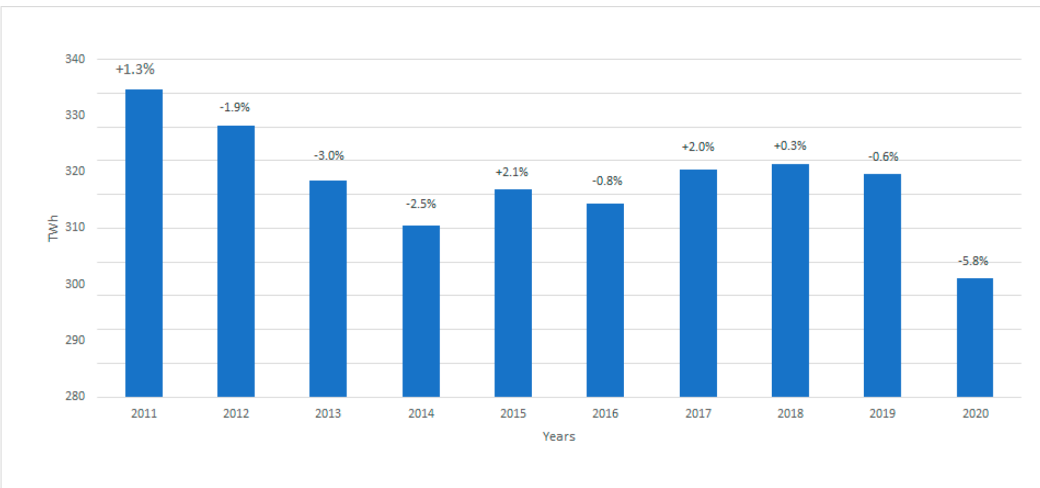


Figure 5. Historical Italian demand profile. The percentage change refers to the previous year.

Regarding the size of PV systems, 99 % have a rated power of up to 200 kW so they are installed in the LV and MV distribution grid; in terms of globally-installed power this represents 42% of the total PV capacity. In this way, a real distributed generation is produced in Italy [36].

4. Climate Change Impacts on Demand and Electricity Supply of Present-Day Power Systems

Based on the references and methods discussed in paragraph 2, in this section the impact of climate change technology, by technology and demand, is presented, and the results compared when the same technology is presented in both [13,14]. In particular, the impact on the Italian electricity system is highlighted.

4.1. PV Power

Due to global warming, the probable increase in water vapor will likely lead to a decrease in downward shortwave radiation [37]. This effect will likely reduce solar PV generation in the coming decades. The results in [13] confirm this projection. In particular, changes in the ensemble mean for all European countries were estimated to be less than 5% for both the 1.5 °C and 2 °C global warming scenarios. For the 3 °C warming scenario, the decrease is expected to be below 5% for most countries, except for the northern countries (Sweden and Finland) and the Baltic countries, where the decrease is likely to be in the range of 5–10%. It is worth noting that the southern European countries (e.g., Italy) will likely experience a smaller decrease in PV production than the other countries. As expected, the magnitude of climate impacts on PV production increases with the severity of the global warming scenario. Finally, looking at the projections of the models, the magnitude and sign of the changes (positive or negative) were in agreement. This indicates that the model in [13] was robust. Moreover, the scatter between individual models was very low.

In [14], as in [13], a global decrease in European PV generation was predicted at the multi-model mean change (mean changes of the ensemble). Specifically, an annual decrease of ~1% was observed, which was larger for RCP 8.5 than for RCP 4.5. This decrease was the combined effect of a 3–5% reduction in winter and spring, together with a moderate increase in generation in summer and autumn.

Regarding the individual case study countries, the northern European countries (Sweden and Germany) will experience a reduction in PV generation, as in [13], in agreement with [38] which predicted an increase in precipitation and cloud cover in northern Europe. Regarding Italy, [13,14] are in agreement: very small annual reductions were found for Italy. Interestingly, in [14], a large dispersion between the models was observed, in addition to a small sampling uncertainty within each model.

4.2. Wind Power

Focusing on Europe, a +1.5 °C warming level (above preindustrial levels) could likely cause a northward shift of the Atlantic jet (North Atlantic westerly winds) by the end of the 21st century, under the Business As Usual scenario (BAU) and RCP 8.5 [39]. Because of this, wind energy production in northern Europe would potentially increase, whereas in southern Europe (mainly Mediterranean basin) a potential decrease in wind production (even if negligible) has been projected [39].

This result confirms what was previously stated in [40], in which CMIP5 has been used as a database. These projections are also useful to understand the intra-annual and inter-annual variabilities of the wind energetic resource of a given region. Depending on the magnitude of intra-annual variability, the amount of produced energy injected into the electric power system would also change, compromising the adequacy of the system (short and medium term operation). The magnitude of inter-annual variability affects the long term operation of a wind farm, undermining projects and investments for future wind farms in a given region [40]. In [22] the changes in wind speed caused by climate change have been shown for Spain. In particular, four wind farms in four different regions of Spain have been considered. The results showed that, depending on the wind farm considered, a decrease or increase in wind speed was observed, with consistent variations in the annual production (an increase in production if the mean wind speed was forecasted to increase, and vice versa). Focusing on seasonal production, in summer the production was higher than in winter for all four plants. Nevertheless, non-significant changes in wind production have been forecasted; this fact confirms what was stated in [39,40] about the negligible wind energy production changes forecasted for southern Europe.

In [13], considering the ensemble mean results for all countries, a wind power reduction was observed (except for Greece). Unlike PV generation, passing from 1.5 °C to 2 °C global warming scenarios did not imply a higher magnitude change; however, for 3 °C warming scenario marked changes in generation were noticed in most countries. In particular, reductions in production below 5% under 1.5 °C to 2 °C scenarios were obtained, whereas for the 3 °C scenario, the reduction change remained almost at 5%, except for Cyprus, Portugal and Ireland, where reduction exceeded 5%, reaching 10% for Cyprus. For Italy, passing from 1.5 °C to 3 °C warming scenario, the magnitude of reduction increased in a smoother way with respect to other countries (e.g., Cyprus), remaining below 5%. In this sense, unlike PV generation, wind generation variations were not significant between northern and southern Europe but depended on the specific geographical area considered.

With regard to individual climate model responses, unlike PV generation, a marked spread in magnitude and sign of changes among the models were observed. Specifically, noticing that the strongest model projections were country dependent, for Italy, a spread in signs and magnitudes of changes within 5% has been noted.

In [14], the overall European annual wind generation ensemble mean response projects a decrease of about 1% due to climate change. The interesting point of these responses concerns the individual climate model simulations. In [14], coherently with [13], a considerable spread in magnitude and sign of changes among the individual models was observed. Regarding the Italian case study, focusing on summer, the responses of the individual models showed two out of six models with an increase in wind generation (under RCP 8.5) greater than 30%, whereas three out of six models projected a decrease of 10% in production, and the remaining model showed no change in wind generation. The ensemble mean result for summer only yielded an increase in wind production (greater for RCP 8.5 than for RCP 4.5). This fact demonstrates that the ensemble mean response can hide important information in terms of climate change impact projections, leading to misleading results. Moreover, the wind generation projections showed a large sampling uncertainty in each model response, which could be attributed to the intrinsic natural variability of the wind resource.

4.3. Thermoelectric Power

Reference [13] is the only research paper, among the other papers analyzed, that gave results for thermoelectric production in Europe.

For all European countries, the ensemble averages showed a strong decrease in thermoelectric production due to climate change. This result is justified considering that global warming is expected to exacerbate summer river drought and increase water temperatures. The responses of the individual models had a low scatter and agreed in the sign of the changes. This fact was due to the low dispersion of the simulated water temperature changes. The magnitude of the reduction in thermoelectric output increased with the magnitude of global warming, so that the largest reductions were seen in the 3 °C warming scenario. For Italy, the above considerations still apply, in particular a reduction of more than 5% was projected for the 1.5 °C scenario, while the percentage reduction reached almost 10% for the 2 °C scenario and even 15% for the 3 °C scenario.

4.4. Hydropower

In [13], the ensemble mean results projected a marked increase in hydropower production in most countries, except for the southern Europe countries (Greece, Portugal and Spain). For the latter, a decrease that becomes more severe with the global warming scenarios was projected. Whereas for Baltic and Scandinavian countries, an increase in hydroelectric generation with the increase in global warming was projected. This suggests a strong difference between northern and southern Europe countries that should be considered by European energy system policy choices. Focusing on Italy, if the 1.5 °C warming scenario projects an increase in hydro generation of about almost 5%, with the 2 °C scenario, this percentage decreases, until it becomes a decrease in production below the 5% (almost 2%) for a 3 °C warming scenario. Looking at the projections of the individual models, a strong spread between them has been observed, that causes a strong uncertainty in the reliability of the individual models' results. Specifically, for northern European countries, the spread between models is larger than Italy.

Reference [29] confirms what was stated in [13]. The authors of [29] stated that southern, eastern and central Europe will be affected by a decrease in discharge volumes of rivers, that will negatively impact hydropower generation. Italy will be affected by a reduction in hydropower generation, but in a milder way than the other southern European countries (such as France, Spain, Greece).

The above results with regard to Italy are consistent with another work, [41], where a reduction in the range of 3.6–5.7% has been projected (considering an RCP 8.5 scenario).

4.5. Demand

Global warming is likely to lead to warmer temperatures in the near term, so a decrease in electricity demand in colder months and an increase in warmer months is predicted. This consideration was confirmed by the multi-model mean projections of several models for European demand in [14]. Specifically, European annual demand was projected to decrease by 1%, composed of an increase in demand in summer and a decrease in winter, spring and autumn. The projections of the individual models show lower sampling uncertainty and signs of change consistent with the ensemble mean projections. For Italy, the annual ensemble mean projections showed an increase in average annual mean demand (less than 2%) due to a large, almost 5% increase in summer (stronger for RCP 8.5 than for RCP 4.5) and a slight decrease in winter and spring. The projections of the individual models were consistent with those of the multi-model ensemble in the direction of change. It is interesting to note that the annual and seasonal ensemble mean projections for demand in Sweden are quite different from those in Italy. In fact, winter, spring and autumn were projected to decrease by more than 2%, while the decrease in summer was just below 2%. This results in a reduction in demand of more than 2% on an annual mean demand.

The results found in [14] were in line with [42], where an increase in annual electricity demand for Italy of about +1.3% was projected for an RCP 8.5 scenario.

4.6. Alignment of Results

The described results with regard to Italy are synthesized in Table 1.

Table 1. Comparison between [13,14] for Italy.

	[13]			[14]				
	1.5 °C	**2 °C**	**3 °C**	**Yearly**	**Winter**	**Spring**	**Summer**	**Autumn**
Demand	–	–	–	↑	↓	$\boxed{\leftrightarrow}$	↑↑	↑
Wind	↓	↓	↓	$\boxed{\leftrightarrow}$	$\boxed{\leftrightarrow}$	$\boxed{\leftrightarrow}$	↑↑	↑(↓)
PV	↓	↓	↓	$\boxed{\leftrightarrow}$	↓	$\boxed{\leftrightarrow}$	↑($\boxed{\leftrightarrow}$)	↑($\boxed{\leftrightarrow}$)
Hydro	↑	↑	↓	–	–	–	–	–
Thermo	↓↓	↓↓	↓↓↓	–	–	–	–	–

Where: one arrow, two arrows or three arrows mean that there is a reduction/increase less or equal to 5%, 10%, 15% respectively. The left–right arrow means an insignificant variation. The symbols inside brackets are used for the RCP 8.5 scenario, when it gives a response different in sign with respect to the RCP 4.5 scenario.

5. Climate Change and Future Italian Power System Scenarios

The analysis of future scenarios for the Italian electricity system is developed in two parts. First, some references are discussed where the impact of climate change on the electricity systems of European countries are analyzed; from this general analysis, the data for Italy are extrapolated.

Then, the scenarios elaborated by the Italian transmission system operator for electricity (Terna) and gas (Snam), in accordance with the targets set by the European Commission and the Italian government, are explained and analyzed.

Finally, a comparison is made between the two different points of view.

5.1. European Scenarios for Climate Change

The two papers analyzed below assess the impact of future climate change on European electricity generation through future energy systems. The literature sources used to define the scenarios for the future energy systems were different in [13,14]. In [13], the authors used [43] as reference for the baseline mix of European countries (including Italy) in 2012; for the scenarios of future generation mixes, the authors considered a 60% and 80% RES penetration of the considered energy systems, respectively, and used [44] as reference. The climate change inputs used for these energy system scenarios were the 1.5 °C, 2 °C, and 3 °C warming levels. The projections given by the results showed a negative impact of climate change on all three energy mix scenarios for all countries, except for the Scandinavian countries and Latvia, for which the impact will be positive (probably due to the strong presence of hydropower in the energy share of these countries). An important aspect noted in [13] was that total production becomes more robust with regard to the three warming levels when moving from the baseline scenario (2012) to the scenarios with an energy mix of 60% and 80% RES (2050). In this sense, it can be said that an increasing share of RES in an electric power system makes it more resilient and adequate. This fact can be explained by considering that the increase in RES penetration in each country reduces the share of thermoelectric power generation, which is more sensitive to climate change impacts (especially thermoelectric power plants with river water cooling). Focusing on Italy, what has been said before holds true, and Table 2 shows the percentage changes in electricity generation [13].

Table 2. Scenarios for the energy mix (the share of technology subsectors is expressed in %) and the change in electricity generation for the Italian case study in 2050 [13].

	Baseline Mix 2012		60% RES		80% RES	
	Wind	4.5	Wind	11	Wind	14.4
	PV	6.4	PV	29.3	PV	40
	Hydro+Geotherm	16.7	Hydro+Geotherm	15.9	Hydro+Geotherm	14.4
	Thermoelectric	72.3	Thermoelectric	43.9	Thermoelectric	31.1
1.5 °C	−4%		−2.5%		−2%	
2 °C	−6.5%		−4%		−3%	
3 °C	−12%		−7.5%		−6%	

Geothermal power was included in hydropower because of its very small share in the generation mix (almost 2%). Biomass, waste, nuclear and fossil generation were included in the thermoelectric sector. In addition, CCS technology was included in the thermoelectric sector. For their generation mix, the authors [13] selected scenarios for Italy in which nuclear technology is included. It is worth mentioning that in Italy, nuclear power generation is, so far, prohibited by law, since Italian society voted against nuclear technology in two referendums (1987 and 2011) and repealed several laws in favor of nuclear technology. Therefore, the authors of this article consider it unlikely that nuclear technology will be introduced in Italy in the next few years.

In [14], on the other hand, the scenarios for the future energy systems were taken from the European project e-Highway2050 [35], where five evolving energy scenarios were developed: Fossil and Nuclear, Small and Local, Big Market, Large Scale RES, and100% RES. These scenarios were neither predictions nor forecasts about the future, but were extreme scenarios generated to study their impact on the transmission system. Table 3 shows the percentage of the generation mix given in [35].

Table 3. Generation mix (% of total) for the five contrasted decarbonized scenarios [35].

Technology \ Scenario	Small and Local	Big Market	100% RES	Fossil and Nuclear	Large Scale Renewables
Hydro	18%	13%	21%	12%	16%
Wind	28%	32%	52%	17%	40%
PV	23%	10%	24%	5%	14%
Biomass	19%	8%	9%	7%	6%
Nuclear	10%	19%	-	25%	20%
Fossil	4%	18%	-	33%	5%

It is worth mentioning the results obtained in [14], in terms of uncertainty and spread among the models. The differences between the individual climate models (forced by the two emission pathways within each energy system scenario) for each energy scenario were very small compared with the differences projected between the different energy system scenarios themselves. This suggests that, on the one hand, the choice of energy system scenario can mitigate climate change impacts, but on the other hand, the resulting energy system variables themselves are not strongly affected by the RCP 8.5 and RCP 4.5 pathways. In this sense, it can be said that electricity generation resulting from climate change presents a modest uncertainty. This might no longer be the case if a more drastic emissions pathway such as RCP 2.6 were considered. Table 4 shows the average values of wind and PV generation (expressed in TWh) for each of the five future energy scenarios in the 2025–2060 time horizon [14].

Table 4. Results for annual wind and PV generation [14].

Scenario	Gen. Technology	2025	2030	2040	2050	2060
Small and Local	Wind	250	450	500	550	650
	PV	200	250	350	550	800
Big Market	Wind	250	500	550	750	1000
	PV	150	200	250	300	350
100% RES	Wind	500	700	900	1400	1750
	PV	250	300	500	700	900
Fossil and Nuclear	Wind	500	700	1000	450	150
	PV	100	125	180	200	220
Large Scale Renewables	Wind	270	250	200	300	500
	PV	150	125	100	130	180

5.2. *Italian Scenarios for Climate Change*

Italy has published its own Climate Change and Energy Plan (PNIEC—Piano Integrato Energia e Clima) based on the recommendations of the European Commission in 2019. For the electricity sector, this plan set ambitious targets: RES must cover 55% of gross electricity consumption by 2030 (in 2019 the percentage was 35%).

To achieve this, an additional 40 GW of RES generation capacity (especially wind and solar PV) must be installed by 2030. However, due to the recent European "Green Deal", these targets need to be increased: from 55% to 65% of the RES share of electricity consumption. This, in turn, means that Italy must increase from 40 GW to 70 GW RES of generation capacity.

Nevertheless, 2030 is only an interim goal. The final target is full decarbonization by 2050, and electrification of final consumption must reach 55%.

For the electricity sector, the PNIEC envisages the following targets: complete phase-out of coal-fired power generation by 2025; and development of new centralized storage systems (both hydroelectric and electrochemical).

Terna (the Italian transmission system operator, TSO) and Snam (the Italian gas operator) have elaborated two forward-looking energy scenarios:

- Business-As-Usual (BAU)—a technology-driven scenario that takes into account current trends, and in which neither the 2030 targets included in the Clean Energy Package (CEP) and PNIEC, nor the long term targets, are achieved;
- National Trend Italy (NT Italy)—a policy-driven scenario that enables the achievement of the Italian and European targets.

The model inputs used for the BAU scenario differ from those used for the NT Italy scenario. Namely, the input for the BAU scenario is a storyline based on potential socio-economic, technological and environmental developments. Specifically, this storyline consists of a bottom-up approach not forced by political constraints, moderate GDP growth and a slight population decline, minimal incentives for energy efficiency, and only economical carbon phase-out. For the NT Italy scenario, the following inputs were used: an "average" climate year (average of climate years between 1982 and 2016) for the energy market simulations; electricity demand data taken from the PNIEC document, in line with the ENTSO-E national trend scenario; the Pan-European Climate Database (PECD) and ENTSOs database.

Neither the BAU nor the NT Italy scenarios consider the impact of climate change on future energy production.

In Figure 6, a comparison is made between the generation forecast in the BAU scenario and the NT Italy scenario. It is evident that electricity demand is not met by total generation, as electricity import has not been taken into account. Electricity demand depends not only on macroeconomic conditions and demographic change, but also on the strong development of technologies such as heat pumps (HPs) and electric vehicles (EVs), in addition to energy efficiency measures. Both scenarios forecast an increase in electricity demand. The NT scenario shows higher demand values than the BAU scenario only in 2040. This is due to the fact that the BAU scenario does not foresee energy efficiency measures (in contrast to NT).

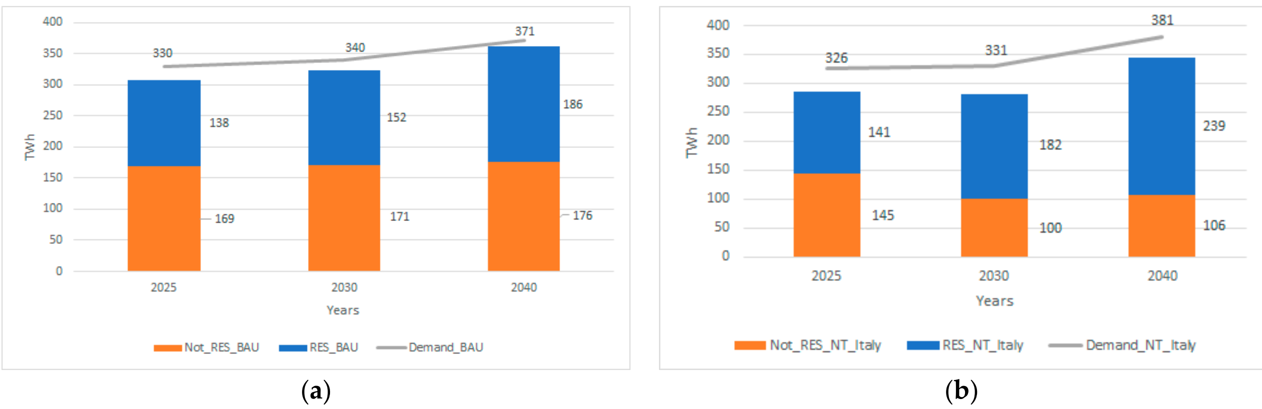


Figure 6. Comparison between RES and Not RES production with demand, Italy scenarios: (**a**) BAU and (**b**) NT.

In terms of the adequacy of a power system, it is crucial to forecast the annual peak power. Figure 7 shows the Italian trend and projection. This projection can be explained by considering that, even if EVs cause a steady electricity demand throughout the year, electric HPs will increase the electricity demand in winter, causing a shift of the peak demand from summer to winter. Therefore, a reversal of the peak demand trend compared with the last decade is possible [36]. Meeting an annual peak demand in winter may complicate the problem of adequacy of the electric system, as winter is when PV energy is least available.

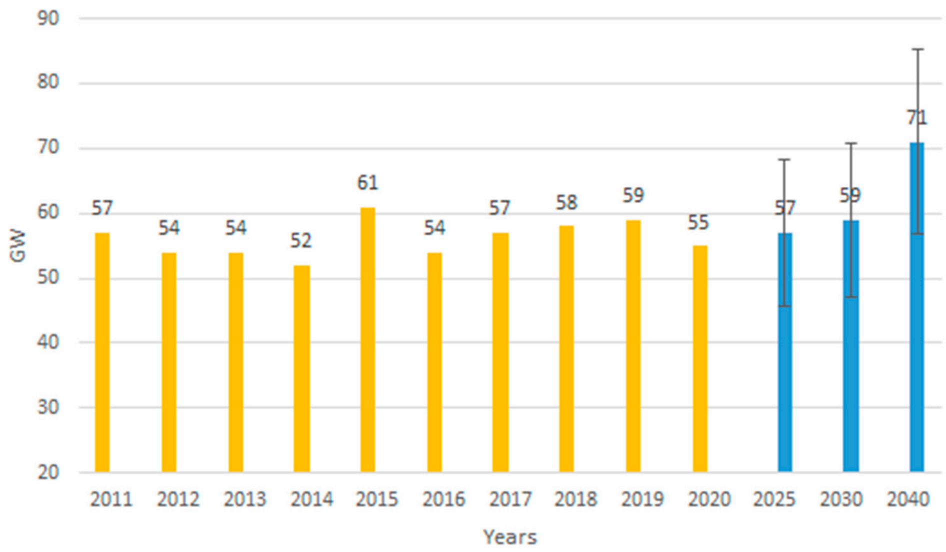


Figure 7. Evolution and forecast of the Italian peak yearly demand in GW.

Figures 8 and 9 show the expected evolution of the total generation capacity for each technology in the two scenarios [36].

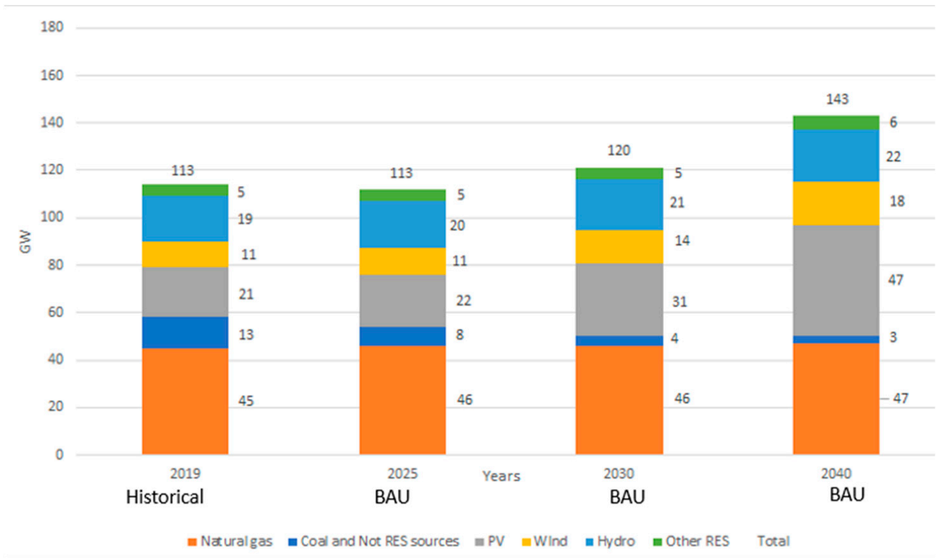


Figure 8. Historical and forecast of the Italian installed capacity per fonts by BAU scenario.

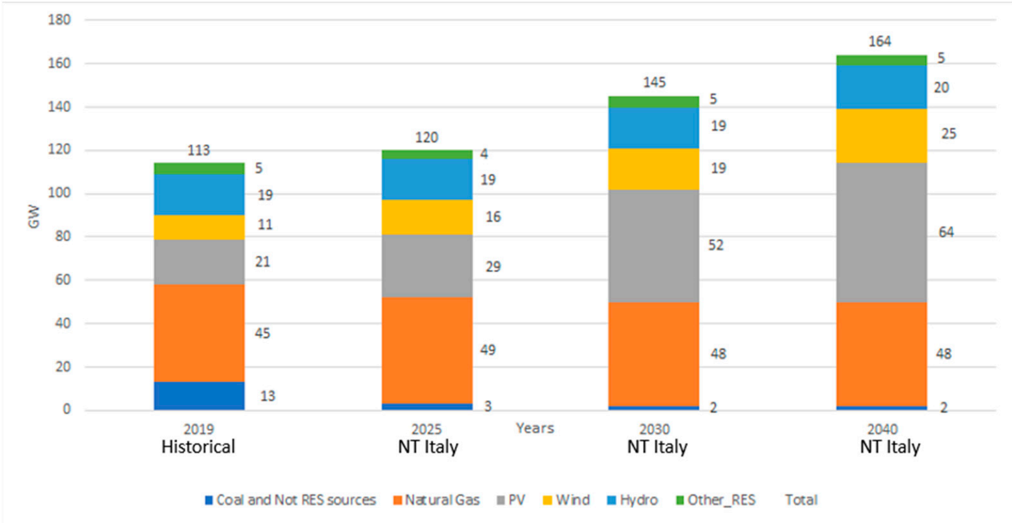


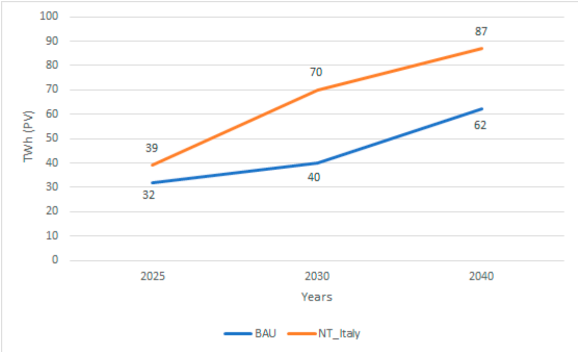
Figure 9. Historical and forecast of the Italian installed capacity per fonts by NT Italy.

It is worthwhile to make a remark on the above figures. Looking at the RES plants, a strong expansion of wind and photovoltaic plants is expected for both the BAU and the NT Italy scenarios. As far as wind installed capacity is concerned, it has already been growing steadily, reaching almost 11 GW in 2019. The BAU and NT Italy scenarios confirm this growth trend, peaking at 19 GW (+78% compared with 2019) and 25 GW (+134% compared with 2019) in 2030 and 2040, respectively [36].

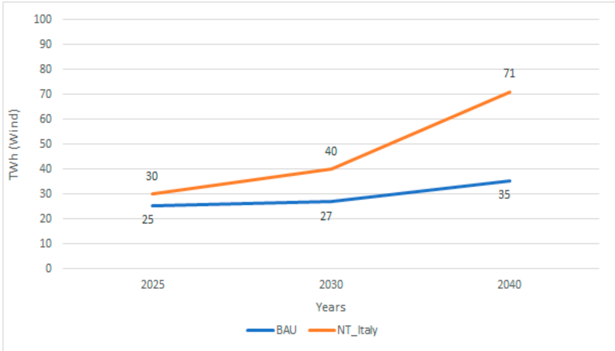
Regarding PV generation, both scenarios forecast a significant growth of PV installed capacity, both at small-scale and utility-scale, due to new incentive mechanisms and decreasing technology costs. In the NT Italy scenario (Figure 9), the largest increase in installed capacity is expected. This scenario forecasts an installed PV capacity of 52 GW in 2030, which is 20 GW more than the BAU scenario, and almost 30 GW more compared with 2019. The NT Italy scenario forecasts that PV generation will increase to 64 GW in 2040 (+243% compared with 2019) [36].

In recent years, a decline in thermoelectric generation capacity has been observed, which can be explained by the closure of a large number of thermoelectric power plants, because of the slowdown in the growth of electricity demand and the sharp increase in generation RES. This change has been reflected in a strong transformation of thermoelectric plants, which have decreased from 76 GW of total installed thermoelectric plants in 2013 to about 62 GW in 2019. This trend will continue in the coming years, slowing down to 55 GW in 2030 for both scenarios. A slight increase of 1 GW in 2040 was projected for the BAU scenario [36]. The highest value of thermoelectric generation capacity, corresponding to 164 GW, will be reached in 2040 for the NT Italy scenario. In particular, the NT Italy scenario shows a stronger growth trend than the BAU scenario, with almost 14 GW (in 2025), 40 GW (in 2030) and 58 GW (in 2040) more, compared with 2019 (+43%, +125% and 183%, respectively, compared with 2018). Conversely, fossil thermoelectric generation is expected to switch to gas in both scenarios (in line with Italian and European decarbonization targets) [36].

After discussing generation capacity, it is worth discussing generation forecasting. Figure 10 shows the generation forecasts for wind and PV technologies [45,46].



(a)



(b)

Figure 10. Italian generation forecast for the time horizon 2025, 2030, 2040: (**a**) PV; (**b**) wind.

Figure 10 shows that for both the BAU and NT Italy scenarios, electricity generation from PV is projected to be higher than wind generation for the entire time horizon. This can be justified considering that Italy, due to its geographical location, benefits from high solar irradiation, but is not affected by strong seasonal winds. It is worth comparing Figure 10 with the results shown in Table 4. Looking at the years 2025, 2030 and 2040, the results in Table 4 show that wind generation in Europe will be larger than solar PV in all five e-Highway 2050 scenarios. Thus, if wind energy will be the largest contributor to production in Europe in the next two decades (among all RES sources), in Italy, photovoltaic will be the largest renewable production source, as can be observed in Table 5.

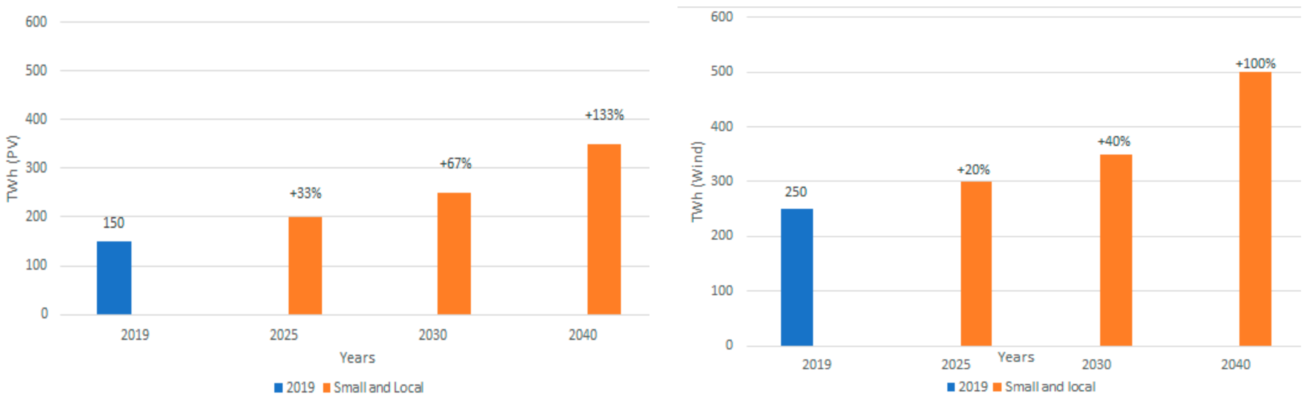
Table 5. Generation mix in time horizon 2025, 2030, 2040 in Italy for BAU and NT Italy scenarios.

BAU	**2025**	**2030**	**2040**
Wind	7.3%	7.7%	9.1%
PV	9.4%	11.4%	16.1%
Hydro	16.1%	16.5%	16.4%
Other RES	7.6%	7.7%	6.8%
Thermoelectric	49.4%	48.7%	45.8%
NT Italy	**2025**	**2030**	**2040**
Wind	9.2%	12.1%	18.6%
PV	12%	21.1%	22.8%
Hydro	15%	14.8%	14.4%
Other RES	7.1%	6.9%	6.8%
Thermoelectric	44.5%	30.2%	27.8%

Coal, natural gas, and other non RES (solid biomass and waste), generation technologies have been included in "Thermoelectric". In particular, for the NT Italy scenario, coal will disappear from 2025. The electricity generation imported by bordering foreign countries has not been reported in Table 5.

5.3. Comparison between European and Domestic Scenarios with Reference to the Italian Power System

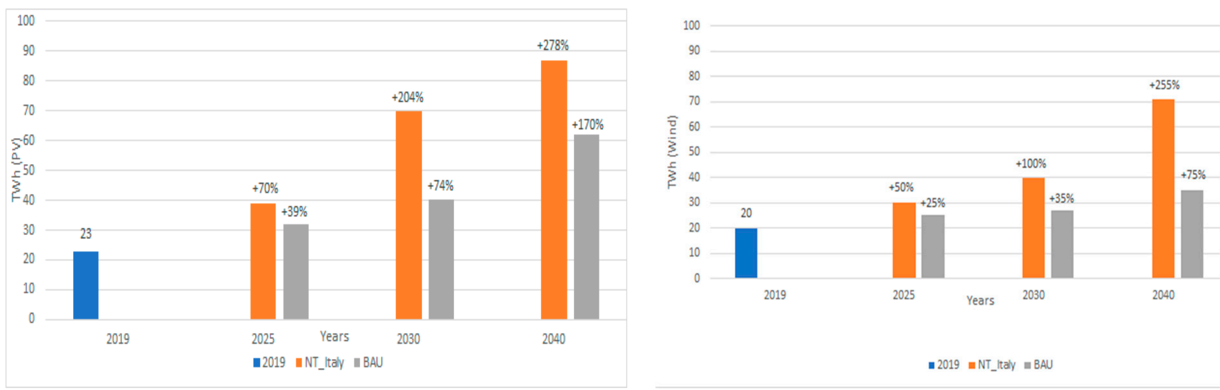
Given the results reported in Table 4 and the data shown in Figure 10, it is possible to compare the different scenarios and see if the trends shown in the BAU and NT scenarios are consistent with those reported in Table 4. Among the five scenarios considered in Table 3, the Small and Local scenario (in the 2030–2050 time horizon) is the closest to BAU and NT Italy (2025, 2030, 2040 time horizon) in terms of wind and PV generation. Figure 11 shows this comparison for wind and solar power generation technology. Figure 11 shows that in Europe, although wind power generation will be larger than PV, the growth rate of PV is larger than that of wind power.



(**a**) (**b**)

Figure 11. Comparison of energy production for the time horizon 2025, 2030, 2040, with respect to year 2019, for Small and Local scenario: (**a**) PV, (**b**) wind.

The rates of increase in wind and PV energy production for BAU and NT Italy scenarios are shown in Figure 12. The reference year is 2019, in coherence with previous figures.



(**a**) (**b**)

Figure 12. Comparison of energy production for the time horizon 2025, 2030, 2040, with respect to year 2019, for both BAU and NT Italy scenarios: (**a**) PV, (**b**) wind.

It is worth comparing the energy mix scenarios proposed in [13,14,45,46]. As mentioned before, nuclear power generation in Italy is not likely in the near future, so the comparison here is made using wind, photovoltaic, hydro and thermoelectric generation. This comparison is meant to be complementary to the papers analyzed in this work, as the generation mix for Italy in 2040, evaluated for the BAU and NT Italy scenarios, is now compared with the energy mix scenario in [13] in 2050. BAU, NT Italy and the energy mix in [13] agree that PV generation will be higher than wind generation. Starting from the BAU scenario, it is possible to say that the BAU values for wind generation agree with the 60% scenario RES and the 80% scenario RES in [13], since wind energy increases in these last two scenarios compared with the BAU scenario in 2040. As for PV generation, the BAU value is plausible for 60% RES, but not for 80% RES, since in this scenario PV generation increases too much. For hydropower, the BAU value for 2040 is consistent with the values for the 60% RES and 80% RES scenarios. For thermoelectric generation, the BAU value is plausible with the value for 60% RES, but not for 80% RES, as the huge decrease in thermoelectric generation would not be compensated by any RES source.

Considering NT Italy with the scenarios in [13], the results for 2040 in NT Italy and 60% RES and 80% RES for 2050 are not compatible, as Italy would reach a share of wind generation of 18.6% in 2040 (according to the NT scenario). For 2050 this value is expected to increase. For photovoltaic, as for BAU, the values are compatible for 60% RES, but not for 80% RES, where the generation share is too high. For hydropower, the results for NT Italy and 60% RES and 80% RES are compatible because hydropower generation is expected to remain stable over time. About thermoelectric generation, the results are not compatible, because by 2040 Italy would already have experienced a 27.8% decrease in electricity generation according to the NT scenario. This incompatibility could be due to the fact that in [13] nuclear energy was considered as a generation technology in the thermoelectric sector.

6. Discussion

- The models used to assess the impact of climate change on the environmental variables that determine the level of production and efficiency of generation facilities, both programmable and non-programmable, and systems that use thermal cycles, are subject to significant uncertainty. For example, the number of equivalent hours to rated output may experience a significant deviation from historical values for the same installed capacity. This uncertainty determines an increase in electrical power reserve levels, to ensure an adequate and reliable system;
- Depending on the technology of electricity generation, a difference in power generation was found depending on the geographical area. Global warming will likely cause more severe and frequent heat waves and droughts, which, in turn, will affect thermoelectric production in southern European countries (including Italy) more than in northern (Scandinavian) countries. In this perspective, EU energy policy decisions should take into account this type of geographical disparity and promote the switch to renewable energy accordingly;
- The uncertainty of the impact of climate change on the future energy scenario could vary depending on the radiative concentration pathways used;
- From an electricity grid planning perspective, continental and national policy decisions and associated scenarios will certainly play a crucial role in the development of each country's production mix, with particular attention to the use of non-programmable renewable energy sources. However, these national plans should take into account the different impacts of climate change between countries. Italy could likely experience an overall annual decrease in available wind and PV energy and thermoelectric efficiency. However, the greatest challenge could be the occurrence of long periods of extreme weather conditions (heat waves, drought). These challenging weather conditions can plunge the electricity system into crisis, which should therefore have a level of resilience adapted to the evolution of the generation mix and climatic changes;
- To achieve the European Union's environmental goals, demanding the increase of RES must be enforced. The papers [13,14] have analyzed the impact of climate change on future energy system scenarios with a high RES share, without considering storage systems. However, climate change impacts should also be studied for power systems that include storage systems. Indeed, it is not possible to imagine a high RES share in an energy system without a corresponding storage system. Moreover, the presence of storage systems could facilitate the planning of those RES systems, such as wind turbines, that are characterized by a high sampling uncertainty regarding the impact of climate change on electricity generation. Thus, it would be advisable to consider energy systems in conjunction with storage systems in research studies on the impact of climate change on energy production;
- The magnitude and sign of spread for the projections of climate change impacts depending on the generation technology considered. Indeed, the projections for wind generation showed a larger range of variation and a large scatter in the sign of the

individual models compared with PV generation technology. This is easily explained by considering that wind has a greater natural variability than solar radiation;

- In analyzing the projections for the effects of climate change on electricity generation, it is necessary to consider the individual models in addition to the ensemble mean, because the response of the latter may hide important details about the projections for the change in electricity generation with an increase in global warming;
- Increasing the share of renewable energy sources in electricity grids could help transmission system operators make the system more resilient to worsening climate change. However, increasing the share of RES should be accompanied by adequate storage systems;
- The NT Italy 2021 scenario forecasts a transition from coal to natural gas that could have harmful effects on tropospheric greenhouse gas concentrations worse than those caused by coal-fired power generation. Indeed, methane has a global warming potential (GWP) that is 28–36 times (over 100 times) higher than that of carbon dioxide (CO_2), which has a GWP of 1 [47]. Therefore, government investment in new sustainable generation technologies that can reduce the use of natural gas is necessary;
- In 2040, according to the NT Italy scenario, PV generation will comprise 22.8% of the future Italian generation mix. This value is comparable with the 27.8% generation share of thermoelectric plants. Moreover, Italian future scenarios forecast an annual peak of electricity demand in 2040 in winter, a season in which PV generation is at its lowest levels. This issue could compromise the adequacy of the Italian electric power system; therefore, it must be properly addressed by the transmission system operator. Appropriate electricity market mechanisms must be promoted by the TSO to ensure good power quality, in terms of voltage and frequency, to the final users;
- In Italy, due to the increasing presence of electric heat pumps, there would be a reversal of the trend of the annual peak demand from summer to winter;
- Projections of electricity demand affected by climate change vary from country to country, as they depend on the macroeconomic indices of each country and, in particular, on the technological and energetic efficiency developments of each country. Moreover, the increase in temperatures due to global warming will likely cause a decrease in the demand for electricity, which is greater in the northern Europe countries in autumn, winter and spring, than in the southern Europe countries.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

A	Cross-sectional area (m^2)
AM	Air mass (1)
AM_{STC}	Air mass at STC (1)
AR5	Fifth Assessment report
AR6	Sixth Assessment report
BAU	Business As Usual
CCS	Carbon capture and storage
CEP	Clean Energy Package
C_f	Hourly plant capacity factor
ΔC_f	Capacity factor ramp rate
C3S	Copernicus Climate Change Service
ECEM	European Climate Energy Mixes
ENTSO-E	European Network of Transmission System Operators for Electricity
ENTSO-G	European Network of Transmission System Operators for Gas
EVs	Electric vehicles
G	Surface downwelling solar radiation (W/m^2)
G_{STC}	Surface downwelling solar radiation at Standard Test Conditions (W/m^2)
GAM	Generalized additive model
GCM	General circulation model
GDP	Gross domestic product
GHGs	Greenhouse gases
GWP	Global warming potential
HPs	Heat pumps
IAM	Optical losses
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organization
MAF	Mid term adequacy forecast
MPP	Maximum power point
NT	Italy National Trend Italy
OECD	Organization for Economic Co-operation and Development
PECD	Pan-European Climate Database
P_{GT}	Power output of the gas turbine at an ambient temperature that differs by ΔT_a from the condition ISO (W).
$P_{GT,X}$	Useful power of the gas turbine at ISO conditions (W).
PNIEC	Piano Integrato Energia e Clima
POLES	Prospective outlook for long term energy systems
P_R	Performance ratio (1)
PV	Photovoltaics
PVpot	Photovoltaics power potential
P_w	Power in the wind (W)
P_{usable}	Power output of the thermoelectric power plant (W)
Q	Water availability (kg/m^3)
Q	Amount of cooling water required (m^3/h)
RBM	River basin model
RCM	Regional climate model
RCP	Representative concentration pathways
RES	Renewable energy sources
STC	Standard test conditions
T_{cell}	Cell temperature (°C)
T_a	Near-surface temperature (°C)
ΔT_a	Temperature difference from the ISO condition (°C)
T_{db}	Dry-bulb air temperature (°C)
T_{health}	Inlet cooling water temperature below which the system works at maximum capacity factor (°C)
T_{outlet_max}	Maxim temperature of the outlet water (°C)

T_{shut_down}	Inlet cooling water temperature above which the system is shut down (°C).
T_{STC}	Temperature in Standard Test Conditions (°C)
T_w	Inlet cooling water temperature (°C)
T_{wb}	Wet-bulb air temperature (°C)
v_H	Windspeed at the hub turbine height and orthogonal to A and at the hub turbine height (m/s)
VIC	Variable Infiltration Capacity
v_{10}	10-m wind speed (m/s)
WG	Working Group I (IPCC)
WMO	World Meteorological Organization
Greek letters	
α_{PV}	Power temperature coefficient at the maximum power point (MPP) $\left({}^{\circ}C^{-1}\right)$
β_{PV}^{II}	Solar radiation coefficient of the power at maximum power point (MPP) (m^2/W)
γ_{PV}	Degradation rate (1)
ε	Error term
$\eta_{el,PV}$	Electrical efficiency (1)
η_{GT}	Efficiency of the gas turbine (1)
$\eta_{GT,X}$	Efficiency of the gas turbine at ISO conditions (1)
$\eta_{PV,STC}$	Electrical efficiency in STC (1)
P	Air density (kg/m^3)
Φ	Scarcity factor (1)

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