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Climate Change Impacts on the Energy System of a Climate Vulnerable Mediterranean Country (Greece)

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Abstract: This paper aims to explore how climate change affects electricity generation (fossil-fueled power plants, hydroelectric stations, wind systems and photovoltaics) and energy demand in residential buildings in Greece for the period up to 2050. In both cases RCP scenarios results are considered in the appropriate spatial and temporal dimension. Energy supply technologies were examined through statistical regression models and/or mathematical equations correlating climatic parameters with energy productivity. With respect to energy demand, bottom-up models were developed that integrate behavioral and policy aspects. The analysis showed that climate change is expected to mainly affect electricity generation from hydro and thermal power plants, while the impacts on solar and wind energy are significantly lower. The range of impacts on hydro potential and electricity generation depends on the geographical location of the power plants and shows significant uncertainty due to the corresponding uncertainty in climate models estimates regarding precipitation and runoff changes while showing significant geographical variations. With respect to energy demand, climate change is expected to affect energy consumption, but the expected range of effects depends on both the implementation and the characteristics (deep vs. shallow renovation) of measures for upgrading the thermal performance of the building stock and the intensity of climate change.

Keywords: climate change; impacts; energy; power generation; demand

1. Introduction

The energy sector has a strong connection to climate change. First, the operation of fossil-fueled power plants results in the generation of greenhouse gas (GHG) emissions, while on the other hand the sector itself is affected by climate change due to changes in energy consumption patterns and production potential. Climate and weather changes affect energy supply through changes in the efficiency of power plants and the productivity of renewable energy sources (RES) that depend directly on climate conditions. For example, the availability of a wind farm depends directly on wind variability, the power generated by a photovoltaic station is proportional to sunshine, and hydroelectric energy is affected by precipitation and surface runoff [1]. At the same time, the increase in air temperature may reduce the efficiency of thermal power stations and complicate the operation of their cooling systems [2]. Climate change also affects the operation of energy transmission/distribution systems, and has a strong influence on final energy demand, especially in the buildings' sector.

Greece, a southern European country located at the Mediterranean basin, is particularly vulnerable to climate change. According to the latest Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), southern Europe and the Mediterranean are hotspots for climate change impacts, suffering from higher-than-average temperature increases, considerable reduction of rainfall and water runoff and extreme events such as flash floods and heatwaves, all posing severe threats for local energy systems and connected sectors [3]. Therefore, updated, reliable and quantitative knowledge on these risks is highly needed for shaping efficient climate change management adaptation strategies. Our paper aims to contribute to this end, focusing on changes in the productivity of various power generation technologies critical to ensuring energy supply, as well as on changes in energy consumption patterns by Greek households.

In energy supply, the number of studies that have investigated to date the quantitative impacts of climate change on the productivity of electricity generation technologies in Greece is relatively limited. Thermal power plants and hydroelectric stations are the two power generation technologies which will be most affected by the climate change. Greek thermal power plants are expected to have a reduction of 8% to 17% of their efficiency mainly due to the increased air temperature and the combination of higher cooling demand and reduced water resources [4]. Regarding hydroelectricity generation, three different studies [4–6] advocate lower productivity in the future climate of up to 24% over the time horizon up to 2050, a rate that may increase up to 33% in 2100. The losses are greater for the RCP8.5 scenario because of higher temperatures and lower rainfall in the future climate, while run-of-river hydropower seems to be more vulnerable to these changes. Various studies [4,7–9] show that changes in photovoltaic stations productivity are expected to be low (up to +/- 3% until 2050). Most studies report also small fluctuations in the productivity of wind farms in mainland Greece, and an increase in productivity (by 5% or more) of off-shore wind systems in the Aegean region in future climate [1,4,10–12]. Only one study out of a total of six examined results in greater fluctuations in changes in the productivity of wind systems due to climate change, at least in some parts of the country, which may reach +/- 15% in 2040 [13]. However, as most of these studies aimed at assessing future impacts across all Europe, their spatial resolution was not always sufficiently high, while many of them also focused on the evolution of climatic indices as a proxy for energy indicators rather than on the latter themselves. Also, some of these studies were rather old and thus did not make use of the latest climate change projections. Thus, our paper aims to address these knowledge gaps and explore each energy supply technology in the context of its required spatial and temporal context while also using three RCP scenarios (RCP2.6, RCP4.5 and RCP8.5) to provide for a thorough and complete picture of potential climate change impacts.

At the other end of the chain, energy demand is directly related to changes in weather and climatic conditions. In general, the higher average temperatures expected in the future climate are likely to result in a reduction in energy consumption for heating and an increase in energy consumption for cooling. However, it is not clear whether the total energy consumption in a system will eventually increase or decrease. Especially for electricity, the increased demand in the summer months for air conditioning may be partially or fully offset by a decrease in the winter demand for heating. However, consumption of other energy resources may be more sensitive to winter weather conditions, as in many countries households use natural gas or oil products for space heating, while electricity is used only in auxiliary heating systems. So far, most studies focused on climate change impacts on the energy demand of the residential sector, with other parts of the economy (e.g., health, food trade, tourism, agriculture) being much less addressed despite their expected sensitivity and vulnerability [14–17]. In the buildings sector, several studies have been carried out and various approaches have been applied to investigate climate change impacts on energy demand in Greece. For example, Eskeland and Mideska [18] found that the effect of increased electricity consumption for cooling will outweigh decreased electricity consumption for heating, resulting in net electricity consumption increases by 10% at the end of the century under the A1B climate scenario. Castaño-Rosa et al. [19] found that households in Greece will see an increase in their electricity consumption in summer by up to 11% in Athens, 17% in Thessaloniki, and 4% in Tripoli in 2050. Tsoka et al. [20] investigated the impact of climate change and urban heat island on heating and cooling energy needs of an urban building unit in Thessaloniki, northern Greece, and estimated that the annual heating energy demand for the future period 2050 is projected to decrease by 19-21% (¬10.6kWh/m2), whereas the cooling energy demand is expected to increase by 60-100% (9.7-15.6 kWh/m2). Droutsa et al. [21] found that if the existing non-residential buildings in Greece are not renovated, the average heating energy use is expected to decrease by 22-26% in 2050, and by 23-52% in 2090, while on the other hand the average cooling energy use is expected to increase by 24-30% in 2050 and by 28-66% in 2090. Despite this wealth of studies, most of these research efforts focus on electricity (mainly due to the lack of detailed data on daily or monthly consumption of fossil fuels) and on the short-term effects on its demand due to changing weather conditions (e.g., heating and cooling degree days) between the historical and future climate. However, such an approach is likely to underestimate or overestimate the long-term effects of climate change on energy demand, as it does not consider potential changes in the thermal characteristics of the building stock as well as the number and the type of appliances used in buildings. Thus, some authors have attempted to integrate these structural changes into the computational process for estimating the effects of climate change on energy demand, as for example through statistical Error Correction Models (see De Cian and Wing [22]). However, these proposed models are characterized by limitations related to diversifications in the energy behavior of consumers, difficulties to integrate technological improvements in devices that occur over time, and uncertainties on the effectiveness of implemented climate change policies. Our paper aims to address these methodological gaps by developing impact assessment models which duly integrate behavioral and policy aspects and thus can provide a more reliable estimate of potential climate change impacts.

In the following sections, the paper presents the proposed assessment methodology, followed by the relevant results obtained and a subsequent discussion and conclusions drawn.

2. Materials and Methods

2.1. Potential impact pathways and main directions for impact assessment

An overview of the possible climate change impacts on the Greek energy system is provided in Table 1, based on relevant research [15,23]. For each energy technology, the main climatic parameters that may affect energy production are identified, as well as the relevant pathways to impacts.

Table 1. Overview of climate change impacts on the energy sector - Most important climate drivers and impacts for Greece.

Energy sector	Climate variables	Related impacts
Energy supply		
Wind farms	Changes in wind speeds and increased temperatures	Changes in the productivity and reliability of wind farms.
	Extreme events (extreme winds)	Can overstress turbine components and activate the cut-out speed control.
Solar systems	Changes in atmospheric water vapor content, cloudiness, and cloud characteristics	Changes in radiation affect the efficiency of solar systems.
	Higher temperatures	Decreases in efficiency of solar systems.
	Extreme events	Damages in infrastructures.
Hydro units	Higher temperatures and changes in precipitation patterns	Changes in the runoff, which affects hydropower generation. Changes in hydropower system operation.
Bioenergy	Higher temperatures and changes in precipitation patterns	Changes in productivity of energy crops.
	Higher CO_2 concentrations	Positive impact on crops.
	Extreme events (droughts, frosts, storms)	Damages to energy crops.
Thermoelectric power plants	Higher temperatures	Reductions in the output of power plants
	Higher temperatures and reduced precipitation	Additional water resources for cooling, which may result to reduced generation or shutdowns. Oil refineries can also be affected by lower water availability influencing the supply of oil-fired power plants.
	Extreme weather events	Erosion in surface mining

Energy sector	Climate variables	Related impacts
		Disruptions of offshore extraction. Disruption in the supply chain. Downing of infrastructures (power plants, refineries).
Energy transmission, distribution, and transfers		
Electricity	Higher temperatures	Reduces transmission capacity of overhead lines.
	Extreme events (extreme winds, extreme ice loads, landslides, floods, wildfires, etc.)	Possible transmission and distribution power lines failures.
Natural gas	Extreme events (mud flows, landslides, floods, wildfires, etc.)	The gas transmission system could be affected.
Energy demand		
Buildings	Higher temperatures	Lower demand for heating and higher demand for cooling.
Transport	Higher temperatures	Changes in the performance of motors and engines.
Industry	Higher temperatures	Changes in the performance of motors and engines. Higher demand for cooling related to food processing and storage, etc.
Agriculture	Higher temperatures and changes in precipitation	May increase the demand for irrigation and the energy use for water pumping.

As already mentioned, our paper focuses on energy supply and demand in the buildings sector, not covering transmission and distribution grids as well as energy demand outside households.

For the quantitative assessment of the effects of climate change on the potential of RES technologies and on the efficiency of thermal power plants, two alternative approaches can be implemented:

- The first approach is based on statistical regression models, which are developed by utilizing historical data and relating the electricity produced by the technologies in question with one or more climatic parameters (e.g., temperature, rainfall, etc.). The models are then applied to the historical and future climate and thus the change in electricity production is attributed solely to climate change. In the context of the present study, such models were mainly used to estimate the climate change impacts on hydroelectricity production.
- The second approach uses mathematical equations, provided by manufacturers or the international literature, correlating one or more climatic parameters with the productivity (or efficiency) of power technologies in question (e.g., wind speed with energy production by wind farms), and here it has been used to estimate the climate change impacts on both RES technologies and fossil-fueled power plants.

The climate change impacts on the energy demand of the residential buildings in Greece are calculated through a bottom-up engineering model that allows the detailed simulation of the evolution of the characteristics of the building stock in the country and the corresponding energy consumption per energy use.

The analysis is undertaken in the time horizon of 2050, utilizing historical (1971-2000) and future (2021-2050) climate data to assess the impacts on energy supply and demand. As regards climate data for the period 2021-2050, the analysis is based on the results of climate simulations with four climate models for the two extreme scenarios RCP2.6 and RCP8.5 as well as the intermediate scenario RCP4.5, to fully cover the range of possible changes in the country's climate and adopting a multi-scenario and multi-model approach to mitigate uncertainties.

2.2. Methodology for impact assessment in power generation

The analysis of climate change effects on wind systems was conducted for eight areas with a high installed capacity of wind farms, namely Southern Peloponnese, Eastern Macedonia - Thrace,

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Evia, South Greece, South Aegean, South Aegean, Central Macedonia, and Crete. The impact of climate change on wind power generation was assessed using the methodology described in Tobin et al. [1]. Power generation of the wind farms was calculated using typical power curves for a 3 MW wind turbine with a hub height of 90m (Figure 1), and wind speed and air temperature data from climate projections for historical (1971-2000) and future (2021-2050) climates. The wind speed of climate projections from 10 m to hub height was estimated using the Karman-Prandtl equation [24]:

$$\frac{W_{z1}}{W_{z2}} = \frac{ln\left(\frac{z1}{z0}\right)}{ln\left(\frac{z2}{z0}\right)}$$

where W_{z1} is the wind speed at hub height z_1 and W_{z2} wind speed at 10m (Z_0).

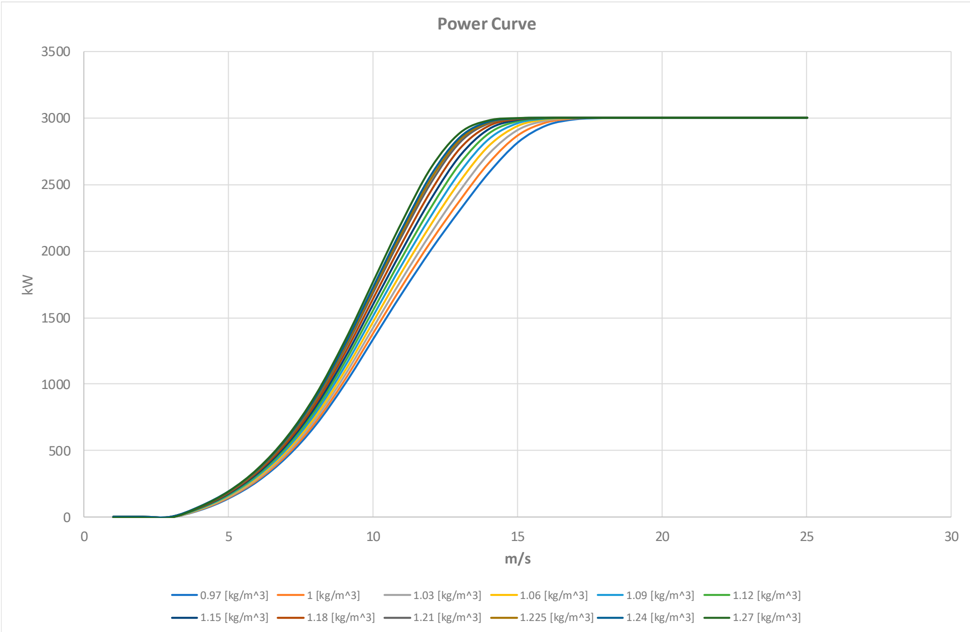

Figure 1. Power curve of a typical commercial wind turbine with nominal capacity of 3MW for various values of air density in kg/m^3.

The analysis of climate change effects on photovoltaic systems (PV) was conducted for four representative areas (one for each climate zone) with many installed PV stations, namely Crete for Climate Zone A, Attica for Climate Zone B, Central Macedonia for Climate Zone C, and Mountainous Macedonia for Climate Zone D. The main climatic parameters affecting the output of a PV cell are solar radiation intensity and air temperature, and wind speed that affect PV cells' temperature [25,26]. Power generation of a PV is calculated by the following equation:

$$P = P_R \cdot \frac{RSDS}{RSDS_{STC}}$$

where:

RSDS is the surface downwelling solar radiation [W/m^2], $RSDS_{STC}$ is the surface downwelling solar radiation at standard test conditions [1000 W/m2] and P_R is PV efficiency.

The PV efficiency is linearly dependent on the temperature difference of the PV cells T_{cell} and the standard test conditions reference temperature of 25 ^{o}C (T_{STC}) according to the following equation:

$$P_R = 1 + \gamma \cdot (T_{cell} - T_{STC})$$

where:

γ coefficient is equal to -0,005/oC [4].

The temperature of the PV cell is calculated through the following equation [27]:

$$T_{cell} = c_1 + c_2 \cdot TAS + c_3 \cdot RSDS + c4 \cdot VWS$$

where:

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TAS is air temperature [°C], VWS is wind speed [m/s], RSDS is surface downwelling solar radiation [W/m²], c1=4.3 ºC, c2=0.943, c3=0.028 ºCm²W⁻¹ and c4=-1.528 ºC sm⁻¹.

Climate data from climate projections for historical (1971-2000) and future (2021-2050) climates were utilized to estimate impact of climate change on PV systems efficiency.

Concerning hydropower, within the framework of our present work, the effects of climate change were assessed in five regions (Western Greece, Epirus, West and Central Macedonia, Eastern Macedonia and Thrace and Peloponnese) where the existing hydropower plants are located, using two different methodological approaches. In the first approach a theoretical model estimating hydroelectric potential GHP [W] in an area, considering surface runoff, water density, and dam height was used [4]:

$$GHP = Q \cdot \rho \cdot h \cdot g$$

where:

Q is the runoff [m3/s], ϱ is the density of freshweater [kg/m3], h is the elevation difference [m] and g is gravitational acceleration [m/s²].

In the second approach a statistical regression model correlating historical values of hydroelectric production per installed MW with prevailing meteorological conditions. Here, the approach incorporates the temperature change in the production of hydroelectric power plants per installed MW (P_{hydro}) and the development of a statistical regression model estimating hydroelectric power generation as a function of annual precipitation and temperature:

$$P_{hydro} = 2.402 \times P - 155.567 \times T + 2222.289$$

where:

P is annual precipitation [mm] and T is annual air temperature [°C]. The R^2 coefficient of the model is not particularly high (0.49), as one might anticipate, given the inherent challenge of accurately capturing hydrological balances within a river basin through statistical models. Nevertheless, the model demonstrates a commendable level of accuracy in approximating the production of hydroelectric power in Greece over a 30-year horizon, which is necessary when comparing historical and future climate data.

Regarding thermal power stations, the increase in air temperature reduces air density and, consequently, the mass flow in the gas turbine of the combined cycle units, resulting in an efficiency decrease. Additionally, increased temperature hampers the operation of the cooling towers of the thermal power plants, ultimately reducing their efficiency. Within the scope of this study, the power generation output of thermal power stations was estimated using the equations of Koch and Vögele [2], simulating the usable power plant capacity P_{thermo} [MW] based on cooling demand q [m³/s] according to the following equations:

$$q = KW \times \frac{1 - n_{total}}{n_{elec}} \times \frac{(1-\alpha) \times (1-\beta) \times \omega \times EZ}{\rho_w \times C_p \times max}$$

$$P_{thermo} = \frac{min\left((\gamma \times Q), q\right) \times \rho_w \times C_p \times max\left(min\left((Tl_{max} - T_w), \Delta Tl_{max}\right), 0\right)}{\frac{1 - n_{total}}{n_{elec}} \times \lambda \times (1-\alpha) \times (1-\beta) \times \omega \times EZ}$$

where:

KW is the installed capacity of thermoelectric power plant [MW]; η_{total} is the total efficiency [%]; η_{elec} is the electric efficiency [%]; α is the share of waste heat not discharged by cooling water [%]; β is the share of waste heat released into the air [-]; ω is a correction factor accounting for effects of changes in air temperature and humidity within a year [-]; EZ is a densification factor accounting for replacement of water in cooling towers to avoid high salinity levels [-]; λ is a correction factor accounting for the effects of reductions in efficiencies when power plants are operating at low capacities [-]; ϱ_w is the density fresh water [kg m-3 515]; C_p is the heat capacity of water [J kg-1 °C-1 516]; Tl_{max} is the maximum permissible temperature of the cooling water [°C]; ΔTl_{max} is the maximum permissible temperature increase of the cooling water [°C]; ɣ is the maximum fraction of streamflow to be withdrawn for cooling of thermoelectric power plants [%]; Tw is the daily mean temperature [°C] of the cooling water and Q is the daily streamflow [m3/s] of the cooling water.

Usable power plant capacity for historical and future climates was calculated in five regions, namely Western Greece, Epirus, West and Central Macedonia, Eastern Macedonia and Thrace and Peloponnese.

For the climate variables used in the above models, climate data for historical (1971-2000) and future (2021-2050) periods were derived from the results of four climate simulations within the EUROCORDEX project database [28]. The climate data are characterized by high spatial resolution (0.11° x 0.11°) and temporal resolution (daily time-step) and they cover three RCP scenarios (RCP2.6, RCP4.5, and RCP8.5).

2.3. *Methodology for impact assessment in energy demand*

The effects of climate change on the final energy demand of the residential sector in Greece were examined through a bottom-up engineering model that allows the detailed simulation of the evolution of the building stock in the country, its thermal characteristics, the equipment used to cover specific energy uses that are affected by meteorological/climatic conditions, but also the energy behavior of users. Such an approach offers greater transparency in the applied computational process and allows the investigation of the vulnerability of the energy system to climate change for different policy scenarios. The analysis is done on a yearly basis throughout the period 2011-2050.

The model developed and used in the context of this analysis consists of:

- A module analyzing the *building stock*, which estimates the evolution of the number of dwellings in the country from 2011 to 2050 and their distribution by energy class. The analysis of the building stock was done yearly, considering population growth forecasts as well as assumptions related to the evolution of the average size of households and the degree of renewal of the building stock (demolition of old and construction of new buildings).
- A *theoretical energy demand* module, through which the total energy requirements of the sector are estimated, further disaggregated on four main energy uses, namely space heating, air conditioning, hot water production, and other electrical uses (lighting, devices, etc.). The analysis is based on the evolution of the number of dwellings per energy class and statistical data on the energy performance of dwellings per energy class, published periodically by the Greek Ministry of Energy and Environment.
- A *final energy demand* module, through which the final energy consumption of the sector of households is calculated annually, based on the theoretical energy requirements calculated previously, the technologies and energy sources used as well as other appropriate adjustments. Specifically, for the historical years of the examined period for which energy balances had been published (i.e., 2011-2019), the results of the model are compared with the data of the energy balances and appropriate adjustments were made, including the incorporation of appropriate correction factors, to capture specific patterns of energy behaviors. Based on these final arrangements the forecast of energy consumption in the time horizon of 2050 was carried out.

Key drivers of the evolution of final energy demand in the analysis carried out are the population, the average size of the households, the composition of the building stock in relation to the energy classes of the dwellings, the technologies used, and possible rebound effects particularly as regards space heating and air conditioning.

For the assessment of climate change impacts on the final energy demand of the Greek residential sector, we have used the outcomes of the same climate scenarios and models used for assessing the impacts of climate change on energy supply technologies. In all scenarios and simulations, the key climate parameter included in the analysis is the mean daily temperature. Based on this parameter, the heating degree days (HDD) and cooling degree days (CDD) are calculated daily, for the historical and future climate, and for all the considered scenarios. Specifically, the HDD and CDD were calculated as follows:

- The HDD are calculated only for the days with mean temperature T_m less than or equal to 15°C. In this case the HDD of a day i are calculated as the difference between the reference temperature

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for heating (taken as equal to 18°C) and the mean temperature of day i. If the mean temperature of the day is greater than 15°C, the HDD of this day is taken as 0.

$$HDD = \begin{cases} 18°C - T_m if T_m \leq 15°C \\ 0 if T_m > 15°C \end{cases}$$

- CDD are calculated only for the days with mean temperature T_m greater than or equal to 24°C. In this case the CDD of a day i are calculated as the difference between the mean temperature of day i and the reference temperature for cooling (taken as equal to 21°C). If the mean temperature of the day is lower than 24°C, the CDD of this day is taken as 0.

$$CDD = \begin{cases} T_m - 21°C if T_m \geq 24°C \\ 0 if T_m < 24°C \end{cases}$$

The monthly and annual heating and cooling degree days are calculated as the sum of the corresponding daily values.

The climate change impacts on the final energy demand of the Greek residential sector were estimated based on the following considerations and assumptions:

- Climate change does not affect final energy demand for water heating and electrical appliances/lighting.
- The change in final energy demand for space heating is proportional to the percentage change in heating degree days between future and historical climate.
- The change in final energy demand for cooling is proportional to the percentage change in cooling degree days between future and historical climate.
- The increase in temperature in the summer period due to climate change does not trigger further penetration of air-conditioning systems, beyond that already incorporated in the model developed because of the improvements in the standard of living.

As already mentioned previously, one of the key factors influencing theoretical and final energy demand in the residential sector and the possible impacts of climate change is the energy performance of the building stock. In the context of CLIMPACT, the bottom-up energy model developed, was used to produce detailed energy balances for four different scenarios as regards the energy performance of the Greek building stock and the associated equipment up to 2050. Specifically, the scenarios developed describe a:

- *Reference scenario*, which expands the current practices and trends regarding the evolution of the building stock and the equipment utilized up to 2050.
- *Shallow renovation scenario*, which adopts the energy renovation of 60,000 homes on an annual basis by 2050, ensuring the improvement of their performance by three energy classes.
- *Deep renovation scenario*, according to which all dwellings with EPC between G and C will be upgraded to B+ gradually by 2050.
- *Full electricity scenario*, where all dwellings with EPC between G and C will be gradually upgraded to B+ by 2050, and at the same time heat pumps will be used to cover 100% of the space heating and cooling needs in the sector.

All scenarios share common assumptions regarding efficiency improvements of the technologies used.

3. Results

3.1. Climate change impacts on power generation

3.1.1. Impacts on wind farms' productivity

The results for the period 2021-2050 and for the 3 examined RCP scenarios are presented in Figure 2 and they are similar to the findings of other studies for Greece (e.g. Tobin et al., 2018). In all

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three RCP scenarios the annual capacity factor is expected to change between -4.0% and + 4.0% compared to the reference period 1971-2000, with the exception of the climate simulation m1 (models CCLM4-8-17 / CLMcom -ICHEC-EC-EARTH), which estimate an 8%-10%increase in some areas of the mainland country (Central Greece, Central and Eastern Macedonia) for the scenario RCP2.6.

Under the intermediate scenario RCP4.5 in Western Greece, in the Southern Peloponnese and in the Southern Aegean a reduction of wind power generation up to 2% is expected, while in Crete an 2% increase under all four climate simulations. In the rest of the regions the results are mixed with the largest changes (varying from -2% to 6%) projected in Eastern Macedonia.

In scenario RCP8.5 in most areas the climate simulations predict increases in the power generation of wind farms except for the simulations with the climate models HIRHAM5 / DMI.ICHEC-EC-EARTH (m2) according to which reductions are expected in Southern Peloponnese, Central and Western Greece and Eastern Macedonia.

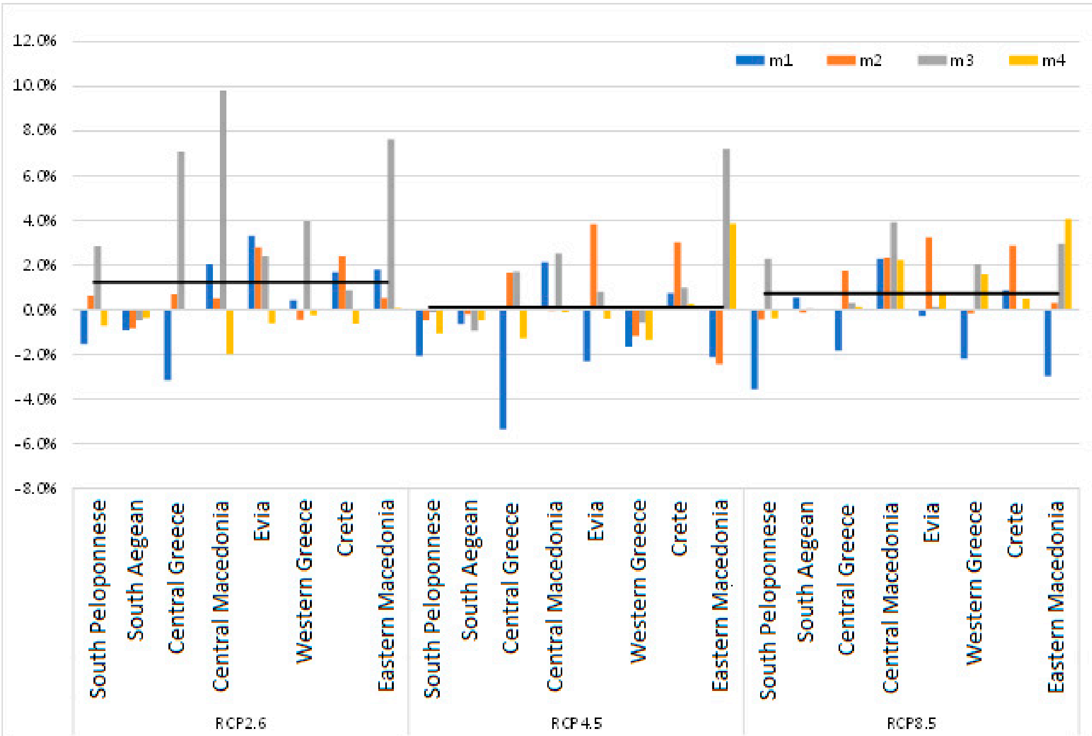

Figure 2. Average change of the annual capacity factor of the wind farms in 2021-2050 compared to the reference period 1971-2000 based on the results of 4 climate simulations in 8 representative regions of Greece under the examined RCP scenarios. The horizontal lines show the ensemble value of the change for all the areas of interest of the country. Climate model simulations: m1: CCLM4-8-17 / CLMcom.ICHEC-EC-EARTH, m2: HIRHAM5 / DMI.ICHEC-EC-EARTH, m3: RACMO22E / KNMI.CNRM-CERFACS-CNRM-CM5 and m4: REMO2009 / MPI-CSC.MPI-M-MPI-ESM-LR.

The differences in the power generation of wind farms are mainly connected to the fluctuations of the changes in the wind speed that are observed between the results of the climatic simulations in each geographical area. On the contrary, the effect of the increase in temperature is lower and it is generally more uniform between the climate simulations in each region. Considering the average of the climatic simulations per region, the changes of the productivity of the wind systems in the future climate are small and range between -1% - 2%.

3.1.2. Impacts on photovoltaics' productivity

The results of the four climatic simulations show that the estimated change in the output of the PV stations does not exceed in any case +/- 2%, showing a difference between climatic simulations but geographical uniformity (Figure 3).

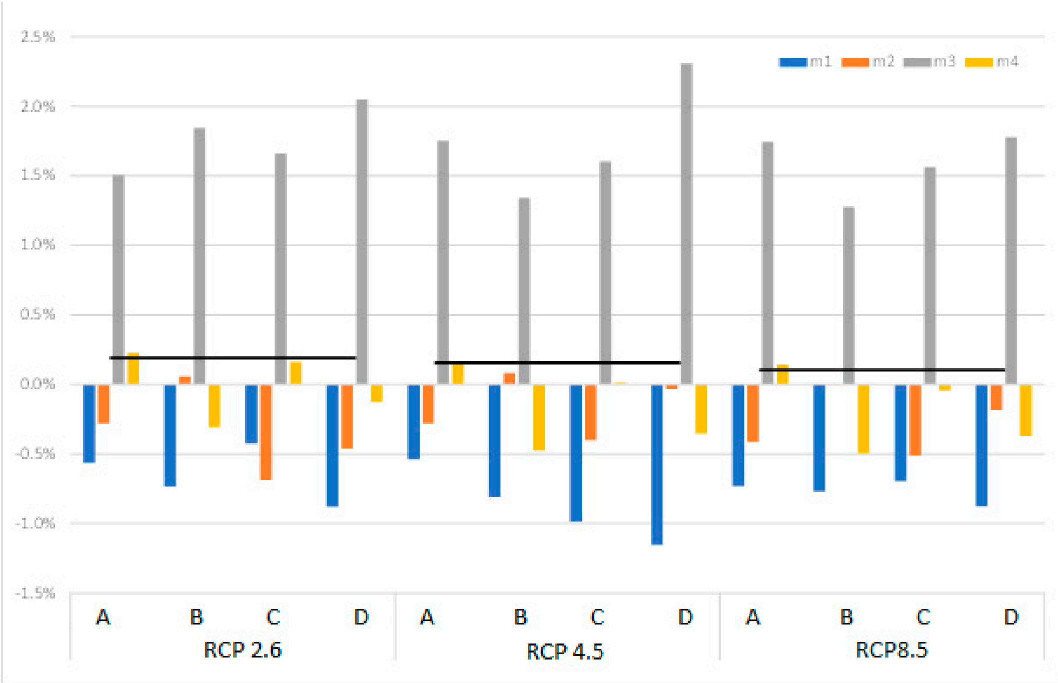

Figure 3. Average change of the annual capacity factor of the PV stations in 2021-2050 compared to the reference period 1971-2000 based on the results of 4 climate simulations in 8 representative regions of Greece under the examined RCP scenarios. The horizontal lines show the average value of the change for all the areas of interest of the country under each RCP scenario. Climate model simulations: m1: CCLM4-8-17 / CLMcom.ICHEC-EC-EARTH, m2: HIRHAM5 / DMI.ICHEC-EC-EARTH, m3: RACMO22E / KNMI.CNRM-CERFACS-CNRM-CM5 and m4: REMO2009 / MPI-CSC.MPI-M-MPI-ESM-LR.

More specifically and according to the results for the climatic simulations with the models CCLM4-8-17 / CLMcom.ICHEC-EC-EARTH (m1), in all three RCP scenarios an increase of power generated is expected in all climatic zones ranging between 1.5% and 2.5%. On the contrary, according to the HIRHAM5 / DMI.ICHEC-EC-EARTH (m2) models, a reduction of the PV power generation between 0.5% -1.0% is expected, while the other two simulations (m3 and m4) project both increase and reduction depending on the region and the examined climate scenario. However, the projected changes do not exceed +/- 0.5% in any case.

3.1.3. Impacts on hydropower potential

Based on the results of the first impact assessment approach (i.e., theoretical models for estimating hydroelectric potential in an area which take into account the surface runoff, water density and dam height), the estimated reduction of the hydroelectric potential in Greece is significant and with a large variation within the models under each scenario (Figure 4), while in some cases, there is even a difference in the sign of the changes between the models for the same area. The wide range of results and the difference in the sign of change demonstrates the uncertainty that exists in estimates of precipitation and runoff changes in climate models. More specifically, changes between future and historical climate range between:

- -44.0% and + 22.9% in the case of the RCP8.5 scenario
- -49.0% and + 11.9% in the case of the RCP4.5 scenario and
- -49.7 and + 8.0% in the case of the RCP2.6 scenario

The above fluctuations are smoothed when the average of the four climate simulations in each region is calculated. According to these ensemble results, reductions 2%-4% are expected in Western Greece, reductions 15% -16% in Epirus, West and Central Macedonia and reductions 5% -10% in Peloponnese and Eastern Macedonia and Thrace.

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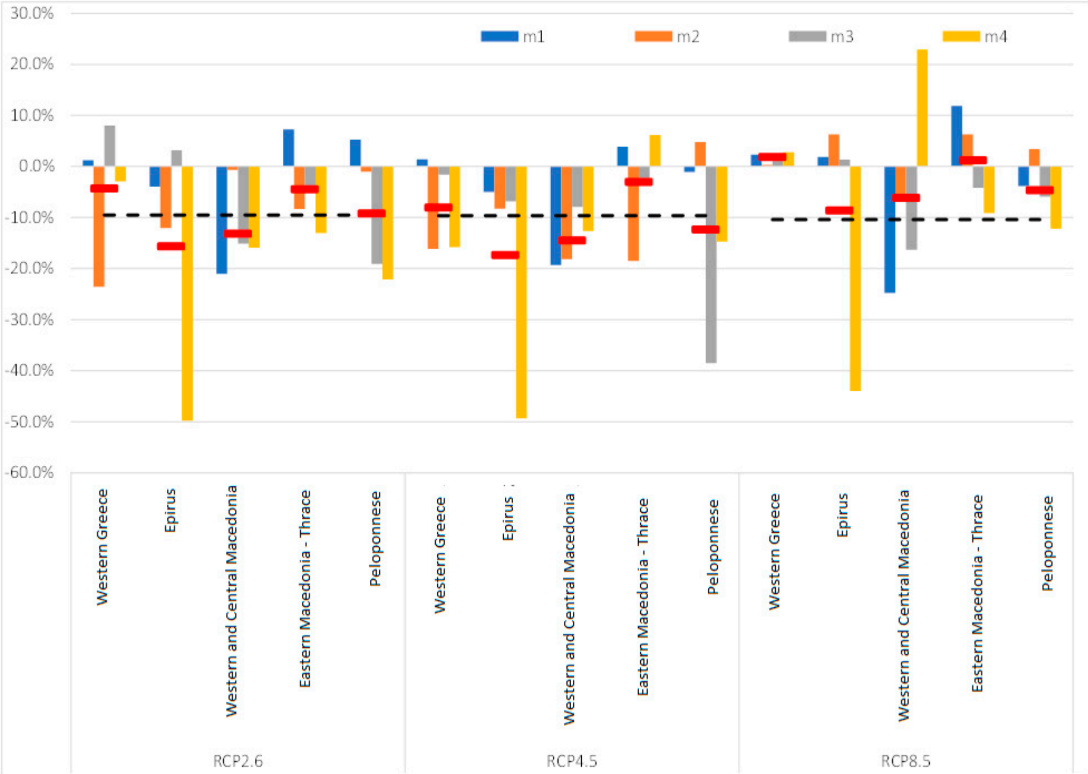

Figure 4. Change of the potential of hydroelectric power during period 2021-2050 in 5 regions compared to the reference period 1971-2000 according to the surface runoff of four climate simulations under the 3 examined RCP scenarios. The horizontal red lines show the based on the ensemble of the results of the four climate simulations. The horizontal black dashed lines show the weighted average value of the reduction of the potential in the country per climate scenario.

According to the second impact assessment approach (i.e. statistical regression models which correlate historical values of hydroelectric production per installed MW with the prevailing meteorological conditions), power generated by hydroelectric stations in Greece is expected to decrease up to 40% -45% during 2021-2050 compared to reference period 1971-2000, while increases are observed in a few cases (Figure 5). The largest reductions in hydroelectric power generation according to the results of the average of the four climate simulations (ensemble) are expected in Peloponnese (~ 20%), Epirus and Western and Central Macedonia (10% -15%), while smaller ones (5% -10%) are expected in Western Greece and Eastern Macedonia and Thrace. The estimated reduction with the second methodological approach is greater than those estimated based only on changes in runoff in Peloponnese and Western Greece, while in the other areas it is similar or slightly increased mainly in the RCP8.5 scenario.

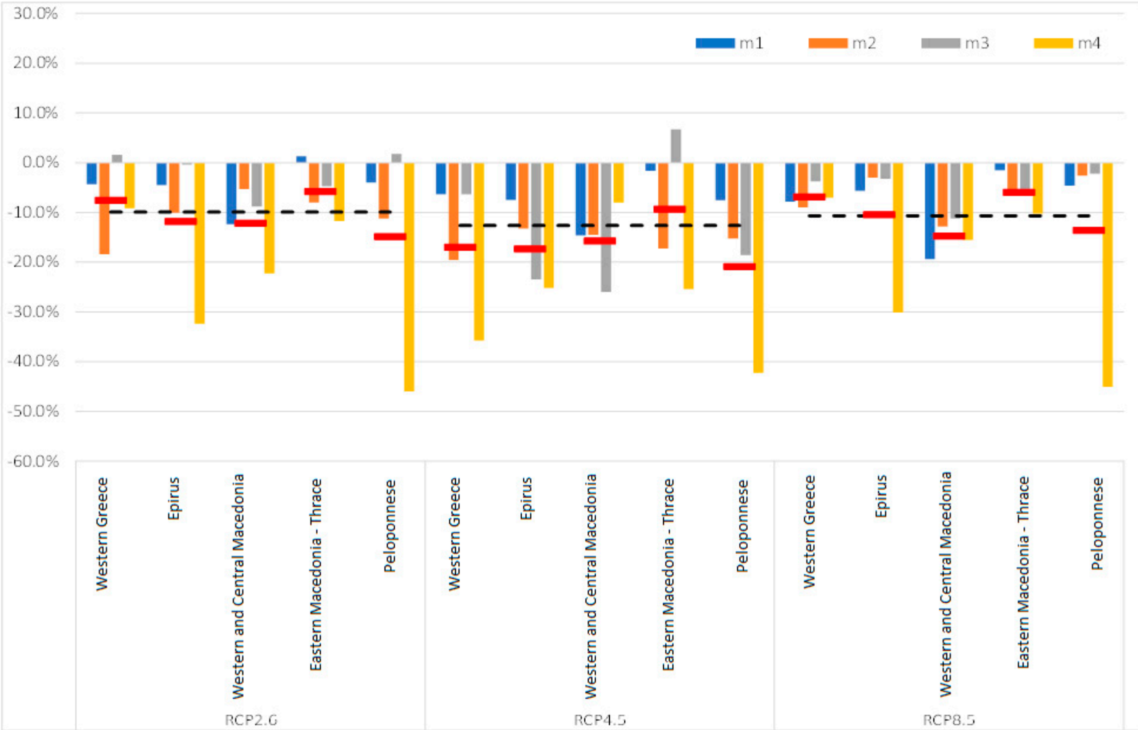

Figure 5. Percentage change of the hydropower generation during 2021-2050 compared to the reference period 1971-2000 in Greece based on statistical regression models and the results of four climate simulations in five geographical regions under the three RCP scenarios. The horizontal red lines show the changes in hydropower generation based on the ensemble of the results of the four climate simulations. The horizontal black dashed lines show the weighted average value reduction of the hydroelectric production in the country for each climate scenario.

3.1.4. Impacts on thermal power plants

Regarding the conventional thermal power plants, a decrease in efficiency is expected due to the increase of air temperature and cooling water temperature in the future climate of the period 2021-2050 under the three climate scenarios examined, for all climate simulations performed and for all regions (Figure 6). The reductions are higher (7% -11%) under the worst-case scenario RCP8.5 and lower under the RCP2.6 scenario (4% -9%), while they do not have a significant geographical variation.

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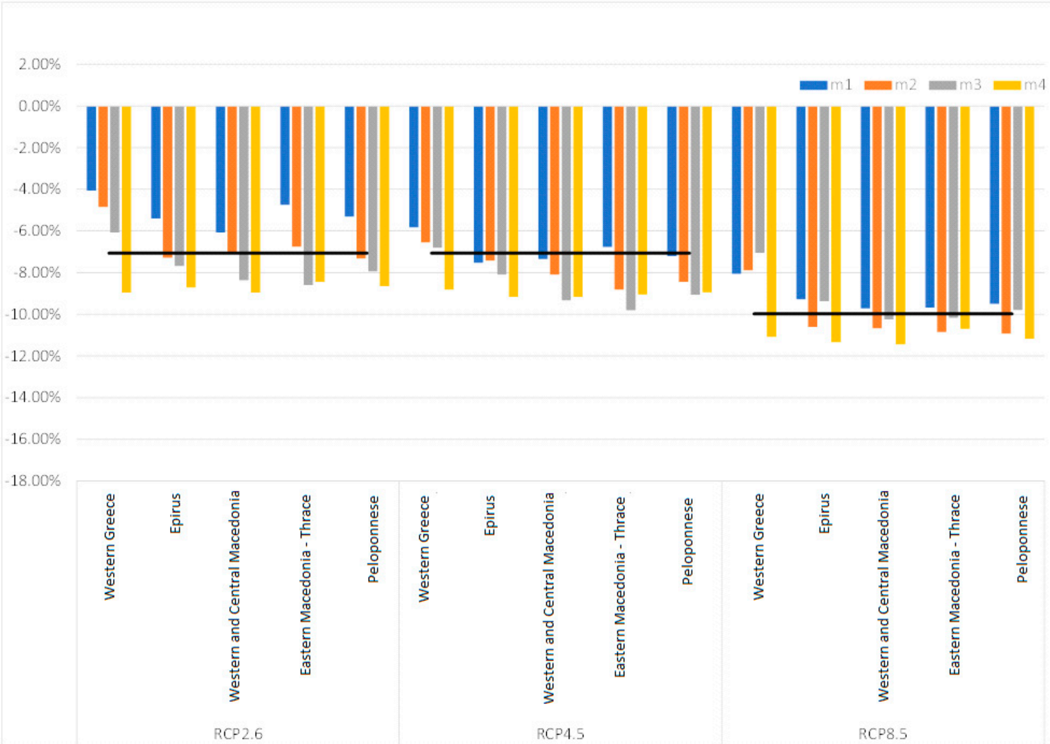
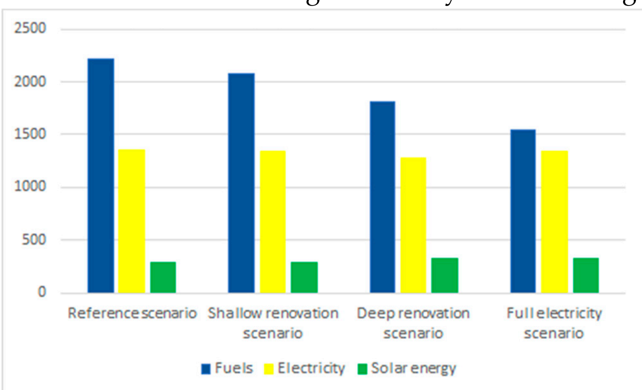


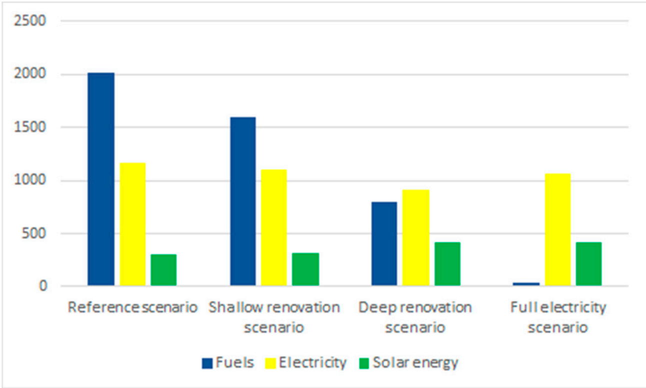
Figure 6. Percentage change of the average annual efficiency of thermal power plants in 2021-2050 compared to the historical climate of 1971-2000 based on the results of four climate simulations in five geographical areas under the three examined RCP scenarios. Climate model simulations: m1: CCLM4-8-17 / CLMcom.ICHEC-EC-EARTH, m2: HIRHAM5 / DMI.ICHEC-EC-EARTH, m3: RACMO22E / KNMI.CNRM-CERFACS-CNRM-CM5 and m4: REMO2009 / MPI-CSC.MPI-M-MPI-ESM-LR.

3.2. Climate change impacts on energy demand

Figure 7 presents the calculated energy consumption per energy carrier in the Greek residential sector by 2030 and 2050 respectively under current climate, based on the scenarios defined for the energy performance of buildings as well as the electrification of the sector (section 2.3). Figure 8 presents an overview of the evolution of the energy consumption in the Greek residential sector in the period 2017-2050, as well as the effect of the main mitigation actions under consideration for the decarbonization of the sector. Obviously, the latter is feasible to the extent that the electricity used for the remaining energy needs of the sector will be generated by RES technologies.



(a)



(b)

Figure 7. Estimated energy consumption by energy carrier in the Greek residential sector in 2030 (a) and 2050 (b) based on the examined scenarios (in ktoe).

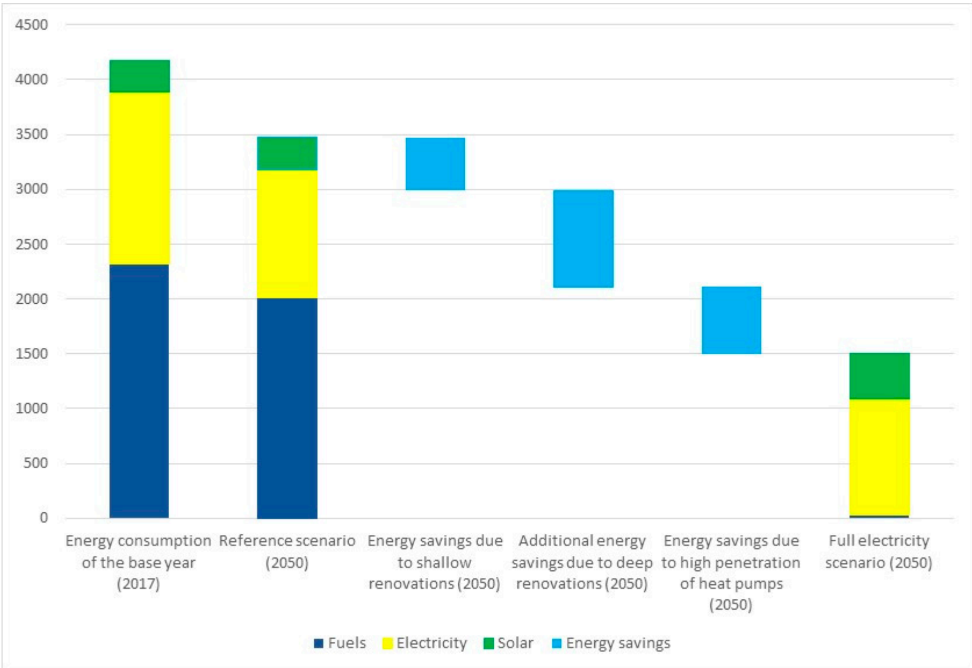


Figure 8. Evolution of energy consumption in the Greek residential sector during the period 2017-2050 based on the examined scenarios (in ktoe).

As already mentioned, climate change, mainly through increasing temperatures, is expected to affect energy demand (theoretical and final) in the sector. In the context of the present analysis, it is considered that climate change will affect only the energy demand for cooling and heating. In Figures 9 and 10, the average annual number of days with increased demand for heating and cooling respectively, for the reference period, 1971-2000 as well as for two future periods, 2021-2050 and 2071-2100 and under three future scenarios (RCP2.6, RCP4.5 and RCP8.5) are shown. Based on these Figures it appears that the future climate is characterized by:

- reduced demand for heating (averaged over all land grid points) by about 10-12% for the period 2021-2050 under all RCPs while for the period 2071-2100 the reductions ranges from about 10% under RCP2.6 to 35% for the RCP8.5 scenario,
- significantly higher increases in the number of days with increased demand for cooling are simulated by climate models for both future periods and under all scenarios. For the near-future period 2021-2020 the number of days almost doubles in all three scenarios (relative increase 80-

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100%) with the future projections indicating about a month with increased cooling demand. For the distant future the increase ranges from about 80% under RCP2.6, to 160% for RCP4.5, while the maximum increase, around 340% is projected under the extreme scenario, RCP8.5.

It should be noted that for both energy indicators the highest changes are simulated in coastal areas as well as in areas with relatively low altitude, while the difference between the future simulations and the reference one was found to be robust in the whole area under consideration.

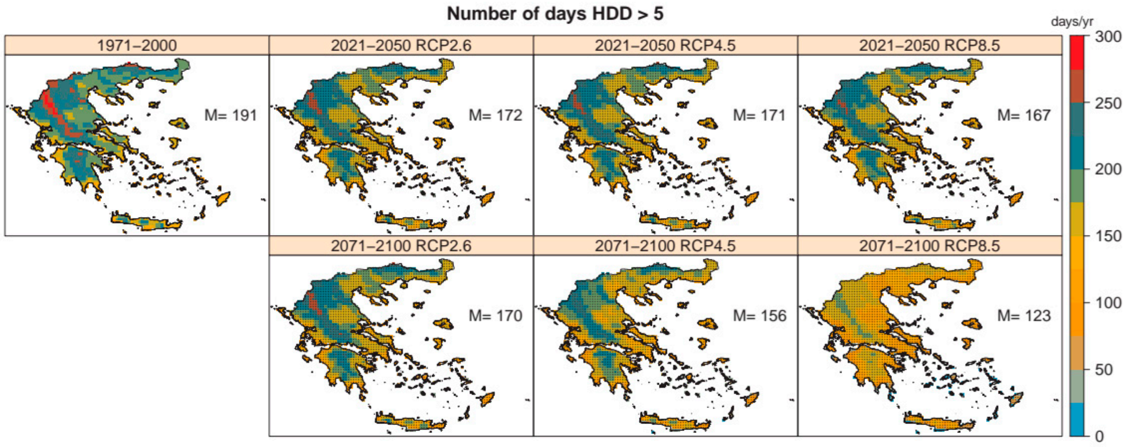

Figure 9. Average annual number of days with increased demand for heating (Heating Degree Days (HDD) > 5) for all simulations. In each panel, M denotes the spatial average over all the grid points covering the area under study with the units being the same as in the color bar. Black dots indicate a robust change (future period and scenario minus the reference one) at the grid point scale.

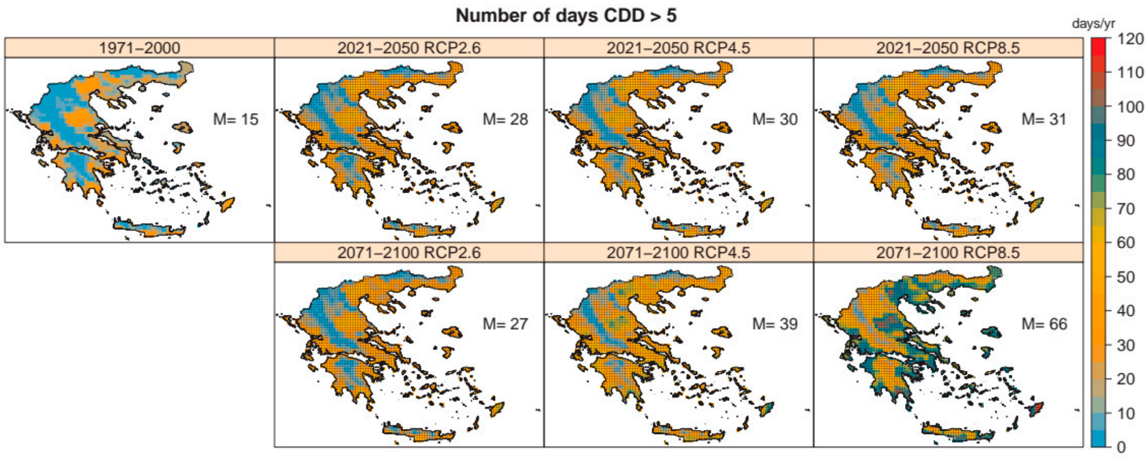

Figure 10. Similar to 1.7 but for the average annual number of days with increased demand for cooling (Cooling Degree Days (CDD) > 5).

To estimate the effects of climate change on energy consumption, it was assumed that the percentage change in heating degree days due to climate change causes a corresponding change in energy demand for heating, and similarly the percentage change in cooling degree days causes a

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corresponding change in energy demand for cooling. The results for the four scenarios developed as regards the future energy consumption (2050) in the Greek residential sector are presented in Figures 11 and 12.

In the reference scenario (2050), climate change is estimated to cause a reduction in overall energy consumption by 4-10% in the RCP2.6 scenario, 4-12% in the RCP4.5 scenario, and 7-14% in the RCP8.5 scenario, but also an increase in electricity consumption by 3-10% in the RCP2.6 scenario, 4-12% in the RCP4.5 scenario, and 4-13% in the RCP8.5 scenario. The increase in electricity consumption ranges from 38 to 153 ktoe (442-1780 GWh) per year in 2050 depending on the climate scenario and the climate model used.

In the shallow renovation scenario (2050) climate change results in a reduction of total energy consumption by 3-9% in the RCP2.6 scenario, 4-11% in the RCP4.5 scenario, and 6-12% in the RCP8.5 scenario. However, electricity consumption increases by 3-9% in the RCP2.6 scenario, 4-11% in the RCP4.5 scenario, and 4-12% in the RCP8.5 scenario.

In the deep renovation scenario (2050) climate change leads to a reduction of total energy consumption by 2-7% in the RCP2.6 scenario, 3-8% in the RCP4.5 scenario and 4-9% in the scenario RCP8.5. Again, the electricity consumption increases by 2-5% in the RCP2.6 scenario, 2-6% in the RCP4.5 scenario and 2-7% in the RCP8.6 scenario. However, in absolute terms the increase in electricity consumption is in the range of 19-57 ktoe/year, reduced by more than 50% compared to the reference and shallow renovation scenarios presented above. The reduction in fuel consumption is in the range of 100-181 ktoe/year, significantly lower than in the reference and shallow renovation scenarios.

Finally, in the full electricity scenario climate change does not significantly affect either the total energy consumption or the electricity consumption. Given that in this scenario all thermal energy end-uses are covered by electricity, the increased cooling requirements are outweighed by the reduction in the demand for space heating, without any significant impact on the power generation system at least on an annual basis. In absolute terms, the effect of climate change on total electricity consumption in 2050 ranges from -18 to 33 ktoe/year (384 GWh at a maximum) depending on the climate scenario and the climate model used. However, the profile of electricity demand within the year can be significantly differentiated by increasing the summer peaks and decreasing the demand during the winter period.

Figure 11. Percentage change in total energy demand of the Greek residential sector in 2050 due to climate change for all measures scenarios, climate scenarios and climate model simulations considered.

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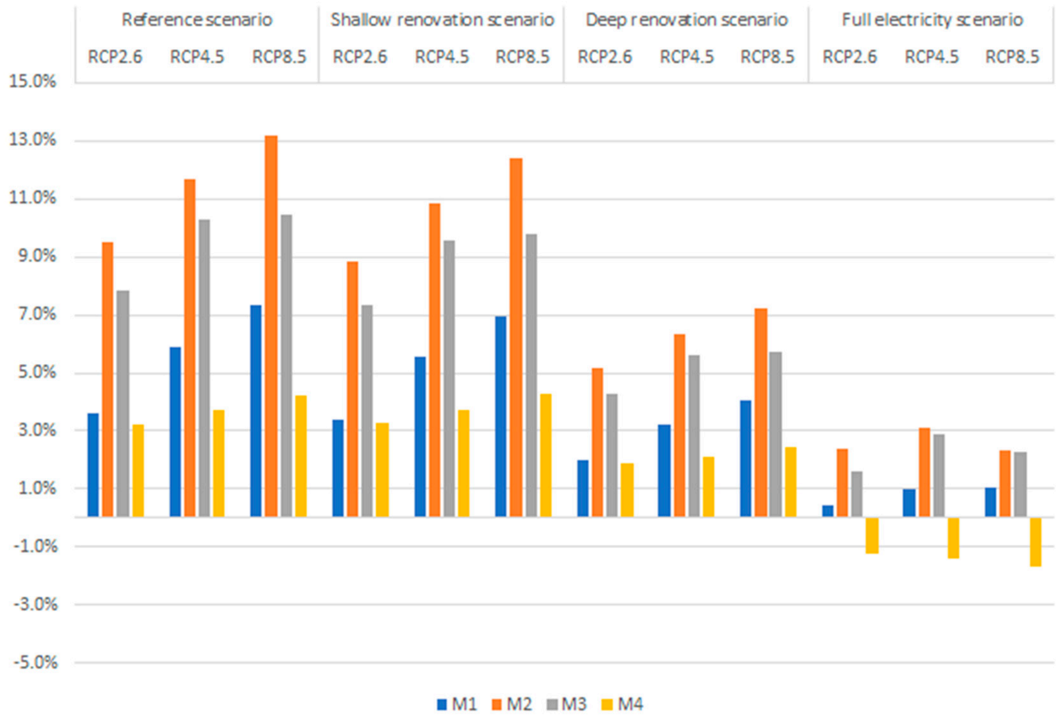

Figure 12. Percentage change in electricity demand of the Greek residential sector in 2050 due to climate change for all measures scenarios, climate scenarios and climate model simulations considered.

Finally, Figure 13 presents in absolute terms the change in electricity demand in 2050, for all energy and climate scenarios analyzed in the context of this work.

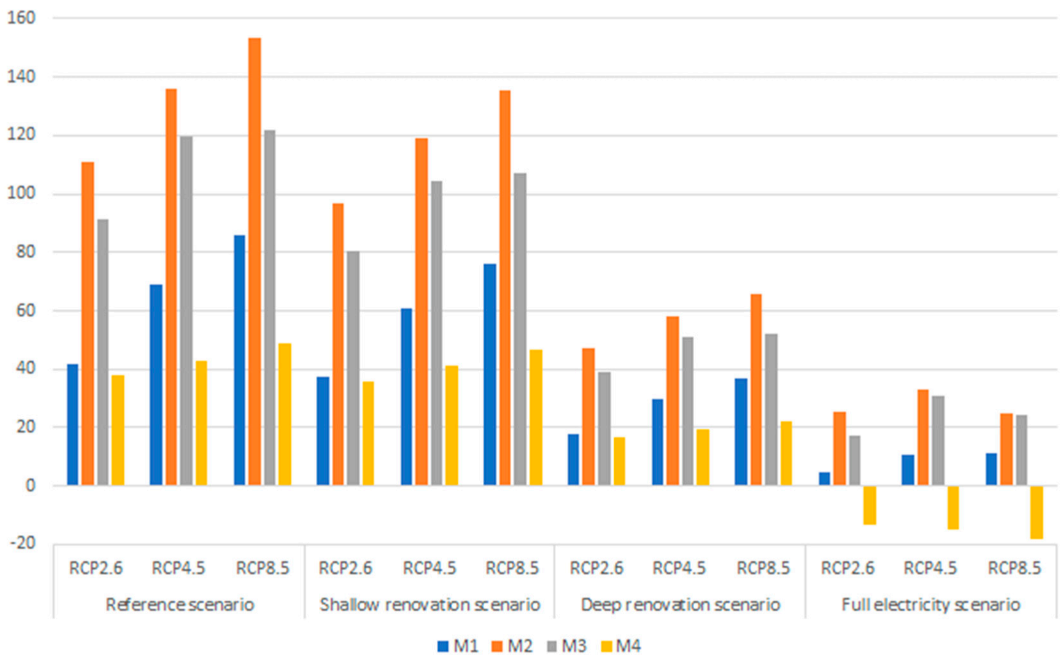

Figure 13. Changes in electricity consumption due to climate change in the Greek residential sector in 2050 for all measures scenarios, climate scenarios and climate model simulations considered (in ktoe).

4. Discussion and conclusions

In Greece, with respect to energy supply, and especially regarding electricity generation, climate change is expected to mainly affect electricity generation from hydro and thermal power plants. Specifically, the scenarios examined show that for hydropower plants the impact will be negative for the period up to 2050.

The range of impacts on hydro potential and electricity generation depends on the geographical location of the power plants and shows significant uncertainty due to the corresponding uncertainty in climate models estimates regarding precipitation and runoff changes while showing significant geographical variations. On average, the expected reduction amounts to 15% -20% compared to the historical climate. It is therefore obvious that for a more accurate assessment of climate change impacts on the production of hydropower plants, a more detailed modeling, at installation level, is required through hydrological models that consider several climatic and hydrogeological parameters.

The impact of climate change on the efficiency of thermal power plants is also negative, though smaller than in hydro power plants. The estimated impacts show smaller geographical variations and less uncertainty compared to hydro power plants as the effects are related to temperature increase. The changes appear to be more pronounced for the RCP4.5 and RCP8.5 scenarios, in which climate change is more intense, and smaller for the milder RCP2.6 scenario. According to the average of the climate simulations (ensemble of the models) the expected reductions range from 6% to 11%.

The impacts on solar and wind energy potential are significantly smaller compared to those of hydro and thermal power plants. Specifically, changes in wind energy potential in the future climate range from -1% to 2% (average of climate simulations) but present significant geographical variation and there are differences between the climate models considered. On the contrary, the impact of climate change on the efficiency of PV stations is small (either positive or negative depending on the climate simulation) and with very small differences along the 4 climatic zones of Greece.

With respect to energy demand, climate change is expected to affect energy consumption in the residential sector, but the expected range of effects depends on both the implementation and the characteristics (deep vs. shallow renovation) of measures for upgrading the thermal performance of the building stock and the intensity of climate change. In general, the scenarios examined show that total energy demand in the sector is expected to be reduced, while electricity demand will increase. In 2050 the reduction of total energy demand may reach 14% compared to the demand under the historical climate, while the increase in electricity demand may reach 13%. There are significant differences in total energy and electricity demand between the climate scenarios considered.

These changes (percentage increase or decrease in fuel and electricity demand) appear to be more pronounced for the RCP4.5 and RCP8.5 scenarios, in which climate change is more intense, and smaller for the RCP2.6 scenario that put emphasis on climate change mitigation. In addition, the higher the ambition for deep energy renovations in the building stock, the lower are the expected changes. In particular, the electrification of the energy demand in the residential sector when combined with the energy renovation of the existing building stock (deep retrofit), result in almost zero changes in fuels and electricity consumption. However, fluctuations in the monthly or daily profile of electricity demand can be significant.

Future research is needed to include in the analysis household income and how it affects choices and behavior but also the effectiveness of climate policies. In addition, the analysis should be extended to the other final demand sectors (e.g., non-residential buildings, industry, transport, etc.) as well to the impacts on energy transmission and distributions networks.

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Data Availability Statement: Not applicable.

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

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