A Review on RES Energy Transition-Climate Change Interaction Effects

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Abstract. The role of CO_2 emissions in climate change from fossil fuel burning is well documented and the need of renewable energy sources (RES) development well accepted. An impetus in the research aiming in proposing mitigation measures and energy transition is currently under way towards a zero-carbon society after the mid of the century. However, an unprecedented growth of RES installations with an unconditional economic development could potentially raise new environmental and societal concerns. Since energy transition will be based on anthropogenic conversion of solar and wind energy sources in useful energy for developing purposes, RES interaction with regional climate should be thoroughly investigated. Moreover, the magnitude and potential impact of this interaction should be assessed in detail in order to avoid potential environmental problems like those caused by the vast exploitation of conventional energy resources in past century. In this frame, the aim of this work is to review the current scientific knowledge on the RES-climate change interaction and the potential effect of photovoltaics (PV) and wind turbines (WTs) electricity generation to regional climate change. Greece is selected as a European case study due to abundant RES availability for energy transition. Contradictory results of global and regional climate models reveal that more research and experimental work is needed for a sustainable development based on renewable energy sources.

Keywords: Climate change · Solar energy · Wind energy

1 Introduction

The continuous exploitation of fossil and mineral fuels the last two hundred years has substantially improved the quality and duration of human life but has disturbed the earth energy balance with higher mean annual temperature and negative health and environmental impact. As a result of increased concern, the Paris agreement was signed by 175 parties with a goal to keep temperature increase even below 1.5 °C. In this context, International Energy Agency has called for urgent actions in the most recent net zero scenario by 2050 towards the replacement of conventional energy resources in the energy mix with renewable energy sources [1]. Is this energy transition feasible? In a simple model of PV and wind turbines development with the same rate as the last year in Greece up to 2030 (14.37% for PV grid installations and 13.83% for WT grid connected

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systems), 10% and 8% respectively up to 2040 and 5% for both up to 2050, 37.3 GW of PV systems and 39.1 GW of WTs will be required for a 100% energy transition in order all the non-industrial final energy use of Fig. 1 to be covered by PV and WTs. Even in the model of Jacobson et al. with a 45.6% reduction in the final energy use of Greece [2], a 19.2 GW of water/wind/solar (WWS) power needs to be implemented with a land area requirement of 0.74% while even higher load will be required in the models of [3] or [4] (Table 1). These power requirements are high but not unreachable since 1864 applications were submitted at the last call of the National Regulatory Authority for Energy (RAE) in December 2020 for RES applications of 45.55 GW (36.339 GW of PVs, 8.704 GW of WTs and less than 200 MW other RES). Therefore, the land and space requirements for such a transition is not negligible. It will account for at least a digit percentage of space area (Table 1). However, there are 419 regions in Greece protected by the NATURA 2000 network that account for the 27.29% of mainland and 6.12% of territorial waters of Greece. In order to be in line with the 14 and 15 UN goals of sustainable development, the protected areas should be left undisturbed without the presence of RES energy conversion systems [5]. This principle conservation is feasible

Table 1. RES energy transition in Greece up to 100% of final non-industrial energy use.

Scenario	PV (GW)	WIND (GW)	HYDRO (GW)	Electricity (TWh) or Total Installed (GW) at 2050 and space requirement	Ref
1	39.1	37.3	3.0	144 TWh (76.483 GW) (100%); 0.7% of land for PV of 40 W/m^2; 7% of space (onshore and offshore) for WTs of 1.1 W/m^2	100% of RES for non-industrial energy use with a Business As Usual scenario
2	7.8	9.1	1.67	WWS: 19.2 GW (100%);0.74% of land for WWS; 45.78% reduction from present needs	[2]
3	12 (23%)	12 (35%)	3.56 + 2.7 HPS	74 TWh (WWS: 30.26 GW + 7.1 NG + 0.125CHP + 0.6BM)	[3]
4	14	11.5	5.5 + 3 HPS + other RES	40 GW RES for maximum 70% CO_2 reduction in 2050 compared to 2005 (70% RES in total final energy consumption)	[4]

in Greece even for an extended windfarm-free zone [6] where wind farms can be applied at moderate wind speed sources [7]. Although, public acceptance of many WTs and PV needs policy attention (e.g. participatory framework of local communities) due to a raising negative attitude against new WTs installations in many places in Greece, new scientific needs are also emerging due to the massive RES utilization. Among these, material availability is important and has received substantial interest with many recent publications and reports. However, the effect on RES-climate change interactions have received much less attention. Increasing RES systems deployment will result in an increasing use of solar, wind and water atmospheric energy resources for techno-economic purposes with a direct disturbing effect on the atmospheric energy balance and regional climate at different scale. Although, specific RES-climate change interaction studies are being emerged as individual cases, an integrated compilation of significant findings for both directions (RES to climate change effect and vice versa) is missing from scientific literature. In this context, the aim of this work is to review the research on the RES-climate change loop interaction: the potential impact of climate change to future regional electricity generation from PV and wind turbines and vice versa, the potential impact of PV and wind turbines electricity generation to regional climate change. Due to the abundant RES availability and recent intense efforts for energy transition, the investigation is focused on Greece as a European case study.

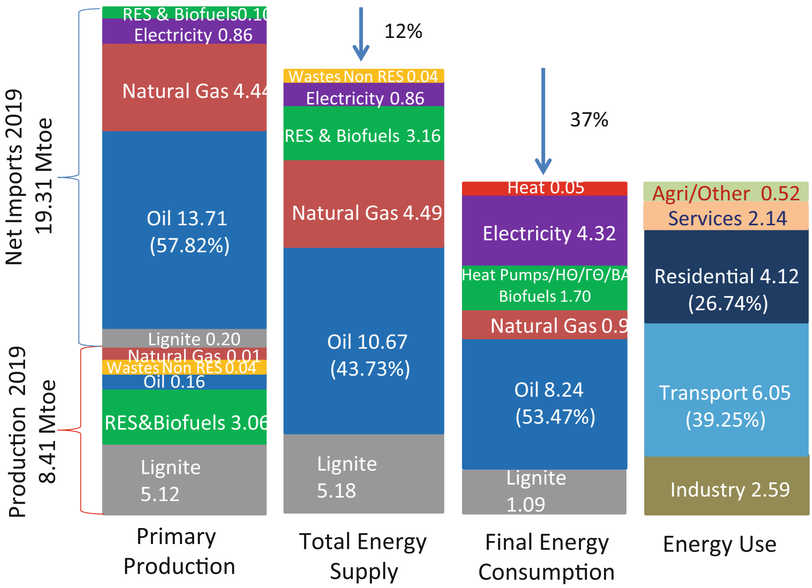

Fig. 1. Energy production, imports and final energy consumption in Greece for 2019 (based on Eurostat data).

2 Methodology

Since all the scenarios of the future energy transition of Table 1 rely mainly on the renewable energy sources of wind and solar, the literature review was not extended to other potential RES in Greece. Articles from the Scopus database that refer to the effect of climate change on these sources and vice versa (specifically for the country or as part of European studies) were analysed in order to provide valuable insights for research gaps and needs as well as to reveal potential discrepancies between the different scales of general circulation model simulation and dynamic downscaling with regional climate models. Although, articles on hydropower and buildings-climate interaction were also evident (with more pronounced climate impact to energy production or needs), their analysis will be reported in future work.

3 Results and Discussion

3.1 The Effect of Climate Change on Solar Energy and PV Electricity Production

Solar radiation has been found globally to be increased by projected climate change till the end of the century, but PV electricity production is also influenced by temperature and wind speed variation. In Greece, Panagea et al. [8] studied the projections of global horizontal irradiation from five RCMs for historical and future periods and found minor increases (2.0–3.0 W/m^2 by 2011–2050 and 5.0 W/m^2 by 2061–2100) in power output to the outweighed of projected temperature increase (+3.5 °C) by the expected increase of total radiation. These results were further confirmed by Katopodis et al. [9] and on average, mean annual global horizontal irradiance (GHI) variations showed values of similar magnitude and pattern between two future scenarios (RCPs 4.5 and 8.5). An enhancement in PV electricity production has been also projected by recent European studies of the three atmospheric variables [10] and for other countries like Germany and Spain although rather as exceptions in Europe [11]. However, under a fixed scenario of high-PV penetration, a general and progressive decline of the generated PV power is found in all regions along the entire period. Finally, in a recent European study, projected solar PV generation on three levels of global warming above preindustrial levels, i.e. 1.5 °C, 2 °C and 3 °C warming that occur at different times among simulations) showed very small changes for the countries of Greece, Portugal, Spain and Cyprus in South Europe [12]. However, the studies have been mainly focused on regional effects on the country scale with the absence of studies at the urban scale where effects of microclimate change or extreme weather events are enhanced [13].

3.2 The Effect of Climate Change on Wind Energy and WT Electricity Production

Climate change impact on wind energy sources in Greece was studied recently by Katopodis et al. [14] by projecting the wind potential of Greece up to 2045 with the EURO-CORDEX RCA4 model data, a horizontal resolution of ∼12 km and the RCP scenarios of radiative forcing of 2.6, 4.5 and 8.5 W/m^2. According to their analysis, the changes in the mean wind speed in Greece were within ±5% and did not vary significantly for the different RCP scenarios. Wind gusts exceeding 52 m/s appeared more frequently in RCP 8.5 by about 2–4 times per decade, affecting mostly the South Ionian Sea while a tendency for calming of the "Etesians" winds over the Aegean Sea in future summers was determined [14]. Latter was not observed in European studies where the wind energy potential is projected to increase in northern and central Europe while it may experience a decrease in all seasons over onshore southern Europe except for the Aegean Sea due to stronger relative influence of local wind systems [15]. A tendency toward a decrease of the wind power potential over Mediterranean areas (but within ±15 and ±20% by mid and late century respectively) was found by Tobin et al. [16]. More recently, the same research collaboration projected wind energy changes positive for Greece while overall reductions in wind power potential were projected (ensemble mean results) for all European countries [12]. These results combined with the stochastic nature of wind point to the need of more regional studies to investigate the impact of climate change on wind energy production.

3.3 The Effect of PV Electricity Production on Regional Climate

The installation of ground-mounted PV arrays has the potential to affect surface albedo, cause shading and intercept precipitation and atmospheric deposition, as well as influencing wind speed and turbulence at the land surface. However, the research studies are limited and mainly focused on the urban microclimate impact.

3.4 The Effect of WTs Electricity Production on Regional Climate

The operation of wind turbines can affect surface meteorology by changing atmospheric boundary layer condition of wind speed, turbulence and mixing, and thus the vertical distribution of energy and exchange between the land surface and atmosphere. Wakes from single wind turbines and large wind farms reduce the rate of radiative surface cooling and enhance night-time surface temperature. According to observations reported by Rajewski et al. [17], changes in the early evening transition due to the generation of turbulence from single wind turbines may influence transport of heat, water, and carbon dioxide from a non-vegetative surface. The only work on the impact of WT electricity production in Greece is reported by Vautard et al. [18] in the frame of climatic impact of wind farms in Europe. Under a power development scenario of 7 GW from 2014 to 2020, authors present mean summer temperature increase up to 0.3 K which depends on WT siting. Moreover, it has been also reported that keeping the global mean temperature below 2 °C can result in higher warming of Europe than the global average with a general increase in heavy precipitation and summer extreme temperatures [19]. According to Miller and Keith [20], the warming effect of wind energy is small when compared with projections of 21st century warming with Business As Usual policies, approximately equivalent to the reduced warming achieved by decarbonizing global electricity generation, and large compared with the reduced warming achieved by decarbonizing US electricity with wind. For the same generation rate, the climatic impacts from solar photovoltaic systems are about ten times smaller than wind systems. In this corresponding scale of regional wind installations combined with PV, it is envisaged that more detailed RES-climate interaction studies should be performed with additional wind farm observations to improve predictive skill of wind energy-atmosphere interactions.

4 Conclusions

It is evident from this review that there have been limited studies on regional RES-climate change interaction and further research attention is needed. In the larger scale of European or global studies, concerns have been raised on the warming effect of wind energy analogous to urban heat islands which can be non-negligible and comparable to temperature reduction upon decarbonization with large scale installation of wind farms. Therefore, it is of paramount importance to improve the accuracy of regional climate change models and reduce the major sources of uncertainty and bias corrections thorough their validation by accurate earth and satellite monitoring systems. Additionally, the effects of variability in future power systems and their demand/supply flexibility should be considered in their interaction with climate change and prioritizing actions should be proposed for a 100% renewable energy transition. PV building integration for zero energy buildings, EV transition with increased share of public transportation and unnecessary travel avoidance could be prioritized with the growth of annual installation rate of WTs and PVs. Mature storage technologies based on batteries for transport and pumping storage for electricity can be complementary used to cover all energy needs with RES. In this context, the barriers to 100% energy transition are not scientific and technical-economic but mainly social, structural and political and with decisive policies and new approaches to implementing technological and behavioural change, the challenges can be addressed.

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