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Abstract

The energy and water sectors face increasing challenges amid sustainability and net-zero transitions, which are integral to meeting the UN Sustainable Development Goals (SDGs). The need for integrated models that connect energy, emissions, and water use is critical for developing holistic and sustainable solutions. This chapter focuses on a water-energy-emissions modelling application for the residential sector, a key development area impacting SDGs related to energy, sustainable urbanization, and environmental management. We apply a combined energy-emissions and water accounting model to assess energy use, emissions output, and water consumption of Greece's residential sector, providing comprehensive, data-driven insights. Such integrated assessments are essential for informed policy evaluation and decision-making. We also analyze Greece's national decarbonization plan to 2050, demonstrating how these models can support policy evaluation and discuss the efficiency of the planned pathways. This approach underscores the importance of cross-sectoral analysis for successful long-term sustainable initiatives.

Keywords: Energy-emissions modelling; WaterReqGCH; Decarbonization; Sustainable Development Goals; Urban development; Greece.

1. Introduction

The foundations of energy policy have undergone substantial shifts. Initially, policies were heavily focused on meeting electricity demands through large-scale infrastructure projects such as power plants, transmission networks, and dams (Zhou et al., 2019). This predominantly supply-driven strategy prioritized centralized generation and distribution, with significant investments from both governments and utilities (Parag, 2014). However, this narrow perspective soon revealed its drawbacks, particularly the overlooked environmental and social impacts of such initiatives (Parag, 2014). Construction and operation of energy infrastructure, such as power plants and dams, frequently led to issues like water scarcity and ecological damages, that initially were overlooked (Ma et al., 2023; Grodsky and Hernandez, 2020).

A parallel transformation occurred in water management, which initially centered on engineering solutions to enhance water supply infrastructure. Over time, it evolved into a broader, interdisciplinary approach that considers water's interactions with other sectors (Alamanos, 2021a; Berry et al., 2015). Concepts having in their core the Water-Energy-Food Nexus illustrate this shift (Olsson, 2013). Research by Schmidt et al. (2022) reinforces the interconnected nature of water management by linking it with food and energy security, emphasizing the literature's gap in these areas. Supporting evidence from Miller et al. (2021), Drenkhan et al. (2022), and Staupe-Delgado (2019) also points to the necessity of nexus approaches having at their core water and energy considerations.

This growing acknowledgment of a need towards more interdisciplinary strategies aligned with the increasing focus on the sustainability transition in energy and water systems (Alamanos, 2024a). Sustainable energy policy has gained prominence in global frameworks like the Sustainable Development Goals (SDGs) and the 2030 Agenda for Sustainable Development. SDG 7 aims to "ensure access to affordable, reliable, sustainable, and modern energy for all", recognizing energy's role as a key enabler of inclusive development. This goal underscores the importance of universal energy access, renewable energy expansion, and energy efficiency improvements as essential elements for broader sustainable development (UNEP, 2017). Energy interconnects with SDGs related to health (SDG 3), climate action (SDG 13), and sustainable cities (SDG 11), reflecting its pivotal role in sustainable economic growth (SDG 8) and addressing global challenges (Chipangamate and Nwaila, 2023; Koundouri et al., 2024a). The integration of digital and automated technologies in energy management is linking energy with other SDGs, such as SDG 9 (Industry Innovation and Infrastructure) and SDG 12 (Responsible Consumption and Production), advancing circular economy principles. Similarly, water has become central in international policies like the SDGs and the 2030 Agenda. SDG 6 is exclusively devoted to water. It aims to "ensure availability and sustainable management of water and sanitation for all", emphasizing its foundational role in development. Water's connection to various SDGs, including health, climate action, and urban sustainability, underscores its importance in achieving broader development goals (Dai and Alamanos, 2024).

In this chapter we focus on estimating energy and water consumptions at national level, along with the associated greenhouse gases (GHG) emissions, from the residential sector. Having accurate energy and water consumption estimates is vital for effective energy and water management respectively and policy formulation (Strengers et al., 2011). These estimates provide essential evidence that help individuals understand their energy and water usage patterns, enabling them to make informed decisions about efficiency and conservation. For instance, by estimating the energy or water consumption of various appliances, households can identify which uses are the most energy-intensive or water-consuming, respectively, and consider upgrades or alternatives that will be more efficient, ultimately reducing their overall energy and water costs and environmental impacts (Spang et al., 2014). Moreover, this kind of consumption estimates are critical for assessing resource scarcity and managing competing demands among various sectors, including residential, agriculture, industry use, or transportation (Garcia and Alamanos, 2023). Understanding how much energy and water are consumed versus how much is available in terms of resources or production capacity, allows policymakers to make informed decisions about resource allocation, necessary investments, and conservation strategies (Koundouri et al., 2024c; 2024d). This information is vital for developing sustainable management practices that balance human needs with environmental protection. Another crucial role of having consumption estimations is their use for future forecasts, which are particularly useful for broader energy and water planning and policy development (Gacitua et al., 2018). Forecasting future needs for both energy and water is a prerequisite for developing strategies and policies. As mentioned, both energy and water planning are incorporated to most countries' national policies, and given the SDG agenda, informed decisions are going to be critical (Koundouri et al., 2024a). Both for the decarbonization efforts, and for the behavioural shifts needed in the energy and water sectors for renewable energy adoption and demand-side management strategies (Lopes et al., 2015). Finally, consumption estimates are essential for evaluating the effectiveness of the associated policies and initiatives. By tracking changes in consumption over time, we can model the impact of specific interventions and adjust strategies as needed (Aydin and Brounen, 2019). The joint consideration of energy and water consumption gives the opportunity to explore targeted interventions and observe the effects to both resources. This feedback loop is critical for ensuring that efforts to promote sustainability are grounded in real-world data and can adapt to changing circumstances (Nejat et al., 2015; Park et al., 2009). Ultimately, having robust consumption estimates enhances transparency and accountability in energy and water use, allowing improved understanding of relevant policies and initiatives aimed at achieving long-term sustainability goals.

The residential sector has a potential to become more environmental-friendly, by applying both supply-side and demand-side management actions, for energy and water, and this will be key for the decarbonization of the sector, as well (Alamanos, 2024a). It is responsible for a significant share in energy and water consumption for most countries (around 26% in Europe), and more often in the core of future infrastructure planning and management (Li et al., 2024).

2. Materials and Methods

2.1 Energy and water challenges and management in Greece

The Greek energy sector faces several significant challenges, primarily its continued reliance on fossil fuels, which account for a substantial portion of energy supply (Tsoutsos et al., 2008). Despite notable progress in renewable energy adoption, fossil fuels still dominate, particularly in non-interconnected islands where diesel generators are prevalent (Manopoulos et al., 2016). The government has set ambitious commitments to phase out lignite by 2028 and reduce overall GHG emissions to net-zero by 2050. However, the transition is complicated by rising natural gas prices and the need for substantial investments in renewable infrastructure (Halkos and Tzeremes, 2012). Furthermore, energy poverty remains a pressing issue, with a significant percentage of the population unable to adequately heat their homes (Loizou et al., 2015). The residential sector, which consumes the largest share of energy in Greece, presents both challenges and opportunities for improving efficiency through retrofitting and adopting renewable technologies (Tsoutsos et al., 2008).

The water management sector in Greece is also grappling with critical issues, in several fronts. Specifically, for the urban water demand, the major challenges are related to water scarcity, particularly exacerbated by climate change and increasing demand (e.g. tourism) (Alamanos, 2021b). Water shortages often lead to conflicts between agricultural and domestic water use (Sarpong et al., 2024). The reliance on groundwater resources has resulted in over-extraction and salinization, further compromising water quality and availability (Alamanos et al., 2019). The management of water resources is often fragmented across various governmental departments, leading to inefficiencies and poor coordination (Alamanos and Koundouri, 2022; Mohtar and Daher, 2016). The residential sector's water consumption pressures are significant, as urban areas experience high demand fluctuations that strain existing infrastructure (Sfyris et al., 2019). Addressing these challenges requires integrated approaches that enhance water resilience while ensuring equitable access for all communities.

The residential sector in the country is a case of particular interest, as it is the major contributor to energy consumption and the second largest water consumer (after agriculture), creating significant pressures on resources (Kourgialas, 2021; Sun et al., 2015). Understanding the consumption patterns of those resources is a critical for the country’s infrastructure and management planning, which need to be updated and modernized (Kourgialas, 2021; Shan et al., 2015). As Greece commits to sustainability goals, reducing environmental impacts and achieving decarbonization, addressing these consumption pressures through targeted policies will be essential.

2.2 The Global Climate Hub response: Integrated Modelling for sustainable pathways

Under the United Nations Sustainable Development Solutions Network (UN SDSN), the Global Climate Hub (GCH) has been developed, an international research-led and research-funded initiative that has the potential to address complex sustainability challenges (Alamanos, 2024b). The GCH is an initiative for change, leveraging science-based solutions for a holistic and equitable transition towards a more resilient and sustainable world. In particular, the GCH provides sustainable pathways addressing specific sustainability challenges, e.g., energy decarbonization, water security, etc. The solutions and pathways proposed by the GCH are based on comprehensive modelling of the various systems under consideration, such energy-water systems (among others, that might include also food, health, climate, economics, etc.) (Koundouri et al., 2024b). The GCH has nine research units with diverse expertise, working in a coordinated and complementary manner. In this chapter, we present an example of the combined work of two units: the Energy and Emissions unit and the Systems Modelling unit (that includes the modelling of water systems).

2.3 The LEAP model

The Energy and Emissions unit simulates energy systems using the LEAP software (Low Emissions Analysis Platform) (Heaps, 2020), to analyze different future scenarios and decarbonization interventions. LEAP is used to simulate the energy consumption across various sectors, including the residential, the fuel mixes used, along with the associated GHG emissions, from multiple pollutants. LEAP has been employed in numerous applications globally, from local municipalities to national governments (Fall and Mbodji, 2022). For instance, countries have utilized LEAP to develop their Nationally Determined Contributions (NDCs) under the Paris Agreement, showcasing its relevance in climate policy formulation. The model's flexibility enables it to accommodate various methodologies, including bottom-up end-use accounting and top-down macroeconomic modeling, making it suitable for integrated resource planning and GHG mitigation assessments (Fall and Mbodji, 2022). This functionality allows for the simulation of specific policies as modelling scenarios, enabling detailed evaluation of their impacts and trade-offs. The model's ability to simulate different scenarios has been particularly useful in exploring ways for decarbonization. For example, one application simulated the integration of renewable energy sources in urban electricity generation, highlighting how LEAP can model transitions towards low-carbon energy systems (Xu et al., 2024). Another study focused on the Guangdong - Hong Kong - Macao Greater Bay Area, using LEAP to explore pathways for achieving net-zero emissions by analyzing different power generation mixes and their associated costs (Liu et al., 2021).

In our model application, the residential sector's energy consumption has been calculated as the product of an activity level (e.g. population) and an annual energy intensity (energy use per unit of activity), according to LEAP's Final Energy Demand Analysis method (Heaps et al., 2020). The activity level (population) has been distinguished between urban and rural, based on the respective percentages of urban and rural population of the Hellenic Statistical Authority (ELSTAT, 2024). In this method we specify an activity level (in our case the population in number of people, grouped in urban and rural), and the energy intensity per use (Equation 1). The uses considered are lighting, cooking, space heating, space cooling, water heating, and other appliances.

$$D_{res,sc,t} = AL_{res,sc,t} \cdot EI_{res,sc,t} \tag{1}$$

Where D is the energy demand, AL is the activity level, and EI is the energy intensity. The index res stands for the residential sector, the sc for the scenario simulated each time, and the t for the years (ranging from the base year to the end year).

The energy consumption is calculated according to Equation 1 for the baseline year (2022) and for each future year in each scenario, until 2050.

The population data used for the activity level, the division in urban and rural population, as well as the respective growth rates that were used in the model as the AL, were retrieved from the official data of the Hellenic Statistical Authority (ELSTAT, 2024) - and the World Bank (2023). The final energy consumption results data were retrieved by IEA (2024), and based on these data we estimated the EI used in the model. IEA also provides data on the specific fuel mixes used to cover each one of the energy uses modelled (e.g. heating, cooling, cooking, lighting by fossil fuels, natural gas, renewables, etc.).

The GHG emissions are then estimated automatically, based on the emission coefficients of the IPCC's Fifth Assessment Report (IPCC, 2014) per use and per fuel type.

2.4 The WaterReqGCH model

The Systems Modelling unit simulates various natural systems, including water. In this work, the water requirements are estimated based on a water accounting tool that has been developed within the GCH, called WaterReqGCH (Alamanos and Koundouri, 2024).

The estimation of water requirements refers to calculating the amount of water needed for a specific sector. Most studies so far have employed a range of econometric techniques like panel data models, household surveys, and national/regional data to capture price, income, household characteristics, and other factors influencing sectoral water demands, hence the data-hungry nature of such assessments (Reynaud, 2015; Schleich and Hillenbrand, 2009). The residential water requirements (W) are estimated by the WaterReqGCH model, by multiplying the activity level, again expressed in population terms (AL) with an average consumption rate per person per day (CR), which is then increased by a losses coefficient (LC) expressing the water lost in various stages (pumping, transmission, distribution), according to Equation 2 (Alamanos and Koundouri, 2024).

$$W_{res,sc,t} = AL_{res,sc,t} \cdot CR_{res,sc,t} \cdot LC_{res,sc,t} \qquad (2)$$

Again, the index res stands for the residential sector, the sc for the scenario simulated each time, and the t for the years (ranging from the base year to the end year).

This is a straightforward calculation approach that requires minimal data processing. The resulting estimate provides a reasonable approximation of residential water requirements, as the typical consumption rates include the effects of various socio-economic parameters on water requirements (Khilchevskyi and Karamushka, 2021). Population data is widely available for countries and regions, often from reputable sources such as national statistical agencies, international organizations (e.g., United

Nations), or databases like World Bank (Di Mauro et al., 2021). In our case, again data from the Hellenic Statistical Authority (ELSTAT) were used for all parameters. This approach allows for flexibility in adjusting the average consumption rate to account for variations in water use patterns or regional differences in infrastructure, while stakeholders and decision-makers can understand and validate the methodology, making this approach more accessible and credible for informing policy and planning decisions (Dias and Ghisi, 2024).

3. Results and Discussion

The LEAP model and the WaterReqGCH models were set up and run for Greece's residential sector. The simulations considered two scenarios, a baseline and a National Policy, described as follows:

- Baseline scenario (or current accounts): This is usually what is defined as the "do-nothing" scenario. The only parameter changing in this case is the population, following the growth rates estimated by the Hellenic Statistical Authority (ELSTAT, 2024) until 2050. In both models, this change is practically reflected in the activity level of each year, assuming that all the other parameters will remain stable.
- Greece's commitment to transitioning to renewable energy sources is evident in its revised National Energy and Climate Plan (NECP) (Greek Ministry of Environment and Energy, 2024). The plan aims for a significant increase in the share of renewables in the energy mix, targeting a 76.8% share by 2030 (Greek Ministry of Environment and Energy, 2024). Additionally, Greece has set ambitious GHG emissions reduction targets, aiming for a 58% reduction by 2030, which reflects its dedication to achieving affordable and clean energy for all (IEA, 2024). In this scenario, the population (AL) is set to the 'default' growth projection, namely same to the Baseline scenario. The parameters that are changing in the NECP scenario are: the percentage of electricity deployment which is going to be used not only in an increased rate but also in additional residential uses (i.e. space heating through heat pumps); the phase out of oil products, such as heating diesel and Liquified Petroleum Gas (LPG) from space heating, Natural Gas phase out from space heating, cooking, and from fueling the thermal electricity generators.

The LEAP model then applies the Final energy Intensity Method (Equation 1) and calculates the energy demand both for the urban and rural population of Greece, per use (space heating, space cooling, water heating, cooking, lighting, other appliances) and per fuel type (Figure 1a). Also, the model estimated the emissions of various GHG pollutants, produced by the fuel combustion to cover the simulated energy demand of all uses of the residential sector in Greece (Figure 1b). The WaterReqGCH model applies the Equation 2 for each year (Figure 1c), following also estimates for monthly distributions, accounting thus for seasonality in water requirements (Figure 1d).

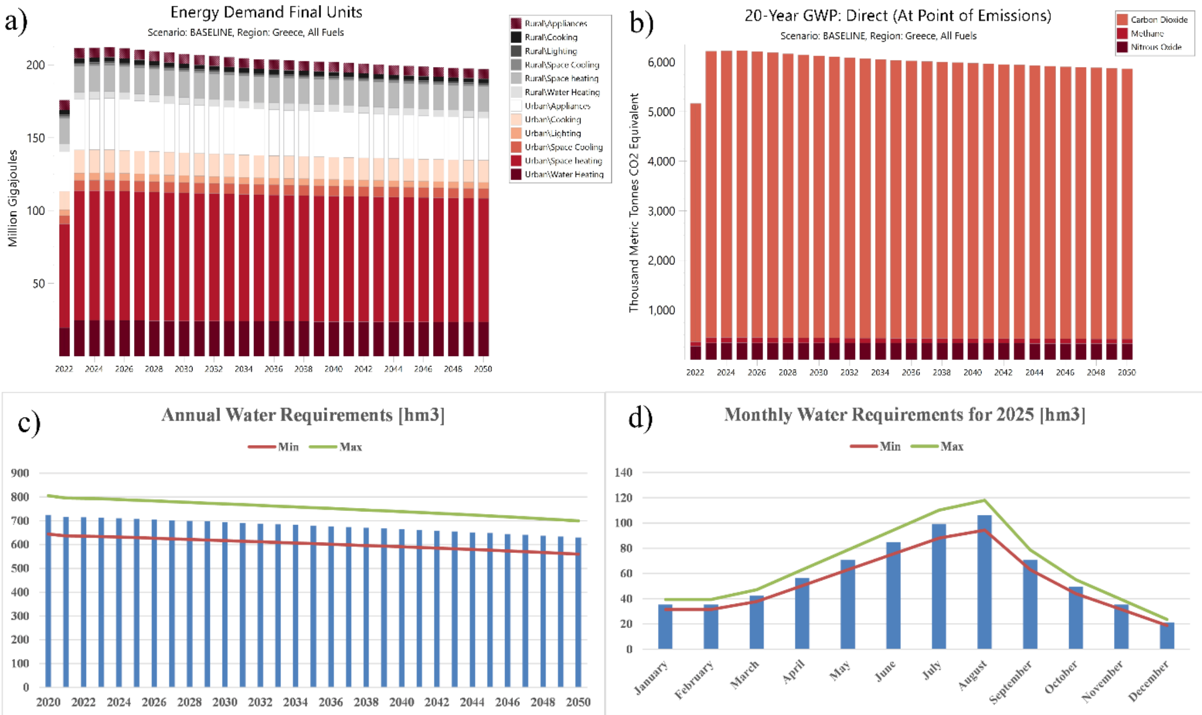

Figure 1. A combined figure for the results of the Baseline scenario by 2050: A) Energy demand; B) Emissions of the main (direct) GHG pollutants – Carbon Dioxide, Methane, and Nitrous Oxide; C) Annual water requirements D) Typical monthly distribution of the water requirements.

The results indicate that the Greek residential sector will maintain its energy demand in high levels under the Baseline scenario (assuming no mitigation and policy measures, and investments in greener fuels and renewables). The decreasing trend of the energy demand over time is primarily driven by the country's shrinking population. In terms of different energy uses, the results highlight the dominance of space heating, water heating, and appliances in both urban and rural settings. This demand structure remains largely unchanged by 2050, and this underscores the challenge of achieving significant energy efficiency gains or behavioral changes in the absence of stronger interventions (i.e., Baseline scenario). Importantly, the urban sector's contribution far outweighs the rural sector, reflecting the ongoing urbanization trend and the concentration of population in urban areas.

Figure (1b) shows the 20-year Global Warming Potential (GWP) of direct GHG emissions. The emissions are dominated by Carbon Dioxide (CO_2), with minor contributions from Methane (CH_4) and Nitrous Oxide (N_2O). Despite some reduction by 2050 (caused by the reduced energy demand, which is driven by the population in this case), the emissions remain substantial, emphasizing the urgency of transitioning to cleaner energy sources, especially for heating and cooking, to meet climate targets.

Figures (1c) and (1d) detail the water requirements, as resulted from the WaterReqGCH model. Annual water demand exhibits a slow but steady decline due to the shrinking population, similarly to the energy demand results. Nevertheless, the gap between minimum and maximum requirements, representing uncertainties such as changes in water transmission, distribution, and use efficiencies, as well as average consumption rates (which can be influenced by market dynamics, education, or climatic variations), remains significant. This highlights the critical need for adaptive water resource management strategies. A critical element supporting such efforts is the knowledge of the seasonal water demand, as shown in Figure (1d). As expected, it peaks during summer months, aligning with higher temperatures, tourists, and increased cooling needs. This seasonal variability places additional stress on water resources, particularly in drought-prone regions.

Together, these results highlight the interdependencies between energy and water in Greece's residential sector. This joint analysis demonstrates that achieving Greece's sustainability and decarbonization goals requires both technological and behavioral changes, alongside policy frameworks that integrate energy and water management to ensure resilience amidst climate uncertainties. Towards this direction, we evaluate the NECP policy, and the results are presented in Figure 2.

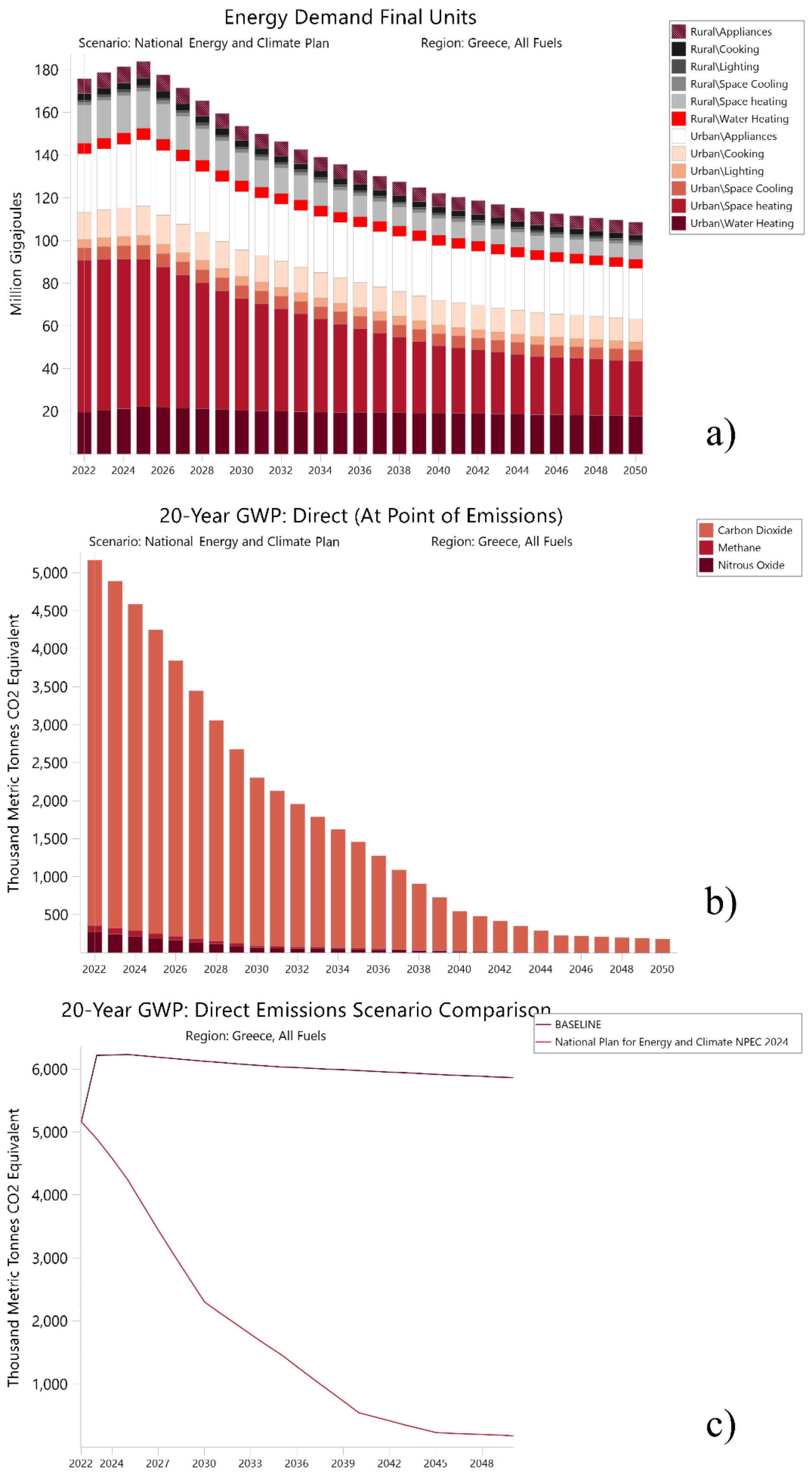

Figure 2. A combined figure for the results of the NECP scenario by 2050: A) Energy demand; B) Emissions of the main (direct) GHG pollutants – Carbon Dioxide, Methane, and Nitrous Oxide; C) Emissions comparison between the Baseline and the NECP.

The energy demand in the NECP scenario exhibits a steady decline over time, from nearly 180 million GJ in 2022 to under 100 million GJ by 2050 (Figure 1a). This trend reflects the influence of energy efficiency measures and programs for buildings, and the adoption of cleaner technologies outlined in the NECP. Moreover, a significant shift in energy consumption patterns is evident, with a "turning point" after 2027: traditional energy-intensive uses, such as water heating and space heating, reduce their shares, while urban appliances maintain more stable levels. The specific shift is going to affect the overall consumption trend, giving a decreasing pattern to the next 25 years that are following that turning point. This reduction highlights the ongoing transition toward efficient devices and modernized urban infrastructures.

Figure (1b) indicates that the GHG emissions (dominated by CO2) decrease substantially, from over 5,000 thousand metric tonnes of CO2 equivalent in 2022 to nearly zero by 2050. In particular, during the first period of NECP's implementation, there is a transition phase, where Natural Gas and petroleum products are slightly replaced by cleaner fuels until 2030. After 2030 the consumption decreases further, since the deployment of renewable fuels is gradually increased, and residential building blocks have incorporated energy saving policies. The reduction of GHG emissions continues then until 2050 with slower rates, since most fossil fuels and Natural Gas are gradually removed completely, according to the NECP. This decline underscores the NECP's effectiveness in mitigating climate impacts from the residential energy consumption side.

This effect is more evident in Figure (1c) where the Baseline scenario and the NECP scenario are compared in terms of their emissions. Under the NECP scenario, emissions sharply decline compared to the Baseline one. By 2050, the NECP strategy achieves near-complete decarbonization, whereas the Baseline has a nearly stable trend (since only population does change). This stark contrast underscores the importance of proactive climate policies and action (as SDG 13 emphasizes).

The results of the WaterReqGCH model under the NECP do not change, as this policy does not assume any interventions at the water sector. The results highlight the role of well-structured policies like the NECP in driving decarbonization. The reduction in energy demand and emissions directly aligns with Greece's commitments under the Paris Agreement and supports several SDGs. The joint analysis of energy and water sectors though, highlights the need to consider complementary policies (like the NECP) for the water sector, and also implement them.

4. Relevance to the SDGs

The LEAP model allows for a comprehensive analysis of energy consumption across the residential sector, its various uses, and fuel types. Also, by simulating also a real-world policy scenario, as a tool, it can identify the effects of such strategies to reduce GHG emissions while promoting energy efficiency. This analysis is crucial for understanding how different assumptions can impact overall emissions and for evaluating the effectiveness of policies aimed at transitioning to cleaner energy sources. The WaterReqGCH model complements the energy analysis of LEAP by providing essential data on the residential water consumption. This offers an additional parameter to consider, which is crucial for a more holistic policy planning. It helps identify trends in water usage, seasonal patterns, assess the sustainability of current practices and challenges (e.g. losses), which can be helpful for proposing measures to enhance water efficiency. This dual approach ensures that both energy and water resources are managed together, which is an opportunity for more sustainable approaches, addressing the interconnected challenges of resource scarcity. By definition, this problem, and the approach followed, along with the insights gained from these models are directly aligned with several SDGs.

First, since the focus here is the residential sector, it is directly connected to SDG 11: Sustainable Cities and Communities. Addressing the residential sector helps make urban and peri-urban areas more sustainable by improving energy and water efficiency and resilience. These outcomes are critical for addressing the challenges of urbanization under SDG 11, ensuring cities are resource-efficient and capable of supporting both growing and decreasing populations while minimizing their ecological footprints (UN, 2015).

Another directly connected SDG is SDG 7: Affordable and Clean Energy. The energy component of the of the LEAP model aligns with SDG 7 by analyzing energy consumption patterns, fuel mixes, and potential increases in renewable energy shares. This alignment with SDG 7 is vital for fostering economic growth while minimizing environmental impacts (IEA, 2024).

Similarly, the water component of the WaterReqGCH model makes the presented approach relevant to SDG 6: Clean Water and Sanitation. By modeling water requirements in conjunction with energy demand, these tools provide valuable evidence for sustainable water management. They ensure that the increasing water needs of the residential sector are known, so it paves the way for checking the availability of water resources, in order to not overexploit them. This logic directly supports the targets under SDG 6 aimed at equitable access to safe water and efficient use of water resources (UN, 2015).

The emissions component of the joint application of LEAP and WaterReqGCH makes the approach also relevant to SDG 13: Climate Action. Assessing GHG emissions in the residential sector contributes to SDG 13 by quantifying the environmental impacts of energy use and per fuel type, providing a detailed assessment. Moreover, it is important to note the ability of the models to evaluate the effectiveness of decarbonization strategies, such as the examined scenario for Greece. These insights support climate mitigation and adaptation efforts (IPCC, 2014; UN, 2015).

The integrated models encourage responsible resource use by exploring or suggesting improvements on energy and water consumption and reducing emissions (such as the scenario simulated for Greece), and this justifies the relevance to the ‘SDG 12: Responsible Consumption and Production’. These actions align with SDG 12’s focus on sustainable consumption patterns and reducing the environmental impacts of resource use (UN, 2015).

Another relevant SDG is SDG 9: Industry, Innovation, and Infrastructure. The use of integrated modelling applications such as the LEAP – WaterReqGCH approach presented, reflects innovation in sustainable infrastructure and systems analysis. These models exemplify how advanced analytical tools can provide useful information for policy evaluation, better planning and implementation of resource-efficient systems, aligning with SDG 9 (UN, 2015).

Last but not least, there is an indirectly link to SDG 3: Good Health and Well-being, as well. The presented models support SDG 3 by outlining opportunities for cleaner energy solutions that improve air quality, reducing health risks associated with air pollution. The simulated GHG emissions and their reduction potential through the explored scenario for Greece is a clear example of this connection. Furthermore, the modelling insights for potentially improved water management also can contribute to public health by ensuring clean water supplies (UN, 2015). These are all fundamental aspects of SDG 3.

At this stage, it is important to note that more alternative runs of the model can be used to test more different scenarios and policies, considering even combined measures. This can further connect the decarbonization efforts with the SDGs mentioned above, or even with additional ones. The base evidence provided by the presented modelling approach can provide critical insights into sustainable resource management, climate action, and public health. These models are instrumental in answering key aspects that are necessary for informed decision-making for policymakers and stakeholders.

5. Concluding Remarks

Integrated modelling approaches, such as the combination of a LEAP model for residential energy demand and emissions with the WaterReqGCH model, provide critical insights into the nexus of energy, water, and climate systems. These models are vital for addressing sustainability challenges, offering evidence-based solutions to improve resource use, reduce GHG emissions, and ensure equitable access to energy and water. Such assessments allow also the exploration of the impact of national plans, and the associated trade-offs to multiple parameters. The relevance of these models and the evaluation of the national policy plans extends to several key SDGs, underscoring their broad applicability.

In reality, the presented application is one of the first attempts to use such integrated modelling insights in Greece. Greece has been slow in adopting scientific evidence into both policymaking and policy evaluation within specific targets. As discussed in the previous section, this approach is also relevant to multiple SDGs, and indicates areas for improvements in terms of resource use efficiency and emissions reduction. That would be crucial to support the country's progress to key SDGs. According to the European Environmental Agency, Greece identified and endorsed eight national priorities for SDG action, giving priority to seven SDGs: 11, 7, 6, 13, 12, 14 and 15

(Papada and Kaliampakos, 2016; 2020). The five first SDGs out of these seven prioritized ones are relevant to the approach presented in this chapter. In terms of the country's progress on these SDGs, although there some encouraging elements, there are still persisting challenges. For example, with respect to SDG 11, the main urban sustainability initiatives focus on energy-efficient housing and thus emissions reduction, public transport improvements, and disaster resilience (Papada and Kaliampakos, 2016). The "Smart, Resilient and Climate Neutral Cities" initiative demonstrates Greece's commitment to enhancing urban sustainability, but the integration of more holistic sustainability strategies into urban planning is crucial for achieving SDG 11 (Hellenic Government, 2024). Focusing more on energy and SDG 7, there is an advance in renewable energy infrastructures (especially wind and solar), but there are persisting challenges in energy efficiency and energy poverty (Streimikiene et al., 2021; Papada and Kaliampakos, 2020). These investments in renewable infrastructure are also relevant to SDG 9. Regarding water and SDG 6, the country faces challenges with managing water resources, exacerbated by climate change, over-extraction, economic and infrastructure mismanagement (Angeli et al., 2020). The environmental aspects of the energy sector, as reflected in SDG 13, are primarily addressed through the NECP targeting significant emissions reductions by 2030 and carbon neutrality by 2050. Despite progress, challenges persist in transitioning from lignite dependence, transition to cleaner fuels, and adapting to climate shocks (Greek Ministry of Environment and Energy, 2024). These decarbonization efforts combating pollution and improving air quality contribute to public health and well-being as well (SDG 3). Finally, by addressing consumption patterns and promoting sustainable practices among businesses and consumers, including the residential sector, Greece supports the objectives of 'responsible consumption and production' outlined in SDG 12 (Streimikiene et al., 2021).

The findings of this research emphasize Greece's potential to transition its residential sector toward a low-carbon future through data-driven policies and sustainable practices, fostering environmental and economic resilience. the complementary nature of the SDGs also highlights the need for complementary policies across all sectors (water in our case), as there is a potential to further reduce consumption and combat water scarcity and competition among users. The implementation of such policies is key for the sustainability transition, and further efforts are needed. For example, even if the NECP is implemented, it seems that there is still a certain amount of emissions (although small) to achieve full decarbonization. So, future efforts should focus on the implementation of such policies, as well as further efforts towards more environmentally friendly urban energy and water systems. Exploring efficient energy technologies, using diverse renewable energy mixes, biofuels or geothermal potential, along with water use efficiency, education and behavioural-targeted measures to consume responsibly, will play also a critical role in the challenging future.

Overall, by addressing challenges related to water management, energy transition, urban sustainability, responsible consumption, climate action, health improvement, and innovation in infrastructure, Greece has the potential to make significant contributions towards a more sustainable future. The integration of holistic assessments and scientifically-supported insights, such as those provided by models like LEAP and WaterReqGCH is a helpful approach for developing infrastructure sustainably, creating targeted measures, and robust policies that can support a sustainable economic growth.

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