D2.3 Impact Assessment

Cool LIFE

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List of Acronyms

CFC	Chlorofluorocarbons
COP	Coefficient of Performance
DR	Diffusion Rates of technology
EEA	European Environment Agency
EED	Energy Efficiency Directive
EEI	Energy Efficiency Improvement
FED	Final Energy Demand
GR	Growth rate of Technology
GWP	Global Warming potential
HCFC	Hydrochlorofluoro carbons
NbS	Nature-based solutions
PED	Primary energy demand
PUED	Practical useful energy demand
SC	Space Cooling
TRL	Technology Readiness level
TUED	Theoretical useful energy demand
UED	Useful energy demand

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Keywords list

- Passive measures
- Active measures
- Space cooling
- Impact assessment
- Final Energy Demand
- GHG emissions

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Executive summary

The Impact Assessment carried out under the CoolLIFE project tackles the rising demand for space cooling across the EU-27, focusing on its implications for the environment, economy, and society. The study evaluates the effectiveness of measures to reduce energy consumption and GHG-emissions for meeting cooling needs such as passive cooling measures and technological improvements in active cooling. Making use of a building stock modelling approach, the study offers a comprehensive analysis of current and prospective scenarios up to 2050. This modelling approach forms the core of our analytical method, enabling projections of space cooling demand and the varied impacts of diverse strategies across different EU member states and sectors.

In the study, we make use of the Invert/EE-Lab model, a bottom-up building stock simulation model that enables projections of space cooling demand and the potential impacts of diverse strategies across different regions and sectors within the EU. This modelling approach incorporated sensitivity to parameter changes and was validated with data from other sources to ensure robustness. While inherent uncertainties in data inputs and parameter sensitivity were acknowledged, the methodologies employed are replicable and scalable, providing a reliable framework for future evaluations. A range of scenarios from business-as-usual to ambitious projections were analyzed to understand the potential outcomes of different policy and technological pathways. These scenarios illustrate possible futures based on the levels of adoption of passive measures and technological innovations, providing insights into their performance under changing climate conditions and informing policy-making.

The findings revealed that integrating high-efficiency passive measures alongside technological advancements could significantly reduce cooling energy demands by up to 55% by 2030 and almost 80% by 2050 compared to a baseline scenario. These strategies are particularly effective in non-residential sectors due to higher baseline energy demands. Moreover, the study highlights the importance of sector-specific approaches, given the varying characteristics and requirements across different regions.

Environmental impacts assessed mainly focused on reductions in greenhouse gas emissions, notably CO2, and NOx-emissions, with strategies outlined potentially mitigating emissions considerably by 2050. We conducted a techno-economic assessment to compare scenarios involving active cooling technology deployment against those with passive cooling measures. Additionally, we analyzed the economic and social impacts of rising cooling demand using the MICAT tool. The economic assessment showed a better payoff of passive measures with an increase in diffusion rates of the technology. The gross added value of the Energy Efficiency Improvement (EEI) investments needed in the best case scenario, which considers both a high adoption rate of passive measures and accelerated uptake of more efficient active devices, were calculated for each MS. Compared to the baseline scenario, it is shown that GDP of the EU-27 region could be increased by close to 6000 Million EUR annually until 2050. This can be translated to an additional employment of an average 124 000 to 300 000 full-time employment years in each year on the EU-27 level. The reduction in air pollution from sustainable cooling solutions has a positive health impact. On the EU-27 level the number of casualties can decrease by 145 deaths per year when the improvements for the year 2050 are implemented. Additionally, 36 600 lost working days can be avoided for the same geographical coverage and year. It is also shown that the distribution of the co-benefits in the different MSs from the EEI actions are different than the energy savings, due to the country specific macro-economics, the fuel mix of electricity production, exposure to pollutants and the healt risks associated with those. It is seen that the health co-benefits have been proven to be relatively higher for Poland, Italy or Germany, compared to their energy savings.

The study underscores the need for robust policies to promote the adoption of energy-efficient cooling technologies and passive cooling measures. Recommendations for policymakers include:

- Incentivizing the adoption of passive measures through financial incentives and supportive regulations.
- Promoting technological innovation and the diffusion of advanced cooling technologies.
- Developing flexible regulatory frameworks that can adapt to new insights and technological advancements.
- Enhancing public awareness and engagement to foster a culture of sustainability and energy efficiency.

The methodologies and findings from the impact assessment study provide a valuable foundation for such ongoing evaluations and should inform future policy adjustments and practical applications Moreover, the results offer a viable starting point for member states to incorporate cooling demands into their national comprehensive assessments of efficient heating and cooling potentials in line with the Energy Efficiency Directive, Art 25. This study highlights the urgency of adopting coordinated actions and policies to manage cooling demands sustainably across the EU, paving the way for achieving broader energy and climate objectives.

1. Introduction

Space Cooling (SC) demands are rising, globally accounting for over 16% of the entire building sector's final electricity consumption, about 2000 TWh/yr worldwide. A 6.5% rise was observed globally in 2021 compared to a 4% annual average since 2000, which is eight times faster than the heating demand [1]. This growth rate is expected to continue in the short and medium runs. These increasing cooling demand patterns highlight the need to prioritize cooling equally in the context of energy planning. Furthermore, unlike heating, space cooling demands are mostly met with electricity-driven appliances, further complicating the development of a discrete decarbonization pathway for the sector. At current rates, space cooling will critically impact the global and European energy demand, but it continues to be largely overlooked. Studies on space cooling are quite scarce, leaving a significant gap in the literature.

The need for cooling in Europe, especially during long heatwaves, is a big problem because of climate change. As per the European Environment Agency (EEA) [2], from 2010 to 2019, the amount of Energy used for cooling in homes tripled in 19 euro-area countries. Although SC only made up 0.4% of all Energy used in homes across the EU in 2019, some countries like Malta, Cyprus, and Greece used a lot more, like 11%, 10%, and 5% respectively. The demand for cooling is expected to keep going up, especially in southern EU countries. Experts think that by 2050, around 8% to 9% of all Energy used in buildings could be for cooling, compared to only 2% in 2012 [2].

The growing SC demand results are primarily driven by global temperature rise, increased affordability of cooling technologies, higher willingness to pay, urbanization, and population growth [3], [4]. As these trends are expected to persist, the demand for cooling is likely to continue increasing. In addition, in the European context, the building stock's heating energy efficiency development and increasing average summer temperatures have further contributed to the rising space cooling demand [5], [6]. Building designs today prioritize preventing heat losses and enhancing winter efficiency. However, this well-intentioned focus can inadvertently create a summer side effect. On warm summer days, these designs obstruct natural heat flows, leading to a surge in the demand for cooling if no counteracting measures are taken. Without the implementation of such counter-measures, the improvements made for winter efficiency may result in increased cooling needs during hotter seasons. Therefore, strategically planned demand reduction measures for heating and cooling are seen as a primary step to control the growth rate of space cooling demand, including optimizing the building renovation measures to meet the optimal settings.

Improvements in cooling efficiency and potential energy savings can be seen from two perspectives. On the one hand, this involves further development of active supply technologies, while on the other hand, it involves the development of passive measures that directly reduce the demand/need for cooling. [7] propose a comprehensive framework to optimize cooling systems using both active and passive measures, aiming to shape sustainable cooling interventions that address socio-economic and environmental challenges. This framework serves as a basis for future research and practical applications in sustainable cooling, emphasizing the urgent need for integrated solutions that balance human comfort with environmental impact.

Improved operating efficiencies of supply technologies can largely contribute to the reduction in the consumption of cooling Energy. The cooling supply at present is primarily electrified and is responsible for the summer peaks in electricity demands. This linkage with electricity demand also makes the decarbonization of cooling highly coupled with the electricity sector's challenges. In terms of supply technology, vapor-compression-based air conditioners currently have global dominance [8], [9]. The continued application of this technology at the same rate as the growing energy demand brings up two potential problems: environmental performance and the additional strain on the electricity load. The International Energy Agency estimates that without any interventions, the growth of air conditioners to supply this space cooling demand will triple by 2050, surpassing 6000 TWh, contributing to over 37% of the global electricity share [10]. In addition, the current air conditioning technologies primarily operate with refrigerants responsible for the release of Chlorofluorocarbons (CFC) and Hydrocholorfluoro carbons (HCFC), which have a known direct effect on the depletion of the ozone layer. Though modern air conditioners have improved their environmental performance [8], the estimated demand they would require to cover in the medium and long run will have significant impacts. The use of refrigerant gases at this scale also threatens to exacerbate global warming by as much as 0.4°C by 2100 [11].

Passive measures in buildings are recognized as viable options for controlling demand and substantially reducing energy consumption, thereby mitigating the spread of active technologies [1]. Integrating passive measures with comprehensive deep energy renovation of building envelopes enhances building resilience, resulting in reduced cooling needs and lower greenhouse gas emissions [2]. Moreover, this approach plays a pivotal role in mitigating the health impacts of climate change and alleviating summer energy poverty. These passive measures could range from simple interventions, like adding blinds to windows, to more complex changes, such as modifying the building structure to accommodate external shading devices. Alternatively, it could involve changing the occupants' behaviour, such as adjusting the cooling system's set temperature or increasing night ventilation when outdoor temperatures allow, which are discussed more in detail in [12]. These nature-based solutions (NbS) are preferable as, unlike active supply technologies, they can significantly reduce cooling demand with no or minimal energy consumption on their own. Shading of buildings is a practical, cost-efficient measure for reducing the space cooling demand in buildings under different climate scenarios [13]. Natural and radiant cooling are also seen as reliable passive measures for demand reduction, in turn contributing to emission reductions and energy savings [14]. [15] demonstrate that applying radiative cooling materials, such as cool roofs and special coatings, can substantially decrease cooling loads by reflecting sunlight and emitting infrared heat with a reduction in electricity for cooling load by 90%. The necessity and extent of these nature-based solutions (NbS) interventions depend on the building's intended use but are largely influenced by its location and the local climate conditions.

The environmental impact of cooling systems is significant, particularly as they pertain to the issues of energy consumption and greenhouse gas emissions. Cooling technologies, including air conditioning and refrigeration, are primarily dependent on hydrofluorocarbons (HFCs), which are potent greenhouse gases. With the rising global temperatures, there is an increasing demand for cooling systems, particularly in developing regions, which subsequently leads to higher emissions of HFCs. This cycle of demand and increased GHG emissions poses serious environmental threats, including global warming and climate change. To combat these negative impacts, strategies such as the adoption of low-global warming potential (GWP) refrigerants, the enhancement of energy efficiencies in cooling systems, and the shift towards renewable energy sources in these technologies are crucial. These measures not only help in reducing the carbon footprint of cooling technologies but also align with global climate commitments aimed at sustainability and environmental protection [16]. The decarbonization of heating and cooling sectors is a critical step towards achieving climate neutrality. The European Environment Agency [17] emphasizes the transition from fossil fuels to renewable energy sources and the adoption of more efficient energy systems as essential strategies. This transition includes integrating advanced technological innovations and regulatory frameworks that encourage lower energy consumption and reduced reliance on high-GWP refrigerants. By doing so, the heating and cooling sectors can significantly diminish their environmental impact, thus contributing to broader environmental goals and adherence to international agreements aimed at climate change mitigation.

In the framework of the CoolLIFE project, we conduct a comprehensive assessment, analysis, and study of the increasing demand for space cooling (SC) and its varied impacts on the environment, economy, and society. This report focuses on evaluating the potential reductions in energy consumption within buildings through the implementation of passive measures aimed at cooling demand reduction. Our study includes an in-depth analysis of SC demand at the building stock level across all EU-27 countries. Utilizing a bottom-up building stock energy demand calculation model, we quantify the useful energy demand (UED) and develop various scenarios to explore the potential uptake of passive measures. By doing so, we examine the resultant effects on SC demand at both European and national levels for the years 2030, 2040, and 2050.

Furthermore, our analysis extends to the assessment of advancements in cooling technologies and the levels of their adoption by building owners. Through this examination, we aim to understand the varying impacts of SC demand reduction on the environment, economy, and society. By evaluating the possible combinations of passive measures uptake, technological improvements, and building owner behaviour, we seek to provide insights into the potential pathways for achieving sustainable cooling practices. Our findings aim to inform policymakers, industry stakeholders, and the public about the implications of different strategies for reducing SC demand and advancing toward a more sustainable future.

Also, under the Energy Efficiency Directive (EU) 2023/1791, Member States are required to perform comprehensive assessments specifically focusing on the efficiency of heating and cooling systems. These assessments are integral to identifying the full potential for enhancing energy efficiency within the cooling sector. They involve evaluating current systems, estimating future cooling demands, and exploring the integration of renewable energy sources and waste heat recovery. The directive emphasizes the need for these assessments to be thorough and align with broader EU energy efficiency goals, ensuring that cooling systems are not only effective but also adaptable to future environmental and regulatory changes [18]. As there is currently no standardized methodology or established best practice for cooling system assessments, we foresee that our approach will provide the member states with a starting point and foundational strategies to navigate and fulfil the directive’s objectives for enhancing cooling system efficiency.

The scenarios and results detailed in this study will be utilized in the CoolLIFE tool's calculation modules for the economic assessment of cooling measures. We plan to further refine and expand upon the scenarios developed here, enhancing the details and accuracy presented in this report. Additionally, this report will serve as the foundational document for developing the datasets for the calculation module. Therefore, additional inputs and updates to the scenarios beyond what is included in this report can be anticipated throughout the CoolLIFE project.

The structure of the report is organized as follows: Chapter 2 details the methodology used in this assessment, providing a comprehensive explanation of the approaches and models employed. Chapter 3 presents a thorough discussion of the results, analyzing the implications of the findings within various scenarios. Chapter 4 concludes with an overview of the key findings, discusses the limitations of the methodologies employed, and offers insights into potential areas for further research.

2. Methodology

The impact assessment carried out in this report builds upon the results of work carried out within the project on Technology and measures [8], focusing on a comprehensive evaluation of Sustainable Consumption (SC) technologies and strategies. This assessment quantifies explicitly the impact of changes in space cooling demand resulting from the uptake of passive measures across environmental, economic, and societal dimensions. The methodology employed in this study is illustrated in **Error! Reference source not found.**, which outlines our systematic approach to understanding and measuring the multifaceted effects of SC technologies. This approach not only assesses direct outcomes such as energy savings and emissions reductions but also explores the broader implications for economic efficiency and social well-being. Through this integrated analysis, we aim to provide a holistic view of the potential benefits and challenges associated with implementing SC technologies in diverse settings.

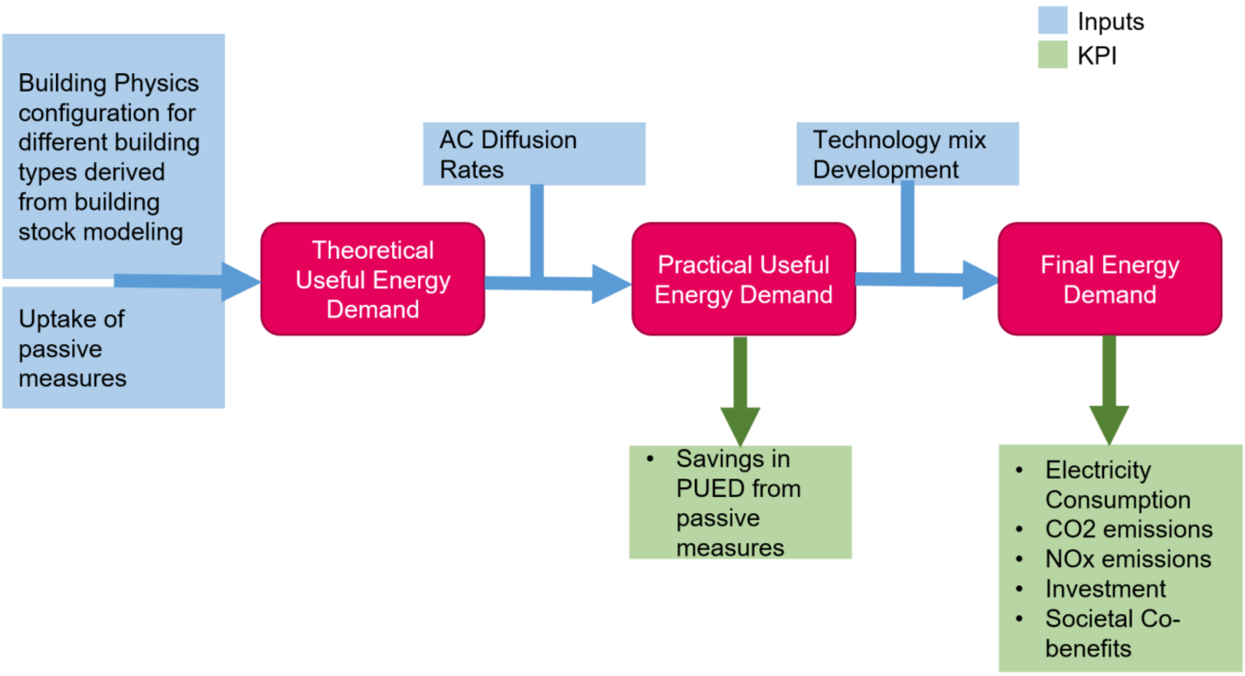


Figure 1. Impact assessment methodology

Given the challenges posed by the scarcity of data on space cooling demand, our methodology is specifically designed to utilize readily accessible open-source datasets. These datasets help us evaluate and understand the patterns of growing demand for cooling across the EU-27 countries. At the national level, we start with the assessment of a bottom-up estimation of the space cooling demand based on the national level building stock distribution for each Member State. For the respective building stock distribution of each country, we configure the building physics parameters to replicate the passive measures. This enables us to estimate the potential energy savings under different scenarios of passive measure uptake.

This configuration serves as the groundwork for calculating the Theoretical Useful Energy Demand (TUED) which can be interpreted as the cooling demand, considering 100% of the built floor area has some space cooling requirements or a 100% diffusion rate of space cooling technologies. With the TUED, we estimate the potential energy savings achievable from the nature-based solutions uptake. Following this, the process incorporates Diffusion Rates of active space cooling, which assess the pace and extent of adoption of active cooling supply technologies in actual market settings. This step is crucial as it translates theoretical potential into practical application, resulting in the Practical Useful Energy Demand. This metric reflects the realistic energy demand for space cooling after considering the market penetration of technologies and measures.

In the subsequent phase of the assessment, we focus on the Final Energy Demand, which indicates the actual energy consumption after the implementation of SC technologies. Here, we consider different rates of technology development and mix of active technologies, acknowledging that advancements in technology can lead to significant changes in energy efficiency, further impacting cooling energy consumption. The methodology tracks the savings accrued from passive measures, notably in electricity consumption, CO2 and NOx emissions reduction, and the overall investment in energy efficiency technologies. Furthermore, it evaluates societal co-benefits such as health improvements and increased productivity resulting from better building environments. This comprehensive approach not only quantifies the direct impacts of SC technologies but also highlights their indirect benefits, providing a holistic view of their overall effectiveness in urban and built environments.

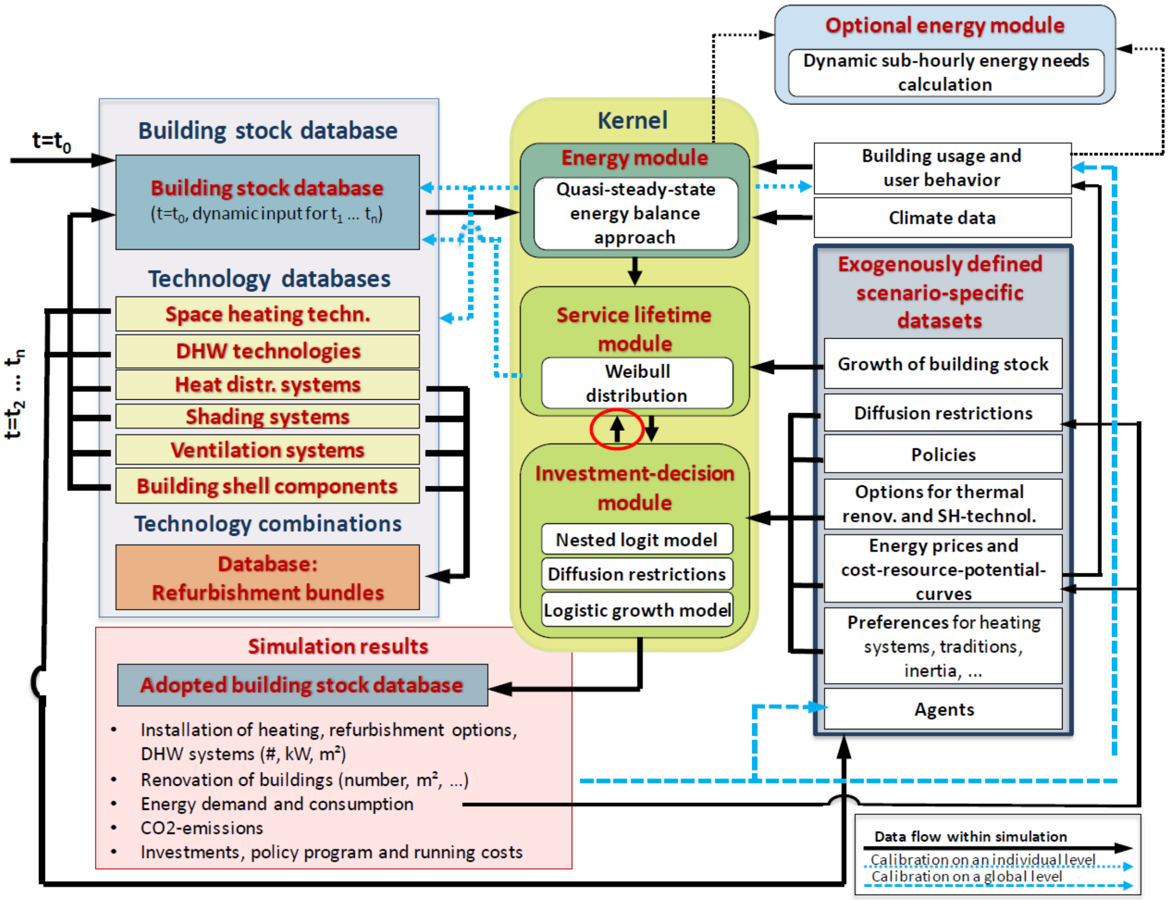
As mentioned above, the overall methodology is implemented for all EU-27 countries. For each country, each input parameter (blue) is adjusted to formulate a baseline, high, and low scenarios. This results in a total of 27 scenarios (all possible combinations per country) per country, where the three levels of demand and the corresponding KPIs are calculated for the years 2022 (base year), 2030, 2040, and 2050.The formulation of each of the scenarios is presented in the respective sections below. This comprehensive approach, employing a diverse array of scenarios, enables us to extensively map out and analyze potential demand and identify a broad spectrum of savings opportunities associated with Sustainable Consumption (SC) technologies.

2.1. Modelling the Theoretical Useful Cooling Demand

To accurately estimate the theoretical useful cooling demand, it is essential to consider a combination of factors that influence a building's cooling needs. These include the building's physical properties, its geographic location, and the behaviour of its occupants. We employ a bottom-up energy demand estimation approach using the Invert/EE-Lab model to comprehensively assess the space cooling demand under varying conditions.

The Invert/EE-Lab is a techno-socio-economic bottom-up building stock model that simulates energy-related investment decisions in buildings, specifically focusing on space heating, hot water generation, and space cooling end-users [19]. Invert/EE-Lab is based on a highly disaggregated description of the building stocks in the different countries of the EU (+ Iceland, Norway, Switzerland, UK), including building type, age, state of renovation, existing heating systems, user structure as well as regional elements such as availability of energy infrastructure, e.g., district heating or natural gas on a sub-country level.

The Invert/EE-Lab model simulates investment decisions in the building shell and the heat supply and distribution systems through a combination of a discrete choice approach and technology diffusion theory. It is a myopic simulation tool that considers the effects of different policy decisions, such as economic incentives, research, and technology development, on the total energy demand, energy carrier mix, reductions, and costs for included end-uses [20]. The model has been involved in over 40 projects in EU-27+ countries for over ten years and continues to be a valuable tool for policymakers, researchers, and industry professionals in the field of energy efficiency and building technology [21], [22].



Source: [22]

Figure 2. Overview structure of Invert/EE-Lab

The Invert/EE-Lab model is designed to estimate the theoretical useful energy demand at a granular level, taking into account each country's building stock and further breaking it down by region. In addition to the calculation of the energy needs, the model also calculates the most advantageous timing for implementing renovation measures across different building stocks. This is critical for planning long-term energy reduction strategies effectively. In this approach, we adjust the input settings of the model so that building shell modifications also accommodate the implementation of the passive cooling measures. This would mean that any energy renovation of a building also includes the inclusion of passive energy reduction appliances. By incorporating these passive measures, the model can more accurately predict how changes to the building's physical structure will impact energy efficiency. Additionally, these settings help simulate the effect of various renovation strategies on energy demand. This includes understanding how insulation improvements, window replacements, and other building envelope enhancements can reduce the need for active heating and cooling, thereby lowering overall energy consumption.

Scenario Definition:

The scenario definition here includes the uptake of passive cooling measures on a building stock level. Initially, to account for the geographical variations in the effectiveness of these passive measures, we have categorized the EU-27 countries into two groups: the Mediterranean and the Rest. The Mediterranean category encompasses all the countries in the Mediterranean region of the EU-27, while the Rest category includes the remaining countries in central and northern Europe.

Subsequently, we identified the key parameters that influence energy demand and which can be effectively altered through the implementation of various passive measures. Drawing on the insights from [8], our approach involves integrating these specific passive measures into the model. This integration allows us to more accurately simulate their impact on reducing energy demand across the different regional categories defined earlier. By structuring the input in this manner, we ensure that the model's output more realistically reflects the potential energy savings that these passive measures can achieve under varying geographical and climatic conditions.

Table 1. Passive Measures based on replicated [8] in the scenarios

Measure	TRL	Savings* *Range of savings are presented as reference and not used calculations in this report
Blinds	9	5% to 15% compared to buildings without shading devices
Drapes (automated)	7 to 9	10% to 20% compared to buildings with manual drapes
Drapes	9	5% to 20% compared to buildings without shading devices
Screens (automated)	7 to 9	15% to 30% compared to buildings with manual screens
Screens	7 to 9	10% to 25% compared to buildings without shading devices
Overhang	7 to 9	15% to 30% compared to buildings without shading devices
Ventilated roof	7 to 9	30% compared to buildings with traditional roofs
Ventilated facade	7 to 9	5% to 15%
Scoop cross ventilation	7 to 9	5% to 20%
Double Skin Facade (DSF)	6 to 8	Up to 10% compared to single-skin facades
Ceiling fan	9	Up to 50% of energy savings on the cooling load
Window trickle vents	3 to 5	n.a.
Thermal mass	7 to 9	5% to 20%

In our analysis, we have devised two distinct scenarios to evaluate different levels of adoption of passive building measures across various national building stocks. These scenarios are defined as "high-efficiency" and "moderate-efficiency," each designed to reflect a range of potential outcomes based on the extent to which passive measures are implemented.

The "high-efficiency" scenario represents a situation where passive measures are widely adopted and optimized for maximum energy reduction. This scenario anticipates a significant decrease in energy demand due to the effectiveness of the measures implemented. The "moderate-efficiency" scenario assumes a more modest uptake of passive measures, resulting in a lower reduction in energy demand. Common to both scenarios are interventions such as shading devices, improved ventilation systems, and behavioural changes aimed at reducing energy consumption.

Both scenarios incorporate passive measures, which are crucial for reducing dependency on active heating and cooling systems and thereby decreasing overall energy consumption. The measures considered include:

- *Shading: Installation of physical barriers to reduce solar gain in buildings during warmer months and to minimize heat loss during cooler periods.*
- *Ventilation: Enhancements to natural and mechanical ventilation systems to improve air quality and reduce the need for air conditioning.*
- *Behavioural Changes: Encouragement of practices such as adjusting thermostat settings and reducing reliance on mechanical heating and cooling systems.*

Due to the constraints of our model, which does not allow for the identification of specific passive measures based solely on parameter combinations, we have adopted a generalized approach. We assume a representative set of parameter combinations for each passive measure, thereby approximating their collective impact on energy demand within the model. This approximation enables us to integrate these measures into our scenario analyses and provide a more comprehensive understanding of their potential to improve energy efficiency across building stocks. This methodological approach ensures that our model can reflect the diverse impacts of different passive strategies and provide actionable insights into their effectiveness at a national scale. The definitions of these measures are available in the Table 2.

Table 2. Passive measure uptake scenario definition

Parameter	Definition	Moderate Efficiency Scenario	High-Efficiency Scenario
Shading activation	Activation of shading devices for the south-facing facade	Manual or time-controlled	Radiation dependent control
Window shading	Share of windows shading on south-facing windows	Low shares of shading devices	High shares of shading devices
g-value	Window solar transmittance	Higher transmittance	Lower transmittance
Z factor	Shading reduction factor	Higher reduction factor	Lower reduction factor
Night Ventilation	Rates of occupant inforced night ventilation	Low increase in rates of ventilation	High increase in rates of ventilation
Indoor Setpoint Temperature	Cooling setpoint temperature	Low increase in rates of ventilation	High increase in rates of ventilation
Thermal Capacity of building	Building properties	Low	High

The definition of the building envelope parameters as per [23] is presented below, along with details on our interpretation of the values to represent the replication of the passive measures. The definitions of the parameters from [23] can be generalized for all countries.

Shading Activation (a_ms_c) factor: The shading activation factor measures the effectiveness of window shading devices based on their inclination angles. This factor quantifies the extent of sun protection provided by these devices, ranging from 0 to 1, where 0 indicates no solar protection and 1 represents complete solar protection.

The shading activation factor can be thought of as the proportion of external shading devices installed on a building's facade, oriented in a specific direction. The effectiveness of these shading devices varies based on their control mechanisms:

i) Time or Manual Control: This variant involves human intervention for operation. Shading devices are adjusted manually or set to operate at specific times. Due to the manual nature of these adjustments, the level of solar protection is generally lower compared to automated systems.

ii) Radiation-dependent Control: This automated approach adjusts the shading devices in response to solar radiation levels. It ensures optimal sun protection because the adjustments are continuous and based on real-time solar intensity, providing higher levels of protection even with the same window orientations and settings.

This structured approach to shading enables buildings to achieve more effective and efficient solar protection tailored to the specific conditions and orientations of each building.

The shading activation factor is applied to all directional facades of a building. Typically, the implementation of shading on southern facades is more extensive due to higher solar exposure, and this has been accurately incorporated into our model. Additionally, shading rates are generally higher in Mediterranean countries compared to Northern Europe due to the former's stronger solar intensity. This regional variation has been fully integrated into the model to reflect realistic sun protection measures across different geographic locations. Details of the exact values for each country of the scenario definition are available in detail in Annex 6.1.

Window shading factor: The window shading factor in our model is defined as the proportion of windows equipped with shading devices in a building. We assign different shading shares to the windows on each of the four façade directions—north, south, east, and west. To enhance realism in our model, we also adjust these shading shares based on the building's geographical location. Typically, buildings in southern countries are modelled with a higher percentage of window shading compared to those in northern countries due to stronger sunlight exposure. Also, in the scenarios, the rate of increase of shading devices in the southern countries is higher than those in the north. Moreover, windows facing south generally have a higher proportion of shading devices than those facing other directions, reflecting their greater exposure to the sun.

g-value: The g-value, or solar heat gain coefficient, is a critical parameter that determines the amount of heat transferred through windows. It represents the fraction of incident solar radiation that is admitted through a window—this includes both the solar radiation directly transmitted and the radiation absorbed and then released inward [24]. To analyze the impact on a building's cooling energy requirements, we model improvements to the g-value of windows. This modelling defines the window g-value according to the type of window glass used, enabling us to assess how modifications to the window specifications can influence the building's thermal performance.

Table 3. Window g-values and types of glasses

Type of Glazing	g-Value
Single Glazing	g = 0.75 - 0.87
Double Glazing low emissivity	g = 0.65 - 0.70
Double-Pane Thermal Insulation	g = 0.52 - 0.65
Triple-Pane Thermal Insulation	g = 0.38 - 0.55
Glass Blocks / Wire Glass	g = 0.60
Sun Protection Glazing	g = 0.25 - 0.50

Source: [23]

For our scenarios, we assume the improvements in the window as given below:

Table 4. g-value definitions for passive measure uptake scenarios

	Moderate	High
Mediterranean Region	Double Glazing low emissivity	Solar Protection Glazing
Rest	Triple-Pane Thermal Insulation	Solar Protection Glazing

z-factor: Another important parameter we consider when assessing window shading effectiveness is the shading reduction factor, denoted as the z-factor. This factor is crucial for determining how effectively a shading device can modify the g-value, which measures the amount of solar heat gained through a window.

The z-factor quantifies the efficiency of various shading devices in reducing the amount of solar radiation that enters a building. It adjusts the g-value to reflect the reduced heat gain when a specific shading device is used. By incorporating the z-factor into our calculations, we can more accurately assess the actual effectiveness of different sun protection devices. This allows evaluation of their impact on indoor temperatures, enhancing our ability to create comfortable indoor environments while potentially reducing the need for air conditioning.

The z-factor varies depending on the type of sun protection device and the original g-value of the window glazing, as seen Table 5. The tables shows the variations in z factor for different sun protection devices based on the g-values of the window. Understanding these variations helps us tailor our choice of shading solutions to maximize thermal comfort and energy efficiency in buildings.

Table 5. z-factor values for different shading devices

Sun Protection Device	g-value	Z factor 0,70	0.50	0.24
External Venetian Blind		0.15	0.15	0.24
External Awning		0.25	0.25	0.36
Internal Venetian Blind		0.70	0.70	0.88
Roller Blind		0.73	0.73	0.88
Highly reflective inner screen		0.48	0.48	0.80
No Shading		1.00	1.00	1.00

For our scenarios, we assume the improvements in the z-factor as given below:

Table 6. Z-factor uptake for passive measures

	Moderate	High
Mediterranean Region	Highly reflective inner screen	External Venetian Blind
Rest	Roller Blind	External Venetian Blind

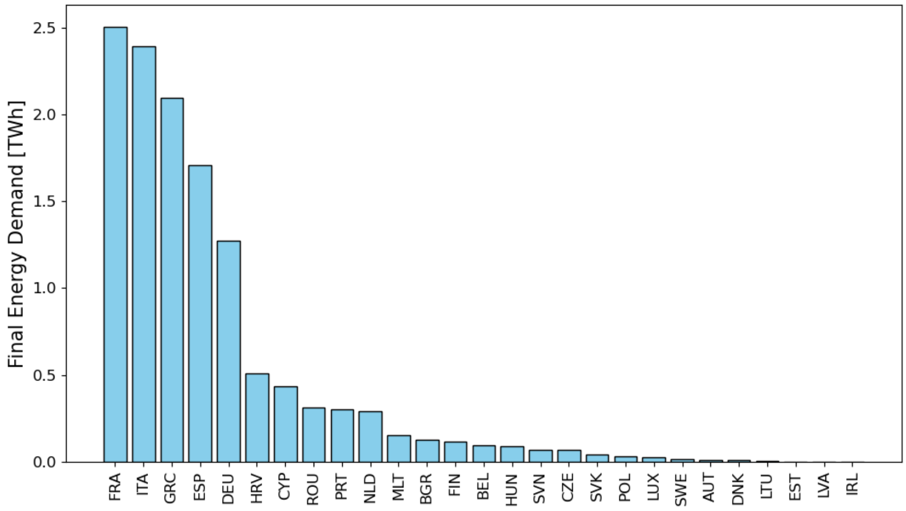
Night Ventilation: The model inputs include the night ventilation rate, which reflects the air circulation rate during the night. This parameter corresponds to the practice of opening windows at night to leverage cooler temperatures to reduce building cooling needs. We associate this parameter with occupant behaviour, although generalizing this behaviour at a national level involves approximations. For our analysis, we use standardized, average rates applicable across all countries. More detailed assessments of the behavioural aspects are conducted within the scope of the project in [12]. Additionally, we implement higher rates of night ventilation in northern countries than in southern countries in both scenarios. This adjustment is made because high-night ventilation in southern countries can increase demand due to warmer ambient temperatures at night.

Indoor setpoint temperature: We also incorporate changes in the indoor set temperature—the threshold temperature at which cooling units activate—as a crucial user behaviour change parameter. We set higher temperature thresholds for northern countries and lower ones for southern countries, aligning with regional comfort needs. For simplicity, we assume uniform set temperature values across each country, although we recognize that there are sector-specific variations. Incorporating these variations would significantly complicate the model. By maintaining a straightforward approach, we can deliver realistic average results without the added complexity.

2.2. Estimating Practical Useful Energy Demand

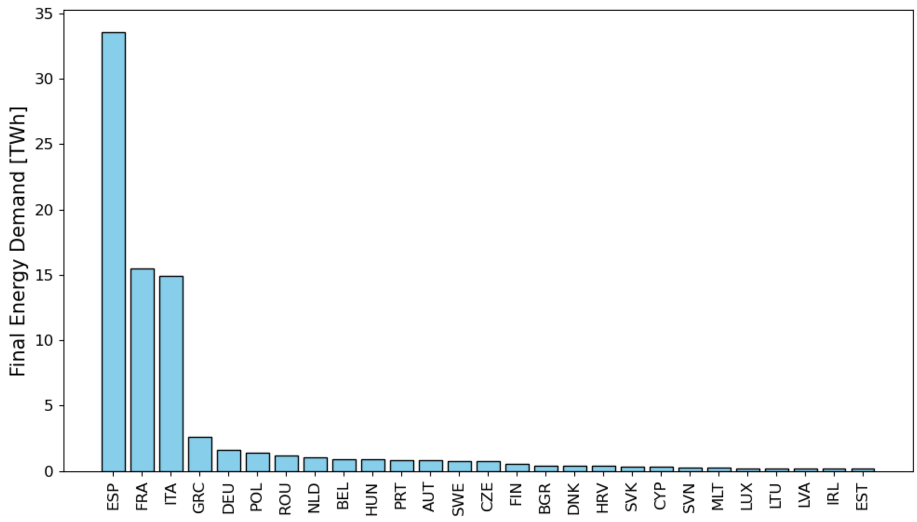
As mentioned in the section above, the theoretical useful energy demand calculated by the invert model assumes that **active cooling is present in more or less all buildings,** which is not the case in Europe. To better understand the actual cooling needs of buildings, we introduce the concept of Practical Useful Energy Demand (PUED). We follow specific steps to estimate this demand at the national level, aiming for a more clear picture of real-world energy requirements.

Data acquisition formed the foundation of our analysis. We obtained historical data for residential cooling demand from the EUROSTAT database [25] (Figure 3), which provides comprehensive statistics for European countries. For the non-residential sector, due to data availability limitations, we relied on the datasets acquired from a European Commission Study [26] (Figure 4). Also, in cases where EUROSTAT data were unavailable, we utilized the Comission datasets for consistency. Data on the Final Energy Demand was available from both of these reference sources.



Source: [25]

Figure 3. Final Energy Demand for Space Cooling in Residential Buildings, by EU Member State, 2021



Source: [26]

Figure 4. Final energy Demand for space cooling in non-residential buildings, by the member state, 2021

Using the historical SC Final Energy Demand (FED) growth rates from the Eurostat data, we estimated projections for 2030,2040 and 2050 (**Equation 1**). These projected PFED from **Equation 1**. These values show demand development based on the historical demand pattern if no interventions were taken. These scenarios are then used for the development of the practical, useful energy demand and, thereon, the final energy demand for the different scenarios.

We convert the Invert results of the Theoretical Useful Energy Demand (TUED) for both residential and non-residential sectors to Theoretical Final Energy Demand (TFED) using country-specific Coefficients of Performance (COPs) identified from the RES Cooling dataset (Equation 2). The national average COPs were again obtained from [26].

$$PFED_{r,y} = PFED_{r,y_o} * [1 + (y - y_0) * GR_r]$$ **Equation 1**

where,

$\boldsymbol{PFED_{r,y}}$	Practical Final Energy demand projection based on reference data
$PFED_{r,y_o}$	Practical final energy demand for 2022
y	Years
GR_r	Historical annual growth rate of active cooling based on data availability per country

$$\boldsymbol{TFED_y = \frac{TUED_y}{COP}}$$ **Equation 2**

$TFED_y$ Theoretical Final Energy demand projection based on reference data

$TUED_y$ Theoretical final energy demand for 2022

COP Average National Coefficient of Performance of SC Technologies

Equation 3

$$DR_{r,y} = \frac{PFED_{r,y}}{TFED_y}$$

$DR_{r,y}$ Baseline diffusion rates based on year y

Now, using the FED from the reference datasets (Eurostat for residential and RES Cooling for non-residential), we estimate the baseline diffusion rates of active space cooling for the given years from **Equation 3**. These diffusion rates are defined as the share of buildings where the energy needs for space cooling are covered with active systems.

Following this, based on the baseline diffusion rates, two scenarios were considered: moderate and higher uptake of space cooling technologies. The definitions of the uptake scenarios are as per the tables below.

Table 7. Active cooling diffusion scenarios

Active cooling diffusion scenario	Moderate diffusion	High diffusion
Category Mediterranean	5% increase in diffusion rates compared to the Baseline	15% increase in diffusion rates compared to the Baseline
Category Rest	2% increase in the diffusion rates compared to the Baseline	10% increase in the diffusion rates compared to the Baseline

$$\boldsymbol{DR_{s,y} = DR_{r,y} + DGR_{s,y}}$$

Equation 4

$DR_{s,y}$ Diffusion rate in uptake scenario S for year y

$\boldsymbol{DGR_{s,y}}$ Diffusion growth rate in scenario S for year y

Utilizing the scenario diffusion rates, we estimated the average Practical Final Energy Demand for each country for each year. Again, making use of the average national COP, we convert the average PFED to Practical Useful Energy

Demand Equation 5. This finally gives us the value of the useful space cooling needs for the building stock in all EU-27 countries.

$$\boldsymbol{PUED_{y,s}} = \frac{\boldsymbol{PFED_{y,s}}}{\boldsymbol{COP}}$$ **Equation 5**

$PU\boldsymbol{ED}_{y,s}$ Practical Useful Energy Demand for a given combination of passive measure and cooling technology uptake

2.3. Estimating the final energy demand

The subsequent stage in our methodology involves assessing the final energy demand, which focuses on estimating electricity consumption for cooling technology supply. This estimation is predominantly influenced by the efficiency of cooling supply technologies. However, due to the diverse range of available technologies and country-specific regulations governing their use, we do not specifically consider individual technologies. Instead, we factor in the average performance efficiency of these technologies to ensure a straightforward approach while maintaining the consistency of our results.

In the baseline scenario, we derive the average national Coefficient of Performance (COP) from [26] and utilize it to calculate the final energy demand. Additionally, we formulate two alternative scenarios: one reflecting high technology development and the other representing moderate technology development. In the high technology development scenario, we anticipate a significant improvement in the efficiency of available cooling technologies compared to the Baseline, while in the moderate technology scenario", rates higher than the Baseline are assessed. By considering these scenario configurations, we can generate a range of electricity demand estimates for each country. This approach allows us to capture the potential variability in cooling energy requirements under different levels of technology advancement, providing valuable insights for energy planning and policy formulation.

2.4. Determining the KPIs

The primary aim of this report is to understand the impact of cooling demand on Energy, the environment, the economy, and society. To effectively quantify these impacts, we establish key performance indicators (KPIs) for assessment.

2.4.1. Energy and Environmental Impacts

To understand the impact of passive measures, we look into the savings potential both at the national and EU levels. By analyzing the implementation of passive measures, we aim to identify the scope of potential savings, considering both useful and final energy demand. In addition, the environmental assessment constitutes a pivotal aspect of our study, wherein we calculate CO2 and NOX emissions. For the emission calculation, adhering to a 2050 net-zero emission pathway, we look into the potential greenhouse gas emissions in 2030 and 2040 under various scenarios of passive measure uptake, diffusion rates, and technological development. For the estimation of emissions in the cooling sector, we make use of GHG emissions data from [27] and [28], which provide emissions on the national level against the consumption of electricity.

To understand the impacts of the passive measures, we evaluate the savings offered by the implementation of the passive measures at the national and EU levels. With this, we try to identify the extent of potential savings. The savings are available in terms of both useful and final energy demand.

For the environmental assessment, we calculate the CO2 and NOX emissions. Taking a 2050 net zero emission pathway, we observe the potential GHG emissions in 2030 and 2040 under the different scenarios of passive measure uptake, diffusion rates, and the development of the technologies.

2.4.2. Techno-Economic Feasibility Assessment

In addition to considering environmental impacts, we also examine the economic aspects of various measures and technologies. By estimating the costs of implementation, we can understand the economic feasibility of different approaches. For each demand scenario assessed in the study, we estimate the national-level implementation costs of both active and passive measures.

From this, we calculate the levelized cost of cooling for active supply technologies and the unit cost of savings for passive measures. These calculations help us compare the potential demand reduction and supply efficiency of each approach. The results could then be used to identify the best combination of passive measures and active cooling technologies for policy development.

2.4.3. Economic and Social Impacts

The economic and social impacts stemming from the investments for installing energy saving measures in the building stock and the energy saved through the above detailed energy efficiency improvement have been calculated. The calculation is based on the methodology and framework of the MICAT project, using the MICATool for social indicators, and applying the methodology of the economic indicators developed within the confines of the project [29], [30], [31]. For more detailed information on the of co-benefits and multiple impacts and their quantification methods, please see deliverable D3.3 Multiple, Socioeconomic Impacts of Sustainable Space Cooling.

From the multiple scenarios assessed in the previous sections, the impact of the sustainable SC measures applied and technological changes implemented have been calculated for the scenario that provides the highest energy savings in the building stock. The calculation for the "High-Efficiency" Scenario that represents a situation where passive measures are widely adopted and optimized for maximum energy reduction, together with the Accelerated

Efficiency Scenario which considers a moderate uptake of technologies and rapid improvements in technology efficiency.

2.4.3.1. Economic Impacts

Economic impacts on GDP have been calculated on country levels based on the previous results. Based on the renovated building stock and the remaining energy demand, investment costs needed to reach the renovation rate are been defined in the analyzed years (2030, 2040, 2050) of the selected scenario. Annual investment costs (CAPEX) have been calculated for both installation of passive measures and for the difference in the investments to reach the number of active devices within the building stock. For the lifetime of passive measures, Medium long lifetimes have been considered, as these measures consist of a combination of several interventions: envelope upgrades, improvement of thermal mass, and also behavioural changes, i.e. thermostat setpoints and night ventilation. Thus within the given range of the CEN-lifetimes, 15-years lifetime has been considered [32] For the active measures a lifetime of 12 years was used in line with the suggestions of the MICAT tool and the Lifetime of equipment in the split and multisplit category, as defined in D2.1. Taxonomy of space cooling technologies and measures. After the lifetime of the given measure, it is considered, that to maintain the same level of energy savings, additional investments are needed.

For each country the average additional annual investments for the three periods (2021-2030; 2031-2040;2041-2050) and two scenarios were calculated, and compared with the reference scenario for both active and passive measures. using these values, the effect on the GDP has been calculated. The methodological steps are based on the methodology developed in MICAT [30] . Using the investment expenditure by type of energy saving measure as an input, the GDP impact is determined using the Gross Value Added (GVA) multipliers, representing the total demand that will be generated in the economy by 1 m. € of additional final demand of a specific sector. In the next step, sectoral allocation of the GVA to each energy saving measure is done, by multiplying by the respective share of each economic activity within the sector with the coefficient representing sectoral allocation share of energy saving investments. As a final step, the economy-wide GDP generation is estimated by applying the level of expenditure by type of measure with the GVA effect generated in the total economy by 1 m€ expenditure.

Two indicators are calculated: impact on GDP expressed in m€ and additional employment, expressed in additional full-time employment years.

The calculation is done separately for active and passive measures, as the GDP and employment effect depends on the types of measures implemented.

2.4.3.2. Social impacts

Energy Efficiency Improvement (EEI) actions can have multiple social benefits as detailed in the literature, summarized in D3.3, section 4. For example, reduction of heat related mortality and morbidity, alleviation of energy poverty, improved productivity due to thermal comfort. However, the field of quantification of these benefits as multiple impacts is yet focusing on the social aspects of space heating, with limited applicability to the summer thermal conditions and the space cooling domain. While evidence exists showing health related benefits of sustainable space cooling on an empirical level, the quantification methodologies of these on national levels are still yet to be developed. Consequently, as the development of these methodologies would require research, involving long-term, large-scale data collection and analysis beyond the scope of this project, the quantification of the social effects of sustainable space cooling solutions is restricted to the benefits that arise from reduction in building energy use.

The quantified health impacts associated to energy savings are due to the reduction of air pollution-related mortality and morbidity, which is caused by local air pollutants (SO2, NOx, primary PM2.5) that are typically emitted in combustion processes related to energy. Reducing energy use hence has a positive effect on the air-quality and the inhabitants health. Although space cooling energy demand reduction considers electricity as final energy, each country has a different electricity mix that contains some energy carriers using combustion technologies (gas, coal, wood). The quantification method developed in MICAT [33] relies on the eventual impacts of PM2.5 concentrations following a standard methodology and parametrization developed for the Global Burden of Diseases studies and the World Health Organization. Country specific values in the calculation are based on IIASA's GAINS model, taking air pollution reductions, national health data, and other factors into account. Two indicators are retrieved using the MICATool: *Air pollution mortality* expressed in reduction of casualties and *Avoided lost working days due to air pollution* expressed in avoided absence days.

Within the calculations the inputs consider 100% electricity among the affected energy mix. As the residential and tertiary sector have different consumption energy mix per country, the impacts of annual electricity savings were calculated separately for these two sectors.

2.4.3.3. Assumptions and limitations

The sectoral allocation tables used, that are given within MICAT, were developed by grouping similar measures that create comparable multiple impacts. For the investment expenditures of this impact assessment of sustainable space cooling technologies and measures, the investment costs for the passive measures were considered as Building envelope improvements, while the expenditures in active cooling are considered as Electric appliances. Behavioral aspects are not considered separately, but as part of the passive measures.

The methodology considers only the GVA impacts from the generated additional demand, but does not assume any other structural changes, or effects of changes in income and prices or the effects on trade balance due to changes in energy imports and exports [29].

The energy savings calculated in the previous sections are customized to the space cooling sector. The baseline assumptions in MICAT are based on the EU Reference Scenario 2020, considering the future trends of energy use through other sectors as well.

Additionally, the methodology accounts for energy savings on an annual basis, which does not take into account the seasonal differences in energy production and energy demand. Hence, the health benefits from reduction of air pollution due to electricity generation for space cooling might be overestimated, as this simplification cannot account for the seasonal variations of the exposure to pollutants.

3. Results and Discussion

3.1. Useful Energy Demand

3.1.1. Theoretical Useful Energy Demand

The theoretical useful energy demand, as defined in the section above, indicates the cooling demand, considering 100% of the built floor area has some space cooling requirements or a 100% diffusion rate of space cooling technologies. The results presented below are the calculations from the Invert Model for the different passive measure uptake scenarios defined in section 2.1.

In the baseline scenario, where no passive measures are implemented, the cooling demand is at its highest. This scenario excludes any form of shading or behavioural changes, which leads to a continuous increase in demand. This rise is primarily driven by escalating ambient temperatures due to climate change coupled with an increase in the building stock per country. The moderate scenario introduces passive measures with lower demand reduction potential. While these measures are less effective, they still contribute to a noticeable decrease in energy consumption. The adoption of basic shading solutions and initial behavioural changes helps mitigate the otherwise rising trend in cooling demand. Conversely, the high-efficiency scenario applies the most potent passive measures available, resulting in significant energy savings. Here, demand reductions range between 50-55% at the European level. The year 2030 marks a pivotal point where substantial reductions are recorded, primarily due to the strategic implementation of advanced behavioral adaptations and the installation of shading technologies during building renovations.

Starting in 2030, behavior change implementation is modeled to reduce energy consumption. This leads to a sudden drop in energy use in 2030, followed by a slower rate of reduction in the following years. Also post-2030, the rate of demand reduction begins to taper as fewer buildings are left that benefit significantly from the implemented passive measures. At this stage, the emphasis shifts towards sustaining the efficiency gains achieved and exploring further technological advancements or innovative strategies to continuously lower energy demand amidst progressing climate change and urban development challenges. These can be observed in Figure 5 & Figure 6.

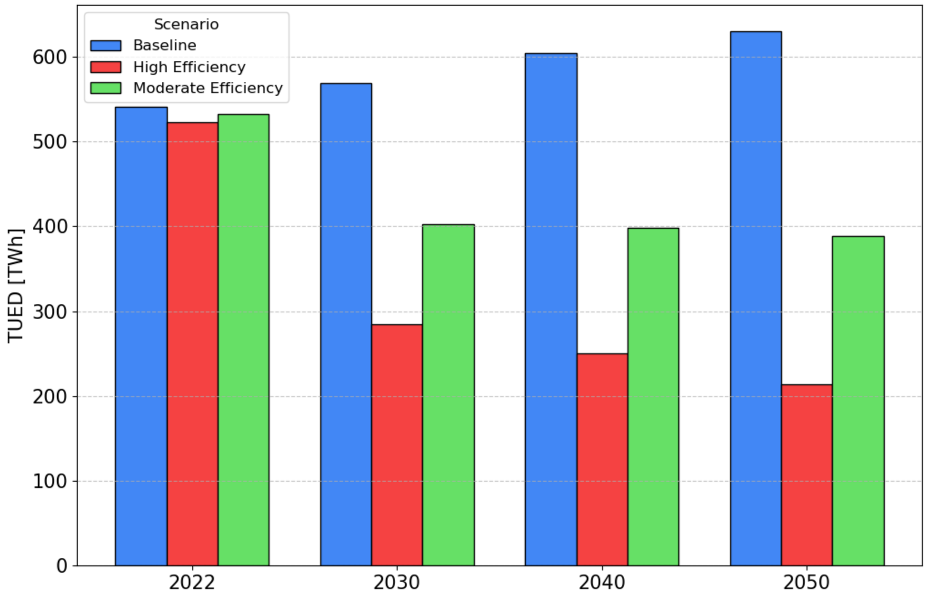


Figure 5. Theoretical Useful Energy Demand EU-27 Residential

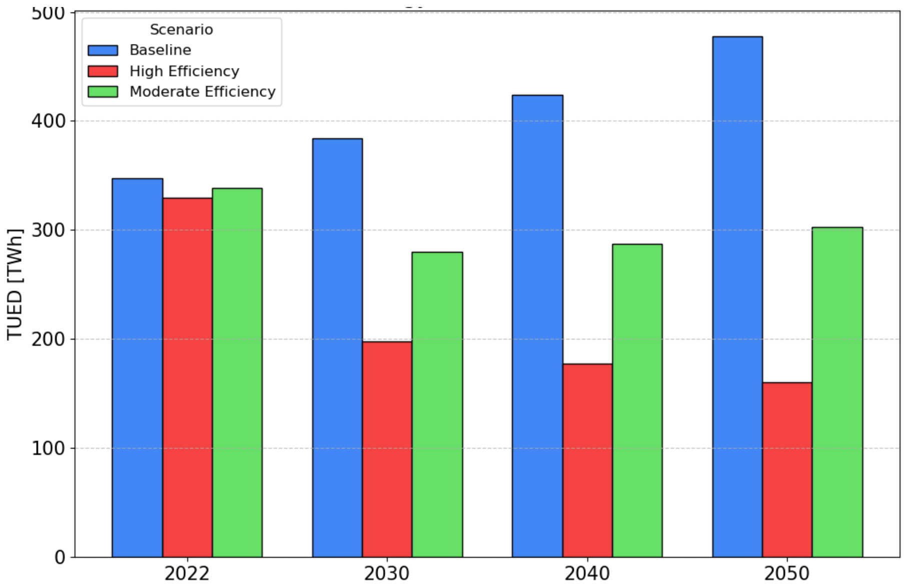


Figure 6. Theoretical Useful Energy Demand EU – 27 Non-Residential

The impact of passive measures on both residential and non-residential sectors shows consistent reduction patterns across Europe. However, due to the significant cooling demand and higher rates of technology diffusion in the non-residential sector, the effects of passive measures are more pronounced in this context. This highlights the substantial influence of passive strategies in mitigating energy use where the demand and adoption rates are greater.

However, the reliability of the Invert model's results must be considered with an understanding of the associated uncertainties, which are primarily due to its heavy reliance on input data and parameters. These uncertainties stem from multiple sources: the quality and completeness of building characteristics and techno-economic data of technologies, as well as future energy prices and interest rates. Moreover, the interactions between various model parameters complicate predictions; these interactions are often non-linear and highly sensitive to changes in external conditions.

To ensure the results from these scenarios are robust and applicable for further development of the CoolLIFE tool and other policy-making processes, we plan to conduct a sensitivity analysis. This will be performed over the phase of the development of the CoolIFE tool. This analysis will help assess the model's accuracy and refine its utility for informing sound policy decisions.

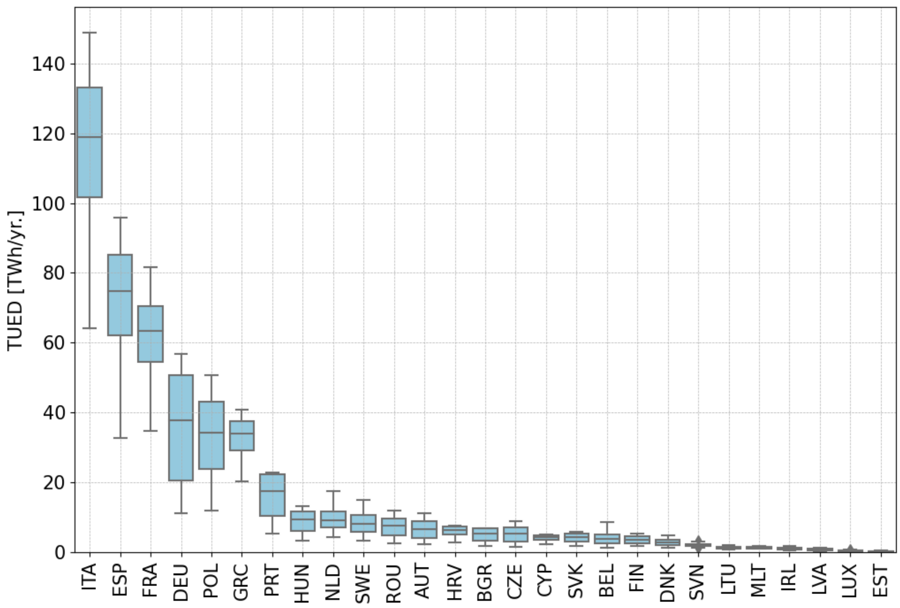


Figure 7. Range of annual Theoretical Useful Energy Demand (TWh/yr) in the EU-Member States, 2022-2050

Figure 7 above shows the potential range of estimates of theoretical cooling demand per country over the time horizon. The highest values originate from the baseline scenarios for the year 2050, where the rising temperature contributes to the demand rise. Details of the scenario results are presented in Annex 6.2. Overall, the figure gives a perspective per country on the ranges of theoretically useful energy demand for SC under different scenarios and over different years.

3.1.2. Practical Useful Energy Demand

In this section, we look int the Practical Useful Cooling Demands (PUED) which incorporate technology diffusion rates per building across various countries within our time horizon. We evaluate three different scenarios regarding technology diffusion as previously defined in Section 2.2. Aside from the baseline scenario, the additional scenarios anticipate a notable increase in the adoption of cooling technologies, influenced by various factors such as enhanced comfort requirements, affordability, and increased exposure to heatwaves and climate change impacts.

The baseline scenario for passive measure uptake in combination with high technology diffusion rates reveals a substantial rise in cooling demands that significantly exceed the baseline levels for both residential and non-residential sectors. In scenarios where moderate uptake levels are assumed, which are still above the Baseline, there is an increase in demand but it is not as pronounced as in the high diffusion scenarios. Without any passive measures, the expected useful space cooling demand in the European residential sector under these high uptake scenarios is projected to reach over 250 TWh, and almost 450 TWh in the non-residential sector.

Efficiency measures, when implemented, can counteract the impacts observed in both the high and low uptake scenarios, potentially restricting cooling demands to even below the baseline scenario levels. In the residential sector, the combination of high-efficiency measures with baseline uptake emerges as the most effective, significantly reducing the projected cooling demand. This demonstrates the potential of integrated passive measures to offset the rise in technology uptake. In scenarios where effective policy measures are implemented to significantly reduce demand through passive measures, even with high diffusion rates, the 2050 cooling demand could be limited to under 80 TWh in the residential sector—almost 50% lower than similar uptake levels without passive measures policies. A similar trend is observed in the non-residential sector, where demand can be constrained to 120 TWh, a drastic reduction from 390 TWh in scenarios without implemented measures (Seen in Figure 8 & Figure 9).

These results underscore the importance of passive measure uptake in controlling the increase in cooling demand driven by higher technology adoption rates. Properly planned and executed policy measures that support the adoption of passive measures are essential for controlling this increase. Such policies not only mitigate the effects of increased technology diffusion but also align with broader goals for energy efficiency and climate action. This analysis provides crucial insights for policymakers to devise strategies that encourage the adoption of efficient cooling technologies while minimizing their impact on energy consumption.

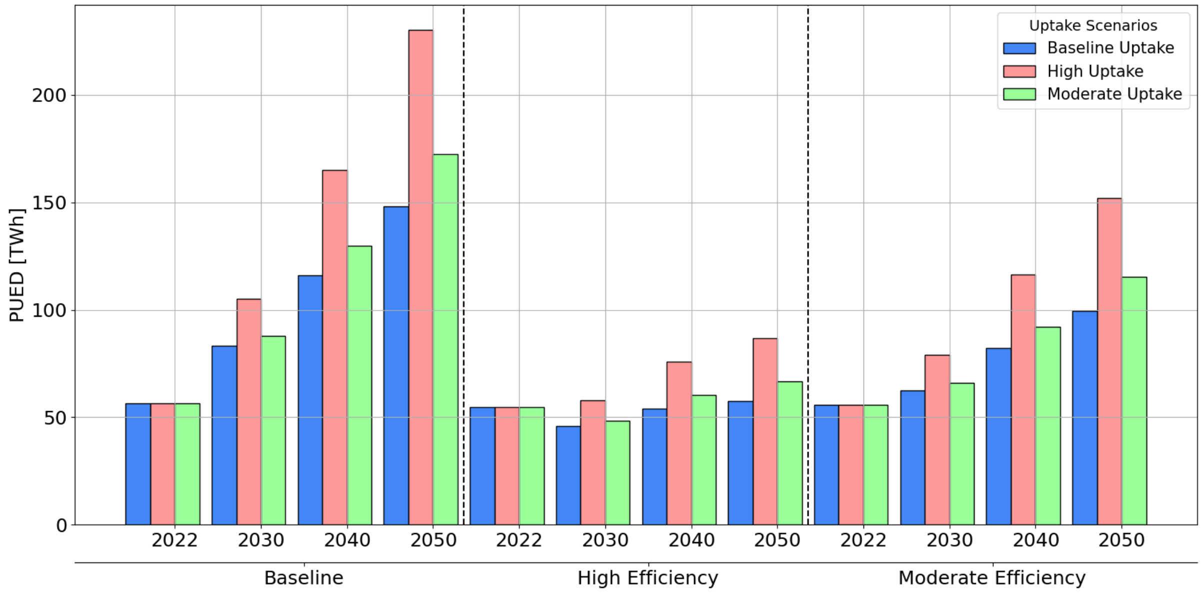


Figure 8. Practical Useful Energy Demand EU-27 Residential (scenarios of active cooling diffusion for three efficiency scenarios)

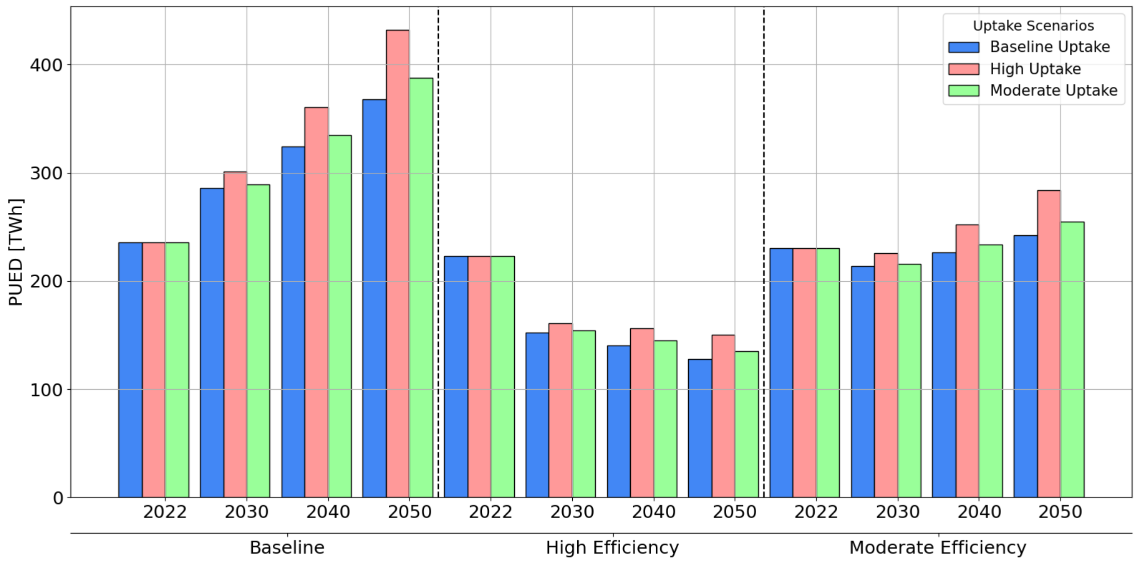


Figure 9. Practical Useful Energy Demand EU-27 Non-Residential (scenarios of active cooling diffusion for three efficiency scenarios)

3.2. Estimating the Final Energy Demand

In this section, we look into the final energy demand (FED), which accounts for the supply technology and the performance factor of the technology, representing the actual electricity input required for space cooling. As noted in Section 2.3, we do not specify any particular technology directly within the scope of this study. Instead, we focus on the Seasonal Coefficient of Performance (SCOP) and analyze it in a manner that assumes the supply technology could be any that would meet these performance standards. Our scenario assumptions are based on anticipated SCOP values, taking into account current and historical trends in technology development.

For assessing the FED, we define two scenarios in addition to the Baseline, where a conservative approach is adopted with no anticipated improvements in technology:

High Technology Efficiency Development: This scenario assumes a rapid improvement in the performance of the technologies.

Moderate Technology Efficiency Development: Here, technological advancements are assumed to progress more moderately. In the baseline scenario, a conservative approach is adopted with no anticipated improvements in technology.

Based on these parameters, we form various possible combinations. One example could be integrating moderate passive measures with high technology uptake and moderate technology improvement rates. This scenario could be applied to either residential or non-residential sectors. However, for simplicity in visualization and assessment within this report, we present only the most distinct scenarios that represent two potential extremes of all scenario combinations. These are termed combination scenarios and are defined as follows:

Current Path Scenario: Adheres to current trends and practices of technology uptake and improvement without significant changes. This scenario implies baseline technology diffusion and baseline technology improvement.

Accelerated Efficiency Scenario: Focuses on rapid improvements in technology efficiency with relatively lower increases in technology uptake rates. This scenario represents the lower limit to the range of final energy demand, highlighting substantial energy savings potential through efficiency gains alone.

Accelerated Uptake Scenario: Characterized by rapid uptake of technologies, despite slow improvements in efficiency. This scenario is the upper limit to the final energy demand, excluding the baseline scenario, showing reduced potential for energy savings due to the high rate of technology adoption.

The analysis, as illustrated in the accompanying figures, shows that the Current Path combination scenario results in a steady increase in demand proportional to ambient temperature changes. The Accelerated Efficiency scenario, even without passive measures, observes significant reductions in energy demand. Conversely, in the Accelerated Uptake scenario, the reduction potential significantly decreases, underscoring the need for substantial passive measures or efficiency improvements to mitigate the effects of increasing diffusion rates. In scenarios like Accelerated Uptake, only about 20% reduction potential is feasible, compared to more than 50% in the Accelerated Efficiency scenario.

With he right balance of policy measures that support passive measures, technology uptake, and efficiency improvements, savings of almost 80% in electricity used for cooling can be anticipated (seen in Figure 10 & Figure 11). These findings highlight the critical role of strategic policy planning and implementation in achieving significant energy savings in the cooling sector. This approach not only ensures effective management of rising cooling demands but also aligns with broader environmental and Energy efficiency goals.

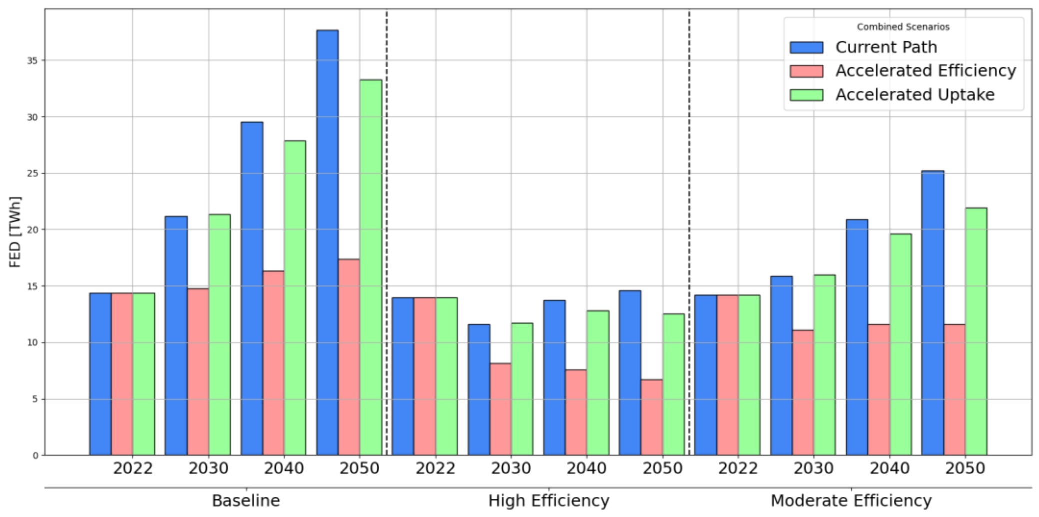


Figure 10. Final Energy Demand EU-27 Residential (scenarios of active cooling diffusion for three technology improvements for three efficiency scenarios)

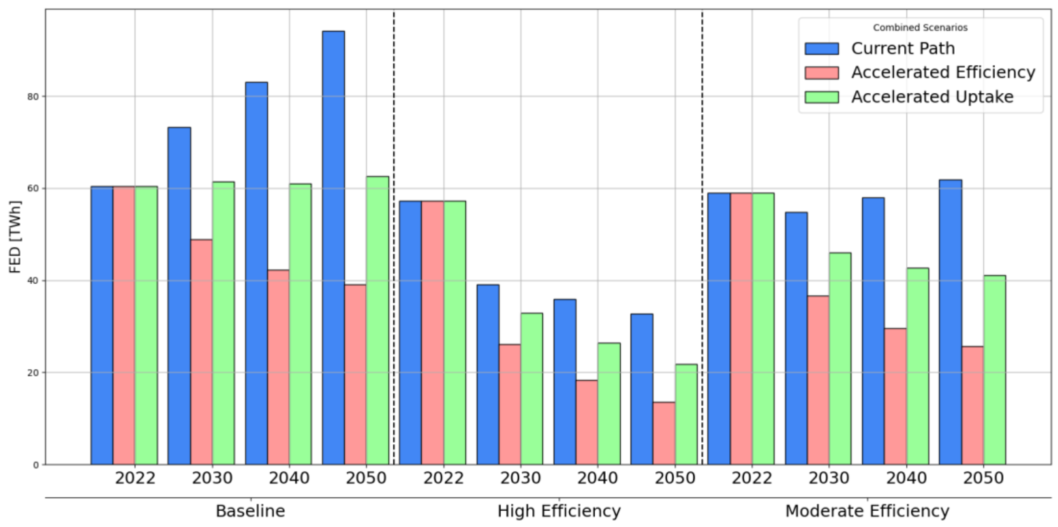


Figure 11. Final Energy Demand EU-27 Non-Residential (scenarios of active cooling diffusion for three technology improvement for three efficiency scenarios)

3.3. Energy Savings

In assessing the impact on final energy demand, a key performance indicator (KPI), we evaluate the potential savings compared to a baseline scenario. The baseline scenario is defined where no passive measures are implemented, the technology growth rate remains constant, and there are no improvements in technology efficiency. Against this Baseline, we compare the outcomes of three combined scenarios to understand the range of potential savings across all European countries.

The baseline passive measure uptake scenario for residential sectors shows potential savings in various scenarios. Notably, in the Accelerated Efficiency Scenario, substantial savings exceed 20 TWh in the residential sector. This scenario features lower technology diffusion rates but significant efficiency improvements, resulting in reduced demand and considerable energy savings. When passive measure efficiencies are included, these savings increase to over 30 TWh in the High-Efficiency Passive Measure Scenario by 2050 (Figure 12).

Conversely, the Accelerated Uptake Scenario shows minimal savings under the baseline passive measure uptake scenario, with an actual increase in demand by 2030. This scenario is characterized by a sharp increase in demand due to the high uptake of technologies without corresponding improvements in efficiency or the integration of passive measures. The lack of factors to counteract this growth leads to a substantial rise in demand, thereby diminishing the potential for savings. Even with the inclusion of passive measures, the savings in this scenario are modest compared to the Current Path Combined Scenario. This underscores the necessity for stringent policies on passive measures and technological development if high technology diffusion occurs.

These findings highlight the critical importance of controlled growth in passive measures. Several high technology uptake scenarios were observed where demand drastically increases, even with the implementation of passive measures. Therefore, it becomes evident that to manage demand effectively, especially under scenarios of rapid technology adoption, robust policy measures are essential. Such policies should not only promote the uptake of advanced technologies but also ensure the simultaneous deployment of effective passive cooling and heating measures.

Looking further, the strategic integration of technology and passive measures can lead to significant long-term benefits. By aligning technology diffusion with aggressive efficiency improvements and comprehensive passive strategies, it is possible to achieve not just substantial energy savings but also enhance the overall sustainability and resilience of the residential and non-residential sectors against future climatic changes. Detailed scenario analysis, therefore, serves as an invaluable tool in guiding policy makers towards making informed decisions that harmonize technological advancements with environmental and economic practicalities.

This detailed assessment of savings potential across different scenarios provides a clear indication of how various combinations of technology uptake and efficiency measures can impact energy demand. By exploring these scenarios, we can better understand the implications of different policy and technology pathways and thus, craft strategies that ensure a sustainable and efficient energy future.

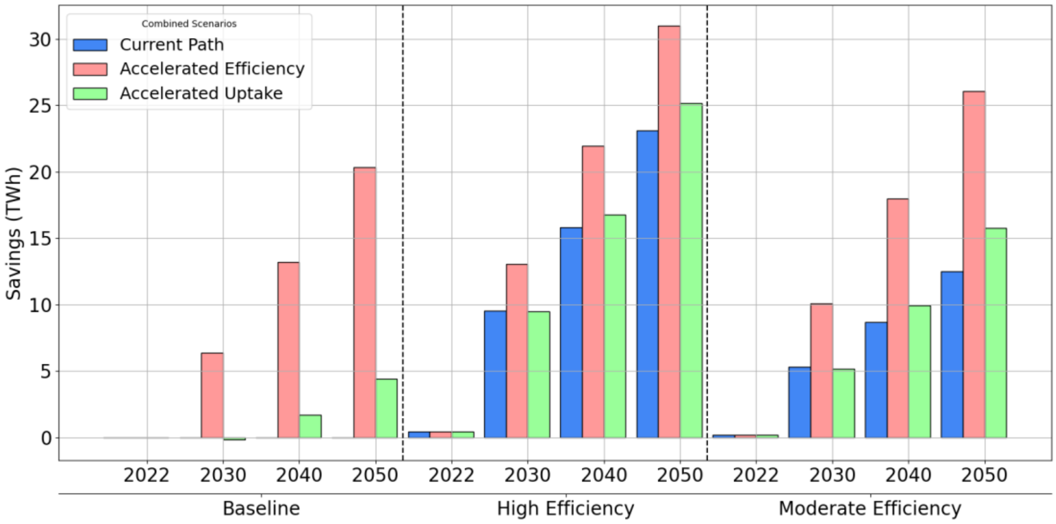


Figure 12. EU-27 Residential Savings (Passive measure + Combined Scenarios)

In the Figure 13, we observe the potential ranges of final energy savings across all countries for the year 2050, excluding scenarios where no reductions occur. This visualization underscores that carefully crafted policies and measures—effectively balancing the rise in demand and technology uptake with strategic improvements in passive measures and technology efficiency—can yield a diverse spectrum of outcomes for final energy demand. This analysis highlights the importance of integrated planning to optimize energy efficiency across different national contexts.

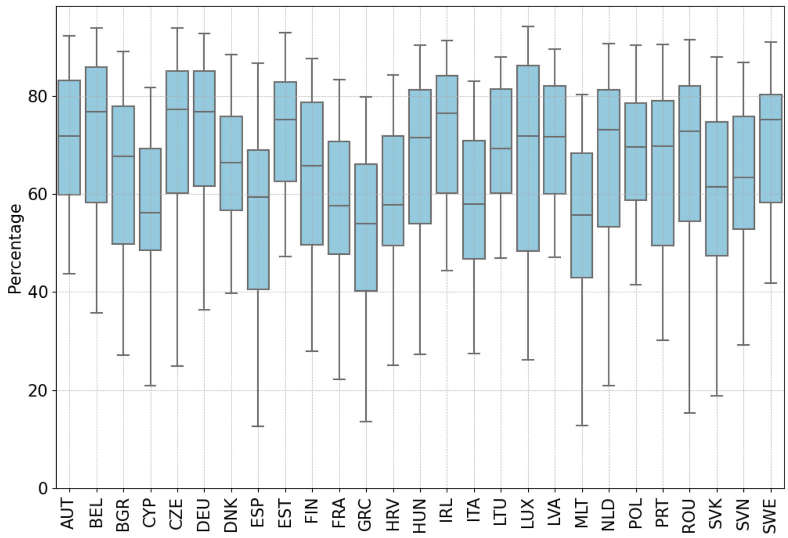


Figure 13. Percentage Savings vs. Baseline (FED residential 2050)

Similar patterns are observed for the non-residential sector (Figure 14). But, considering already high diffusion rates in the Baseline compared to the residential sector, the increased diffusion rates in the accelerated uptake scenario are not high enough to exceed the demand, considering a modest level of technology improvements is also included in the scenario. Hence, more relative savings to the Baseline than in the residential sector are observed.

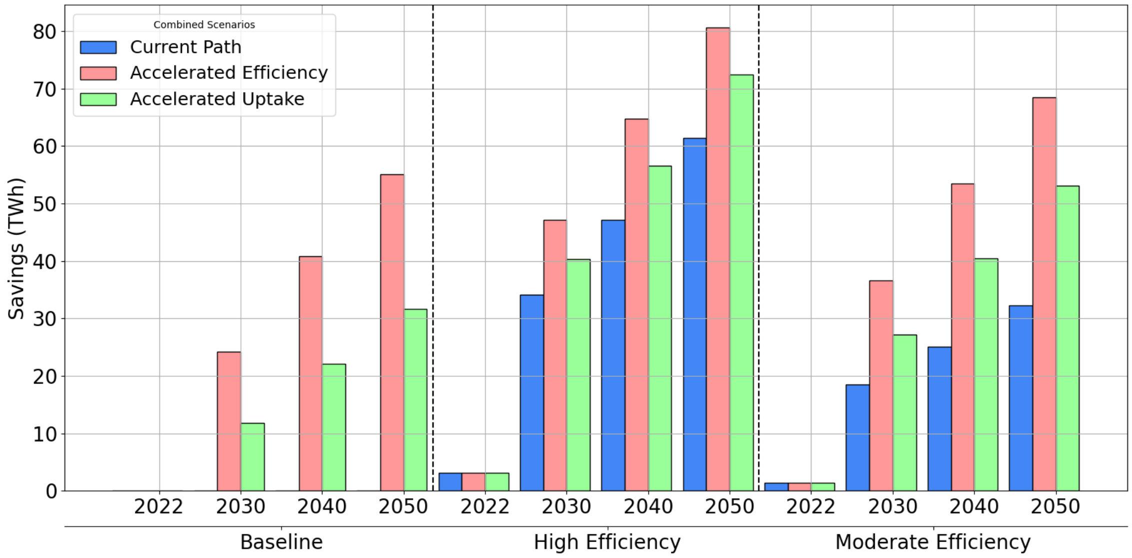


Figure 14. EU-27 Non-Residential Savings (Passive measure + Combined Scenarios)

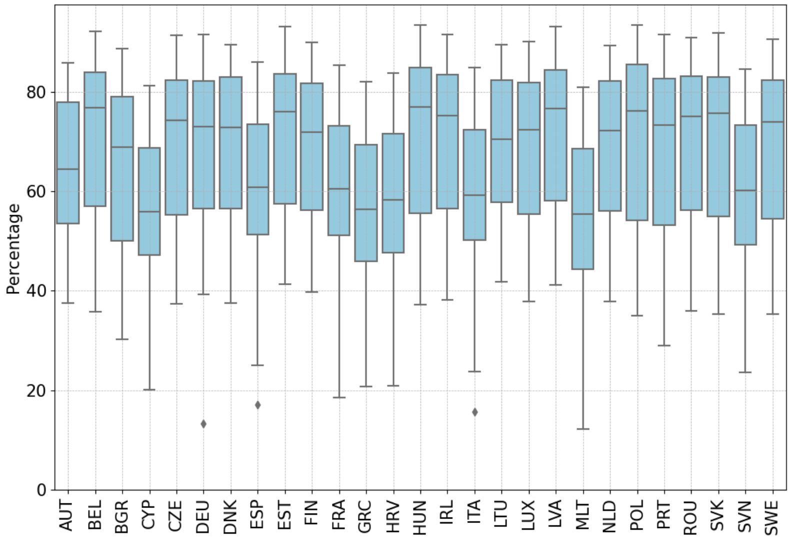
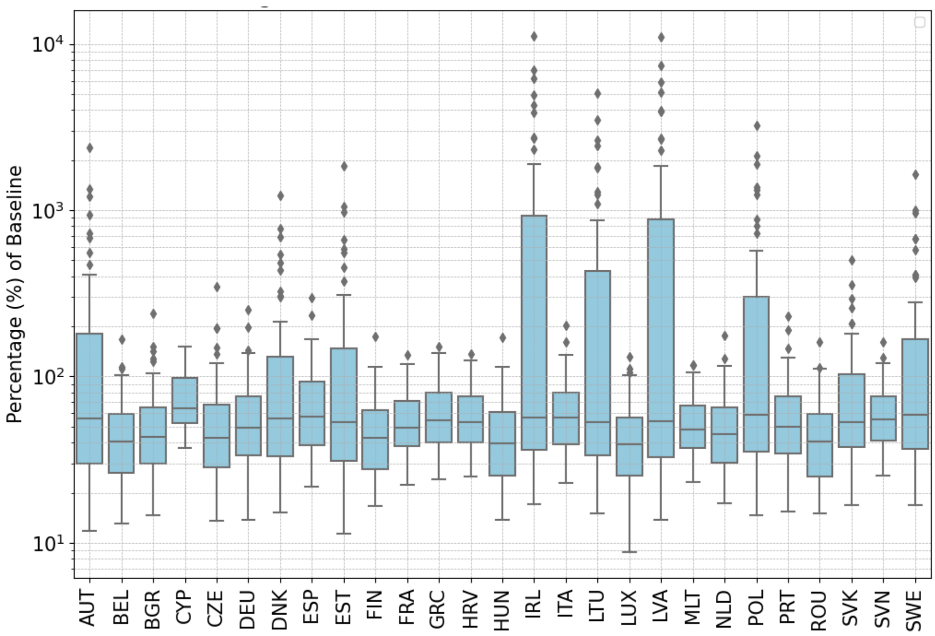


Figure 15. Percentage Savings vs. Baseline (FED non-residential 2050)

3.4. GHG Emissions

3.4.1. CO2 emissions

In our analysis of CO2 emissions, we are focused on evaluating the trajectory toward achieving a net zero emission target by the year 2050. To assess the impact on CO2 emissions details on 2030 and 2040 are presented here, which illustrate the emissions relative to the baseline scenario. Similar to the energy savings calculation we take the baseline scenario as reference for assessment. The baseline scenario represents a lack of uptake of passive measures, constant technology diffusion rate, and constant technology development, which could be associated with emissions without additional interventions or policy changes. For each of these years, we include two sets of visualizations: the first set displays all scenarios under consideration, offering a broad perspective on potential emission trajectories. The second set, however, is selectively filtered to highlight only those scenarios that demonstrate a potential reduction in CO2 emissions compared to the Baseline. For both years combined data for residential and non-residential sectors are presented. This targeted approach allows us to focus on viable strategies and interventions that could significantly contribute to meeting global net-zero targets.



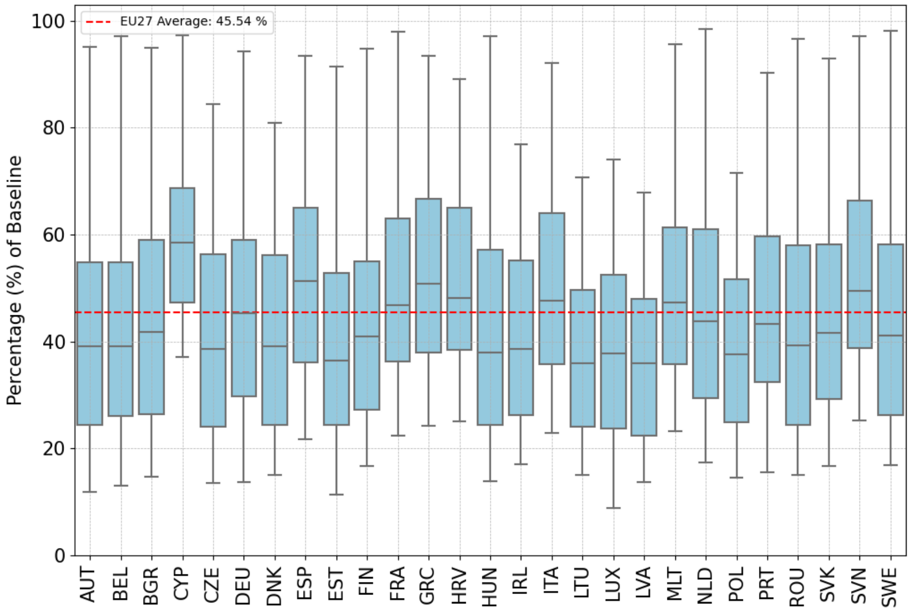
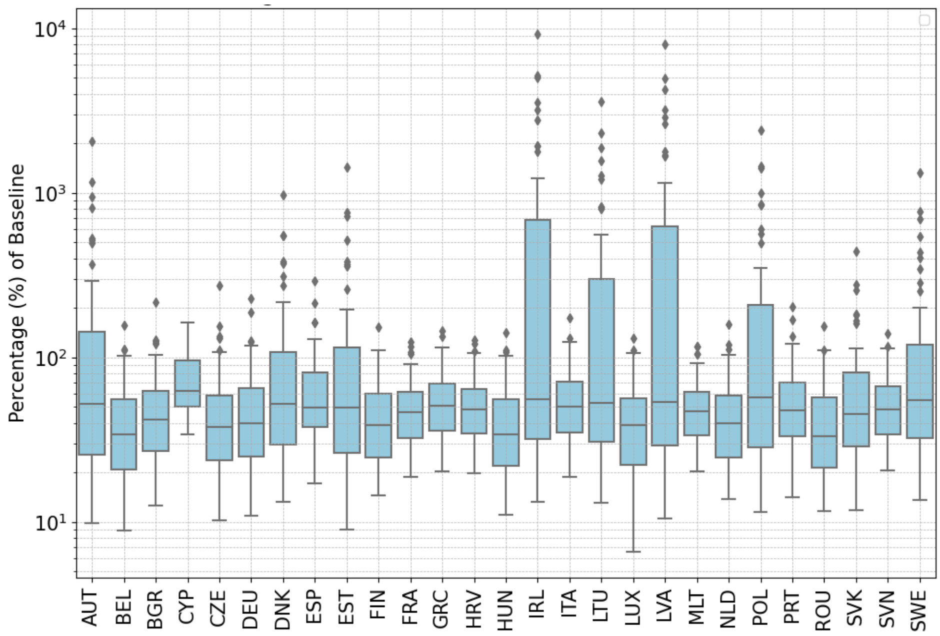


Figure 16. CO2 emissions for 2030 (I- All scenarios II- Filtered Scenarios)

In our 2030 analysis, the data reveal a wide range of CO2 emission reductions across different countries when compared to a baseline scenario. Among the 1,400 scenarios evaluated, approximately 1,200 show a potential for improvement in environmental performance. The reductions in these scenarios range from 10% to 90%, with an average reduction of 45.5% across the EU-27.

However, approximately 15% of the scenarios result in emissions that exceed baseline levels, with some increasing by more than 2000%. These scenarios typically involve increased technology adoption without corresponding enhancements in passive measures or technological efficiency. This highlights a critical need: it is essential to align the adoption of passive measures with policy interventions focused on these areas and broader technological developments. Such alignment is crucial to mitigate rising demands and the consequent environmental impact.

For this 15% group, the measures considered are insufficient to adequately control the negative environmental impacts observed. Although these scenarios are projected to converge toward zero emissions by 2050, the significant increase in emissions in 2030 poses a challenge. This rise is primarily due to the inadequate implementation of shading measures, underscoring the need for policy-level interventions to address these shortfalls and ensure environmental targets are met.



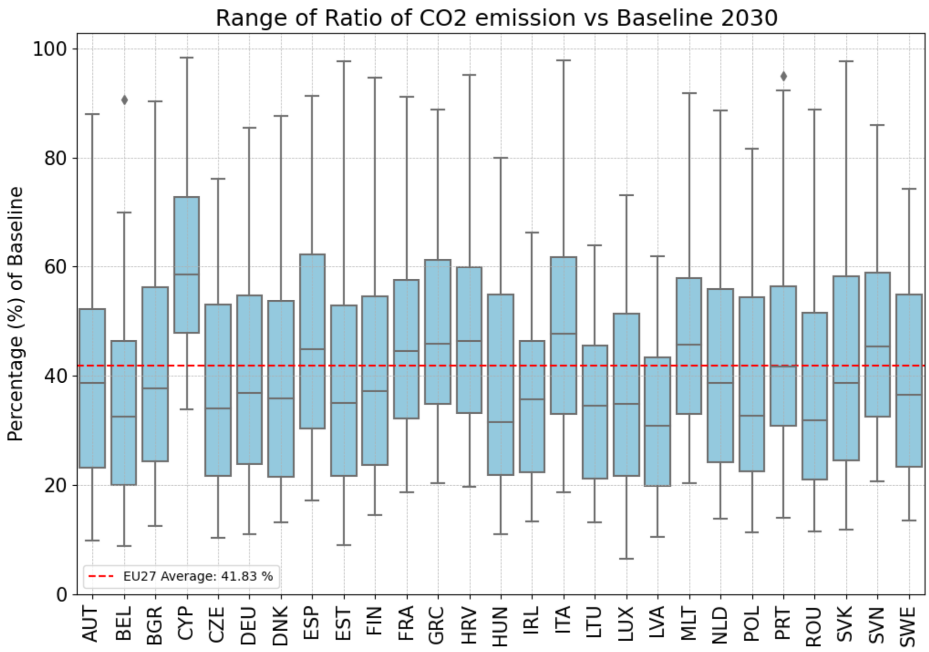


Figure 17. CO2 emissions for 2040 (I- All scenarios II- Filtered Scenarios)

For 2040, similar patterns are observed. However, for the scenarios with reduced emissions, the overall EU average decreases, thus indicating a higher reduction possibility. This primarily comes from the 2050 zero-emission targets. Nevertheless, the implementation of passive measures has shown a higher impact in recent years as more buildings have been renovated and newer buildings have implemented passive measures.

3.4.2. NOX Emissions

Another critical parameter in assessing the environmental impact of increasing cooling demand is the NOx emissions. Similar to our analysis of CO2 emissions, we present here the range of NOx emissions projected for the year 2030, alongside a target of achieving net zero NOx emissions per country by 2050. In evaluating different scenarios, we observe a broad spectrum of potential reductions in NOx emissions compared to the baseline scenario. The most significant reduction potentials are found in scenarios that effectively combine passive measures with improvements in technology efficiency to mitigate the effects of increasing technology diffusion rates.

These scenarios, which emphasize both passive architectural measures and technological advancements, help significantly curb emissions. The rationale behind this is twofold. Firstly, enhanced building designs and improved insulation standards reduce the overall energy demand for cooling, thus decreasing the emissions associated with energy production. Secondly, advancements in technology efficiency ensure that the Energy used is optimized, leading to lower emissions per unit of Energy consumed.

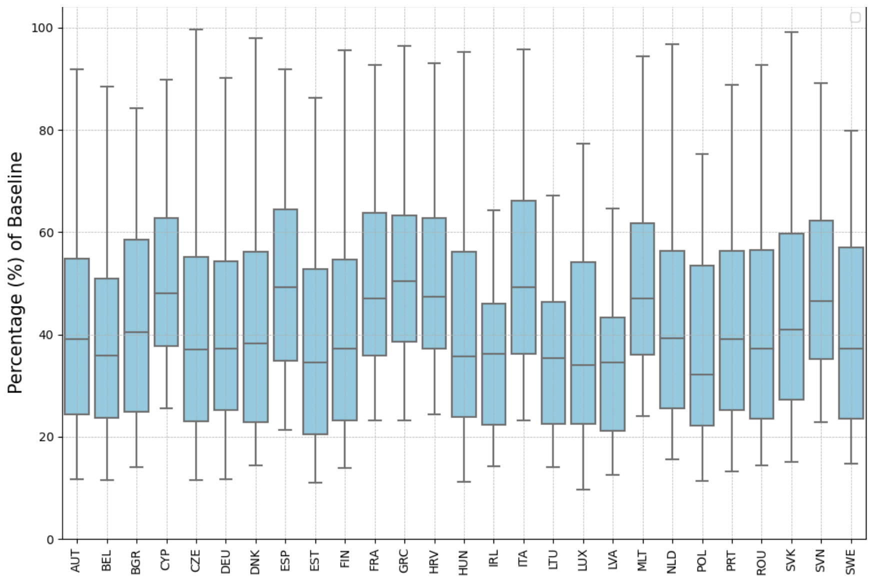


Figure 18. Range of Ratio of NOx emission vs Baseline for 2030

3.5. Economic Assessment

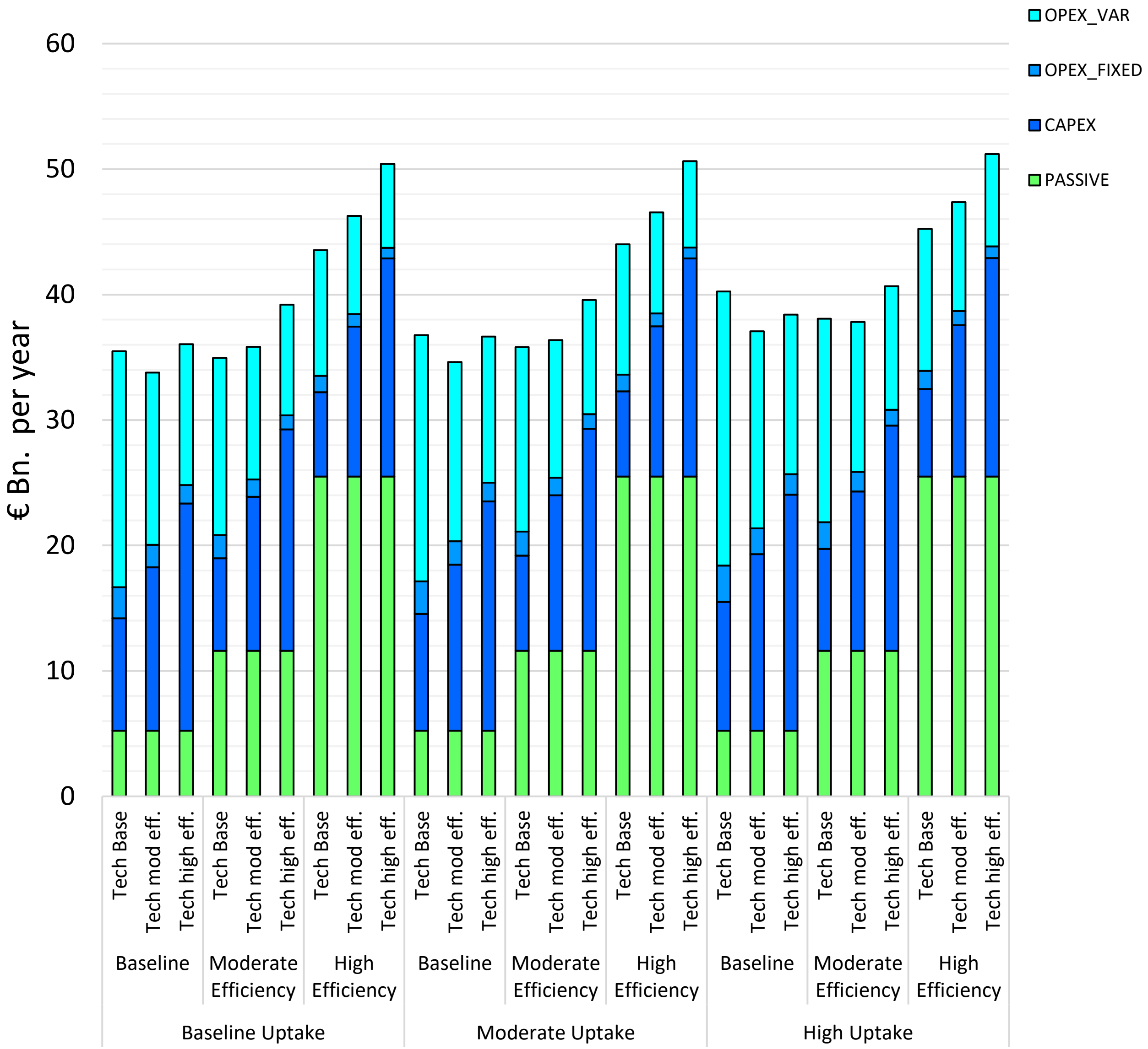


Figure 19. Total Costs for cooling technologies and passive measures- EU27

Figure 19 shows that in the EU-27, costs for passive measures increase as efficiency levels rise. Higher efficiency levels offer more energy savings but come at a higher expense. For active measures, costs increase slightly when moving from baseline uptake rates to high uptake rates. This is due to conservative assumptions about the rate at which new technology will be adopted. With further higher rates of diffusion of technology, this is expected to change. Technology improvements result in higher initial costs, also known as capital expenditure (CAPEX). However, these improvements lead to lower ongoing costs, referred to as operational expenditure (OPEX). The ongoing costs (OPEX) are influenced by electricity prices, which in this analysis are assumed to be conservative.

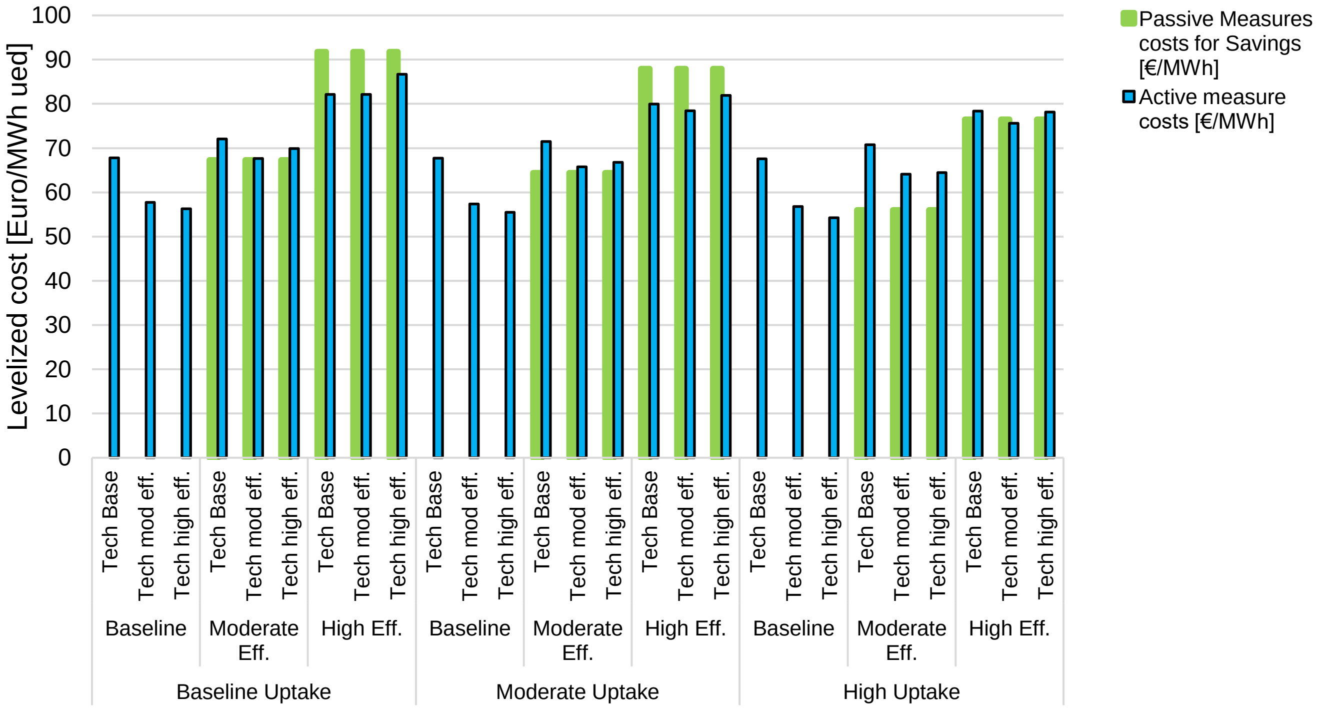


Figure 20. Levelized cost of cooling of active technologies compared against the unit costs for energy savings from passive measures EU-27

Figure 20 compares the levelized cost of cooling, measured in terms of useful energy demand, against the cost of unit savings from passive measures. The chart shows both the costs for passive measures and active measures across different efficiency levels and uptake rates. The analysis considers conservative electricity prices for each country. From this, we observe that passive measures become cost-effective at moderate efficiency levels of passive measures. However, achieving cost-effectiveness at higher efficiency levels is largely possible only at increased electricity prices or with supporting policy framework.

We want to emphasize that the results strongly depend on the assumed market penetration of active cooling. The higher the uptake (which could also significantly higher than our “"high uptake scenario”"), the higher the economic viability of passive measures, following our calculation approach. This will be considered in the following steps of the project and in particular in the related calculation modules of the CoolLife-Toolbox.

3.6. Economic Impact

While the CAPEX of the passive measures increases by applying the given EEI scenario, this results in lower investment costs within the active space cooling sector than the baseline (Current Path Scenario). The rise in passive investment CAPEX is however still a magnitude higher than the loss of CAPEX spent for active space cooling, seen on Figure 21.

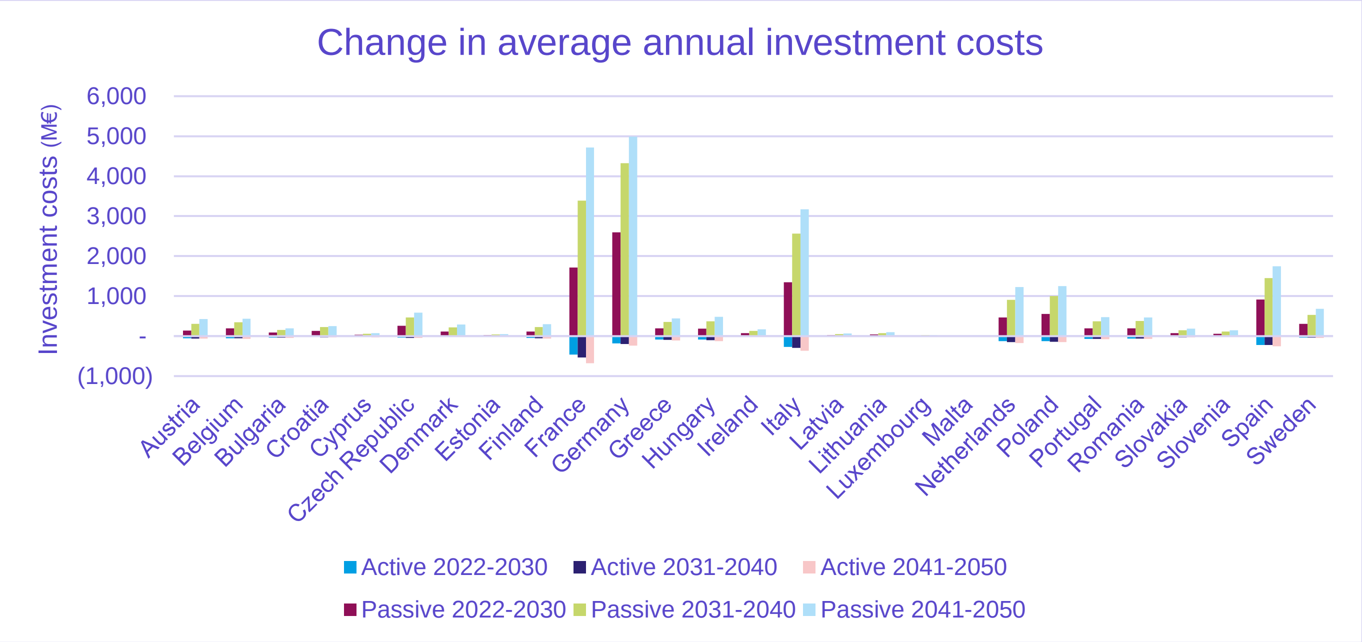


Figure 21. Change in average annual investments used for inputs for economic impact calculations

The highest investments are seen for Germany, France, Italy, Spain, Poland and the Netherlands. The impact on the GDP is seen in Figure 22. The highest impact is for Germany (up to 1700 million €), followed by France, Italy and Spain. Due to the differences in the country specific coefficients representing the added value effect, the ratios are somewhat different than what was seen for the investments costs. The average annual impact on the GDP for the whole EU-27 region is between 5762-5882 million EUR in the given period.

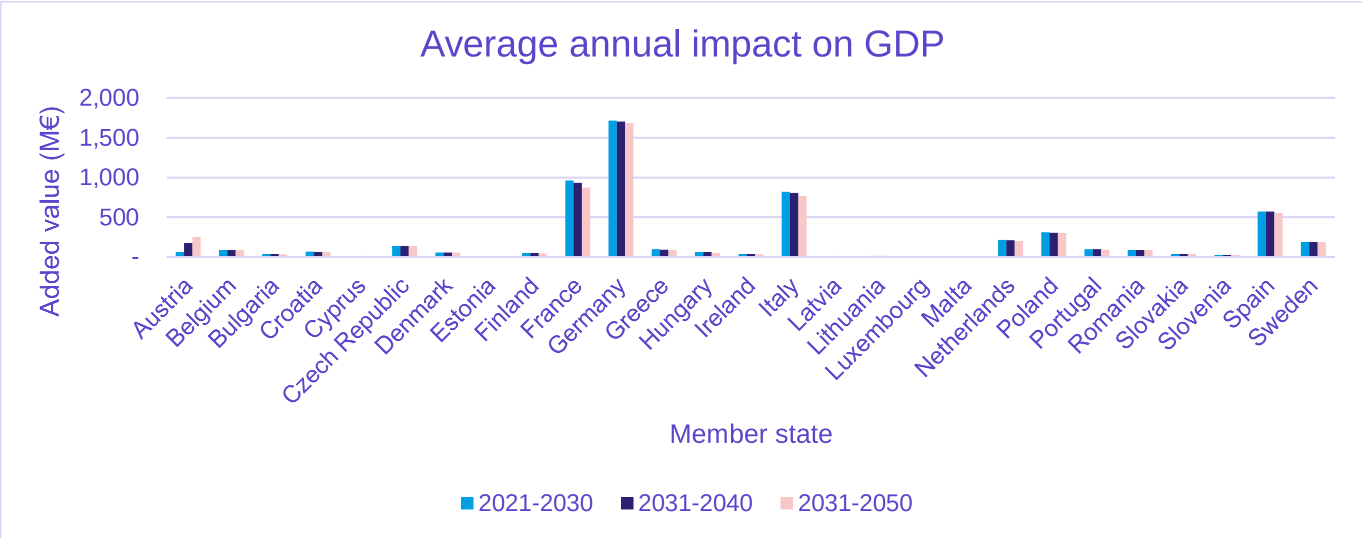


Figure 22. Impact on GDP for the EU-27 countries

Linked to the GDP effect, full time employments will also increase, as new jobs will be created. When implementing the highest rate of energy efficiency investments, the additional employment of average 124 000 to 300 000 full-time employment years are generated annually on the EU level. The highest number of employments generated are in Germany, France, Italy, Poland and Spain.Figure 23)

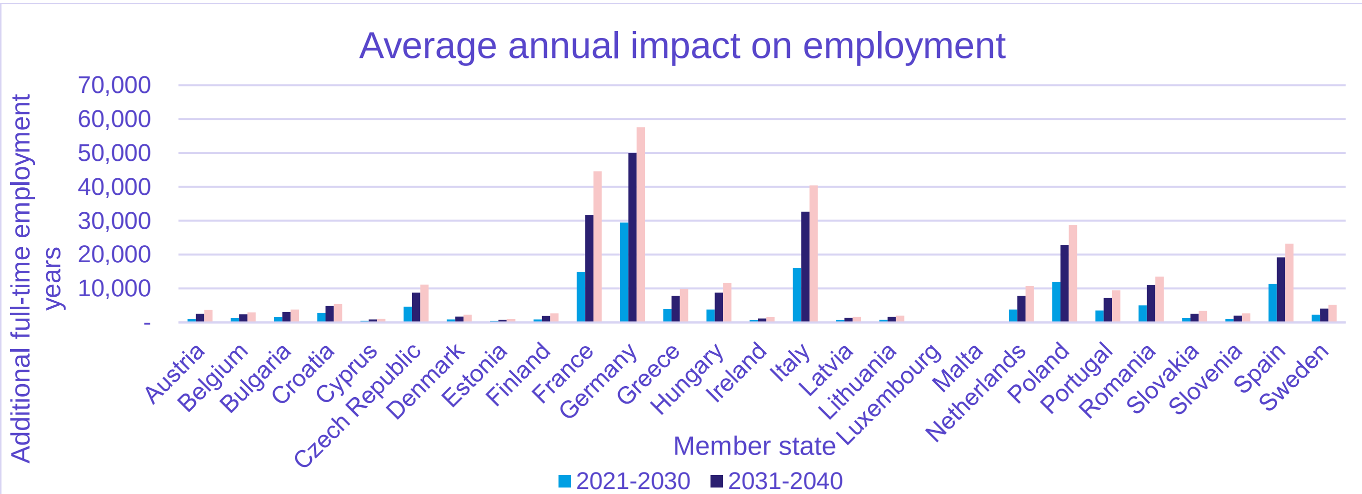


Figure 23. Additional employment for the EU-27 countries

3.7. Social Impact

The total number of avoided deaths is 38 in 2030 and rises up to 145 in 2050. Figure 24) It is seen that the countries mostly affected by the reduction in SC energy use are different than the ones benefiting from the increased GDP rise from EEIs. The countries impacted the most are Italy, France, Poland and Germany, which is different than the list of countries with the highest energy saving potential. This is due to a number of factors, including the percentage of fossil fuels and emissions from combustion technologies in the energy mix, different exposure of the population to the pollutants in question and the health risk associated with that exposure.

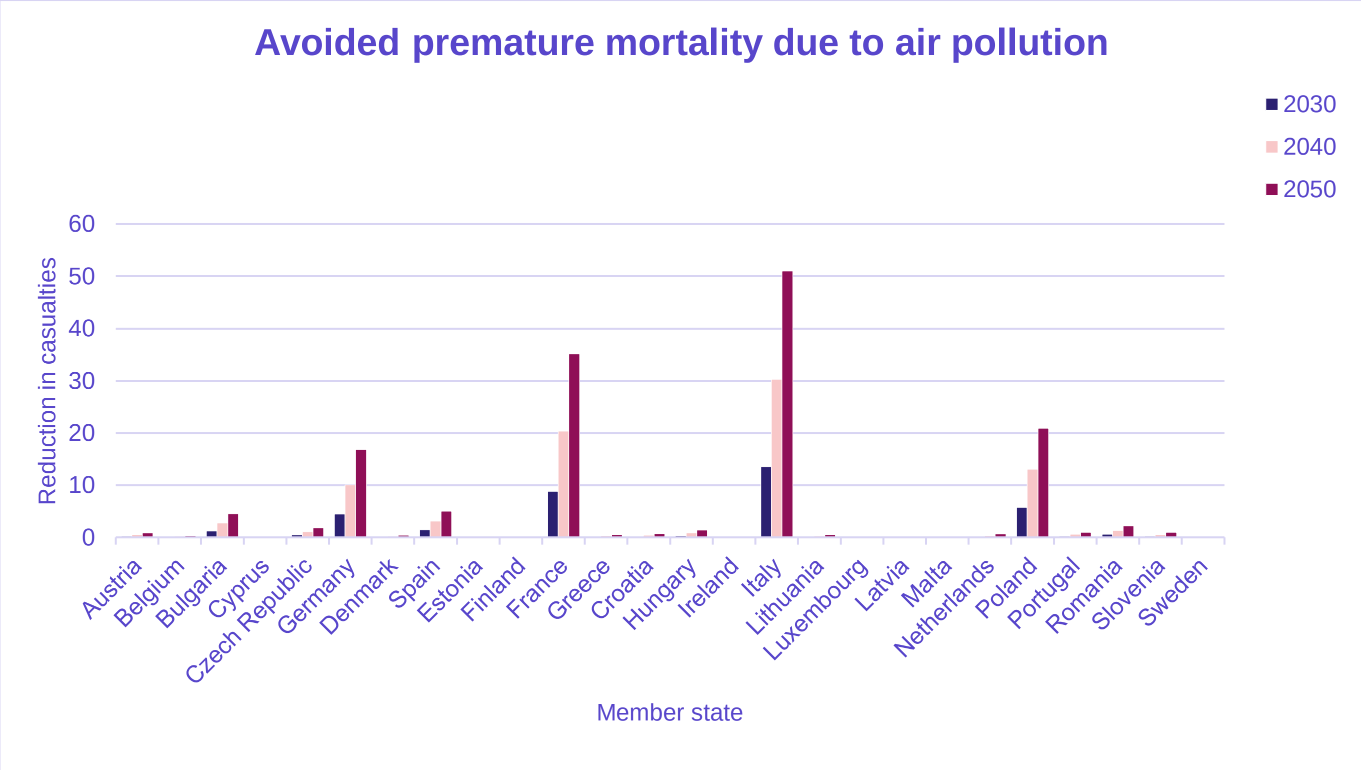


Figure 24. Avoided annual premature mortality due to air pollution (Slovakia is excluded in lack of data)

Similarly, the avoided lost working days due to air pollution can be reduced with the highest numbers in Italy and France, reaching up to 10757 days annually in the former MS. Again, the effect is relatively higher in Poland than what would be expected from the energy savings, as well due to the specific emissions of pollutants and the exposure of the population to those.

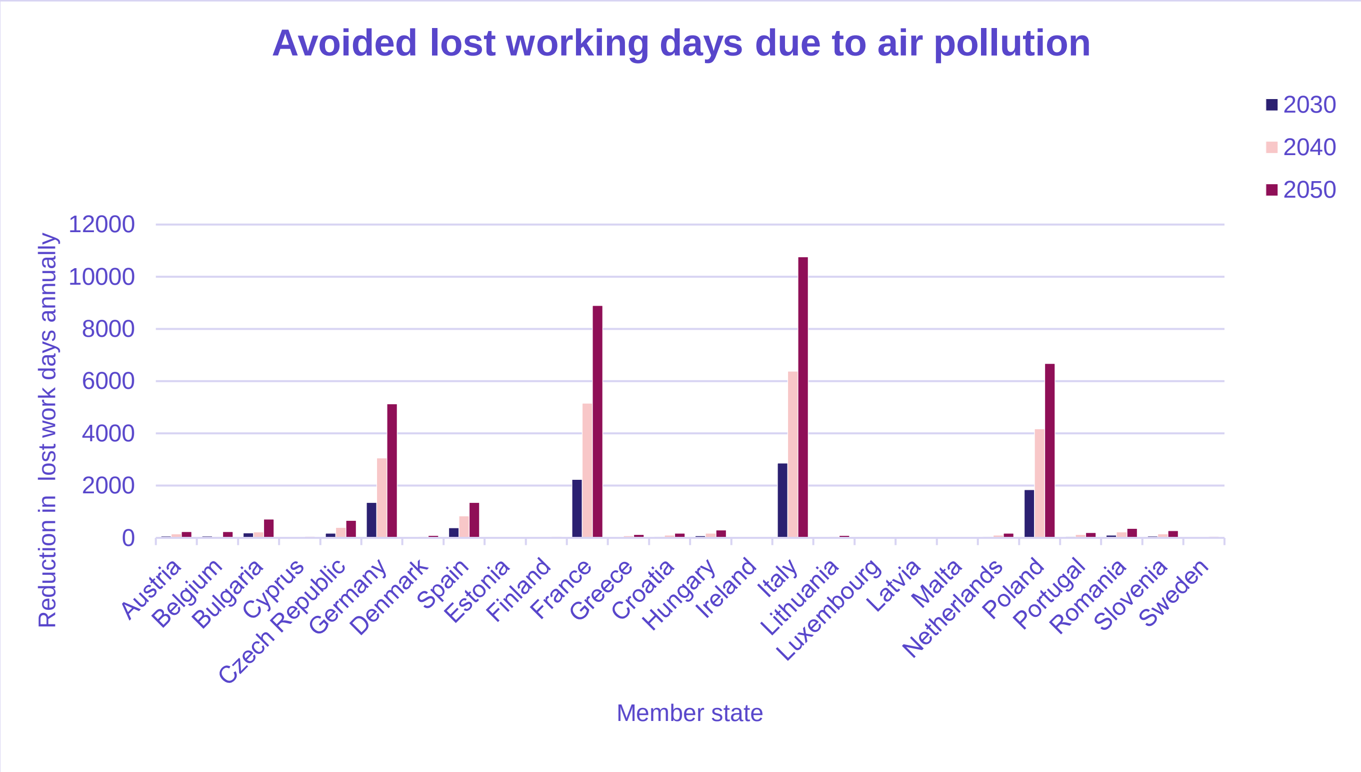


Figure 25. Avoided lost working days due to air pollution (Slovakia is excluded in lack of data)

4. Conclusions

The urgency of managing the escalating space cooling demand within the EU-27, triggered by global warming, urban expansion, and elevated living standards, calls for innovative and robust energy policies. This study of the impact assessment provides a thorough investigation into the effectiveness of passive measures and technological advancements aimed at fulfilling future energy requirements efficiently and sustainably. With this study, we identify the environmental, economic, and social impact of these increasing demands and assess measures that support the development of sustainable cooling practices that not only mitigate energy consumption but also enhance the overall quality of life and align with global climate goals.

We conducted an extensive impact assessment of space cooling technologies and measures. This assessment extended through scenarios leading up to the years 2030, 2040, and 2050 to examine environmental impacts, particularly focusing on greenhouse gas emissions such as CO2 and NOX as well as possibilities for energy savings. We adopted a comparative approach to identify both positive and negative discrepancies against a reference scenario, which provided a comprehensive understanding of the impacts. Furthermore, the project explored scenarios ranging from business-as-usual to more ambitious projections aligning with EU energy and climate goals, assessing the potential variability under different future conditions. The sensitivity of these measures to changing climate conditions was also a critical part of our analysis, ensuring our strategies remain effective under various future scenarios. We also examined the impact of widespread technology adoption on the electric grid, enhancing our understanding of peak demand implications. These thorough investigations have been detailed comprehensively, providing a solid foundation for future strategic developments in sustainable cooling practices.

Our study employed advanced modelling techniques and diverse scenarios to estimate the space cooling demand across various sectors, assessing the impacts of multiple passive and technological measures on these demands. Utilizing the Invert/EE-Lab model, we were able to delve into the details of energy demand dynamics, offering a granular view of how different strategies could potentially perform in enhancing energy efficiency and reducing space cooling demand. Despite thorough checks and validation processes applied during this study, the methodology developed, though robust, inherently encompasses certain levels of uncertainty related to input data and parameter sensitivity. This uncertainty is a natural aspect of modelling such complex systems. Nonetheless, the methodology stands as a strong and reliable framework, carefully crafted to ensure it is replicable and scalable for evaluating cooling demands and the effectiveness of intervention strategies across the European Union. The cautious design of our approach, combined with comprehensive testing and validation phases, confirms our commitment to accuracy and reliability in our findings. However, as with any model-based approach, a residual level of uncertainty remains, highlighting the importance of ongoing refinement and adaptation as new data becomes available and as technological and environmental conditions evolve.

Our analysis highlights that the strategic application of high-efficiency passive measures and technology upgrades can profoundly decrease the cooling energy demand. Notably, in scenarios where these measures were implemented to their fullest extent, we observed reductions in energy demand by as much as 55% by the year 2030. This substantial decrease underscores the potent impact of integrating cutting-edge passive cooling strategies, behavioural modifications, and technological advancements.

Additionally, the study revealed significant variances in potential energy savings between the residential and non-residential sectors, underscoring the necessity for strategies tailored to the unique characteristics and demands of each sector. Particularly, the non-residential sector, with its inherently higher baseline energy demand, demonstrated greater absolute energy savings under similar efficiency improvements, emphasizing the need for sector-specific approaches in policy formulation.

The environmental implications of unmitigated increases in cooling demand could significantly worsen energy consumption and associated greenhouse gas emissions. Our environmental impact scenarios projected that without substantial efficiency improvements and widespread adoption of passive measures, CO2 and NOx emissions would rise steeply. However, these emissions could be considerably mitigated through the combined application of advanced technological deployments and passive cooling measures. To align with the EU's ambitious net-zero emissions target by 2050, it is imperative to actively enhance the performance and adoption rates of low-emission cooling technologies.

To navigate the challenges presented by the rising demand for cooling, we propose several strategic policy interventions:

1. Enhanced Incentives for Passive Cooling Measures: It is crucial to establish policies that encourage the integration of passive measures in building designs and renovations. Financial incentives such as subsidies or tax rebates, stringent regulations, and updated building codes should be aligned to support the widespread adoption of these energy-efficient solutions.
2. Support for Technological Innovation: Increased support for research and development in high-efficiency cooling technologies is essential. Such support will ensure that economically viable and technically advanced solutions become accessible on a large scale.
3. Dynamic and Adaptive Regulatory Frameworks: Regulatory frameworks should be flexible and adaptive to technological advancements and new data on cooling demand trends. This adaptability will facilitate the swift incorporation of innovative cooling solutions into the market.
4. Public Awareness and Stakeholder Engagement: Initiatives to enhance public awareness and education about passive cooling solutions and energy-efficient behaviours are vital. These programs will increase the understanding and acceptance of energy-saving measures and foster a culture of sustainability.

Moving forward, it is crucial to continuously monitor and evaluate the effectiveness of the measures implemented to ensure they achieve the intended energy-saving targets. We anticipate that the methodologies and results from the CoolLIFE project's impact assessment will serve as a robust basis for future evaluations. These findings should be leveraged to enhance predictive models and adjust policies and practices to remain at the cutting edge of technological and societal advancements. Additionally, the scenarios developed and the assessment outcomes could serve as a valuable reference for member states when integrating cooling demand considerations into their national comprehensive assessment reports, in accordance with the Energy Efficiency Directive.

Limitations of the work:

1. *Data Availability and Quality:* The accuracy of the model heavily relies on the availability and quality of input data. Inconsistencies, gaps in data, or outdated information can lead to uncertainties in modelling outcomes. This is especially true for regions where data collection infrastructure is not robust.
2. *Parameter Sensitivity:* The model outcomes can be highly sensitive to changes in parameter settings. While this allows for a detailed examination of various scenarios, it also means that small inaccuracies in parameter estimation can significantly affect the results. Ensuring the accuracy of these parameters is challenging and requires continuous updates based on the latest research and empirical findings.

3. *Assumptions in Scenario Modeling:* The scenarios are constructed based on a set of assumptions which might not fully capture future realities. These assumptions include projections of technology adoption rates, efficiency improvements, and behavioural changes, which are inherently uncertain and subject to change due to policy, economic, and social factors. In particular market uptake rates of active cooling might also be significantly higher than in our "high uptake" scenario. Thus, the results presented in this report do not show the full possible range of resulting energy demand, GHG-emissions and related socio-economic impacts.
4. *Scalability and Applicability Issues:* While the methodology is designed to be scalable and applicable across the EU, regional differences in climate, economic conditions, and building practices are not fully accounted for. This can limit the applicability of the findings in specific contexts or require additional modifications to the approach to ensure accuracy.

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6. Annexes

6.1. Annexe 1: Detailed Scenario Definition

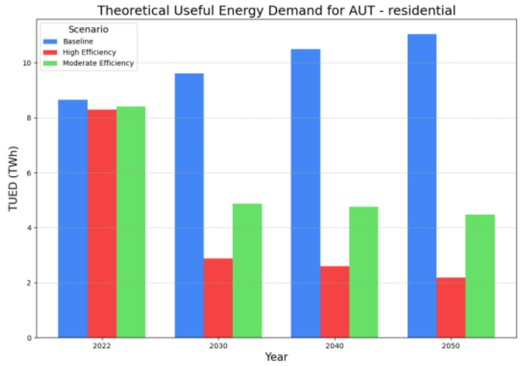
		Scenarios				
Parameter	**Region**	**Baseline**			**Low**	**High**
		Average shading	**New Buildings**	**Refurbished Buildings**		
A_m_s_cool_south						
	Category Mediterranean	0.66	0.66	0.66	0.67	0.88
	Category Rest	0.66	0.66	0.66	0.67	0.79
A_m_s_cool_east_west						
	Category Mediterranean	0.39	0.39	0.39	0.54	0.81
	Category Rest	0.24	0.24	0.24	0.36	0.7

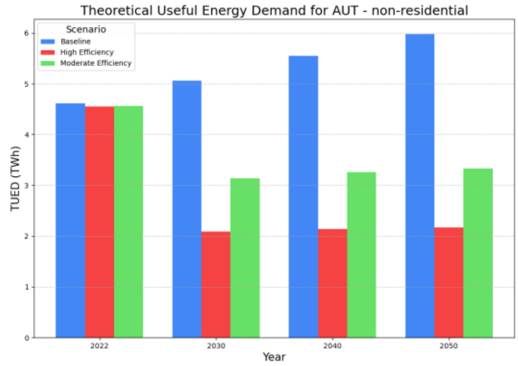
A_m_s_cool_north						
	Category Mediterranean	0	0	0	0.03	0.43
	Category Rest	0	0	0	0	0
Share_additional_shading_south						
	Category Mediterranean	0.5	0.5	0.5	0.67	1
	Category Rest	0.5	0.5	0.5	0.5	0.8
Share_additional_shading_east_west						
	Category Mediterranean	0.33	0.33	0.33	0.39	0.5
	Category Rest	0.33	0.33	0.33	0.33	0.5
Share_additional_shading_north						
	Category Mediterranean	0	0	0	0.03	0.43
	Category Rest	0	0	0	0	0

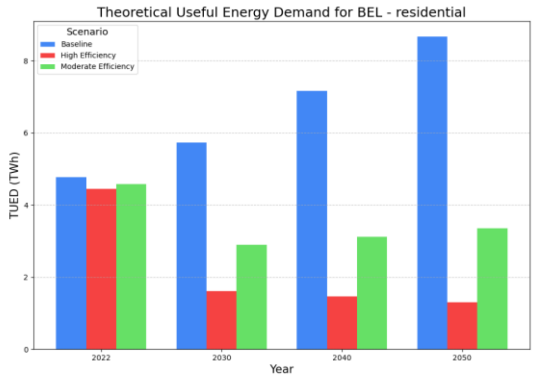
z_factor						
	Category Mediterranean	0.7	0.7	0.7	0.62	0.24
	Category Rest	1	1	1	0.8	0.24
g-value						
	Category Mediterranean	0.75	0.75	0.65	0.52	0.25
	Category Rest	0.65	0.52	0.52	0.35	0.25
Night Ventilation (air_exchnage_rate_night_ventilation)						
	Category Mediterranean	Baseline	Baseline	Baseline	Baseline	Baseline
	Category Rest	Baseline	Baseline	Baseline	Baseline *1.5	Baseline *2
average_indoor_temperature_cooling						
	Category Mediterranean	Baseline	Baseline	Baseline	Baseline + 1	Baseline + 2
	Category Rest	Baseline	Baseline	Baseline	Baseline + 2	Baseline + 4

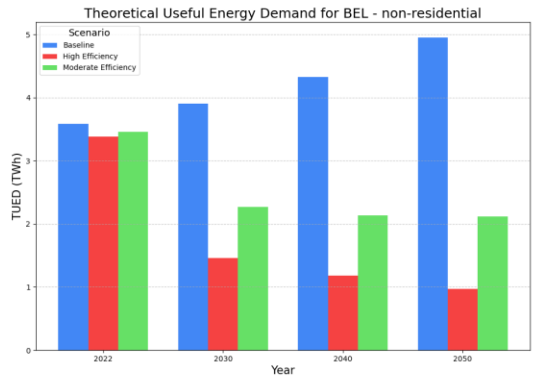
Thermal Capacity of Building (gebaudebauweise_fbw)						
	Category Mediterranean	Baseline	Baseline	Baseline	Baseline	if <60,60, Baseline
	Category Rest	Baseline	Baseline	Baseline	Baseline	if <30,30, Baseline

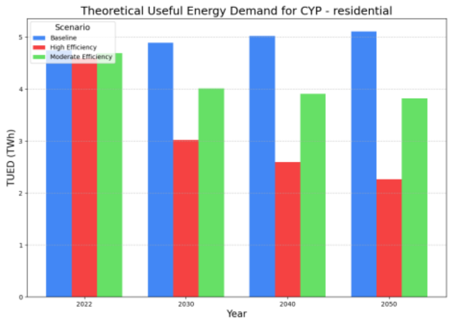
6.2. Country-specific Invert Results – Theoretical Useful Energy Demand










Theoretical Useful Energy Demand for CYP - residential
Scenario
Baseline
High Efficiency
Moderate Efficiency
TUED (TWh)
0
1
2
3
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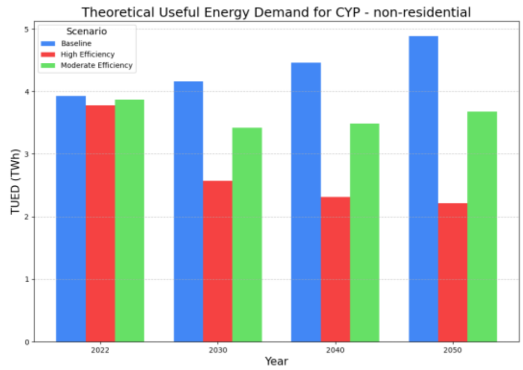
5
2022
2030
2040
2050
Year


Theoretical Useful Energy Demand for CYP - non-residential
Scenario
Baseline
High Efficiency
Moderate Efficiency
TUED (TWh)
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2022
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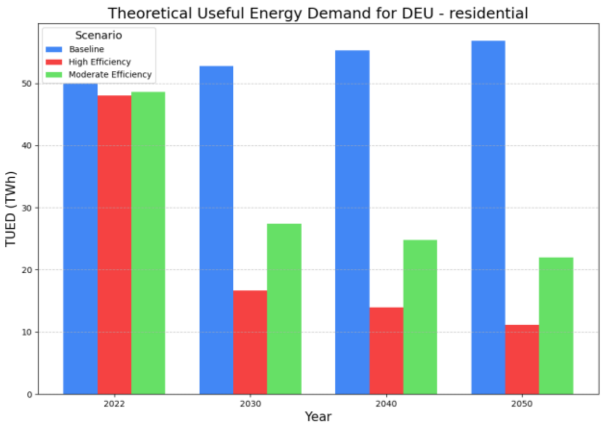
2050
Year


Theoretical Useful Energy Demand for DEU - residential
Scenario
Baseline
High Efficiency
Moderate Efficiency
TUED (TWh)
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10
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30
40
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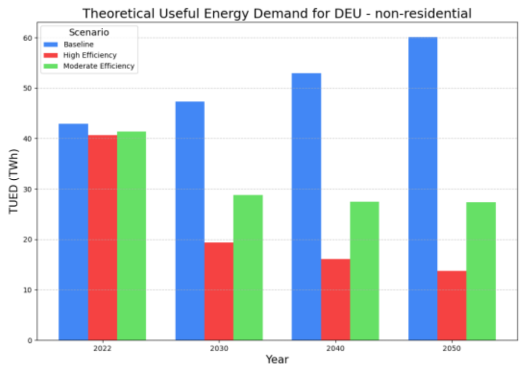
2022
2030
2040
2050
Year


Theoretical Useful Energy Demand for DEU - non-residential
Scenario
Baseline
High Efficiency
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TUED (TWh)
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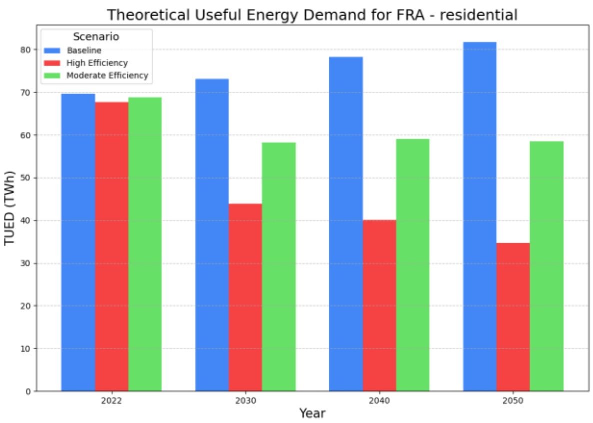
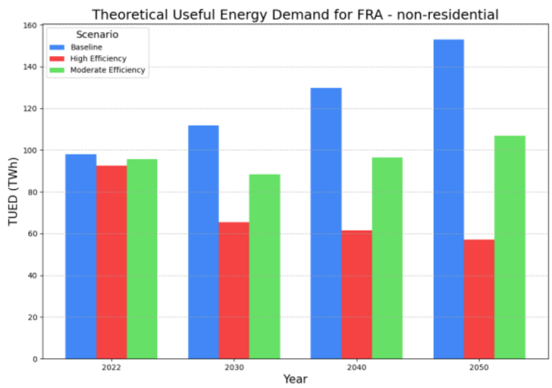
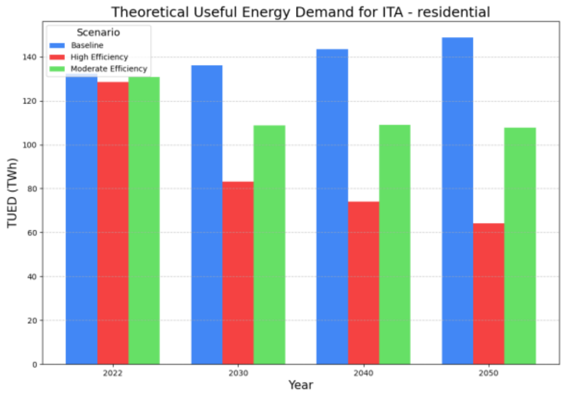
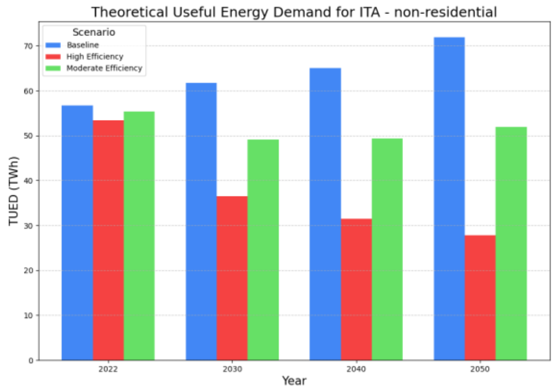
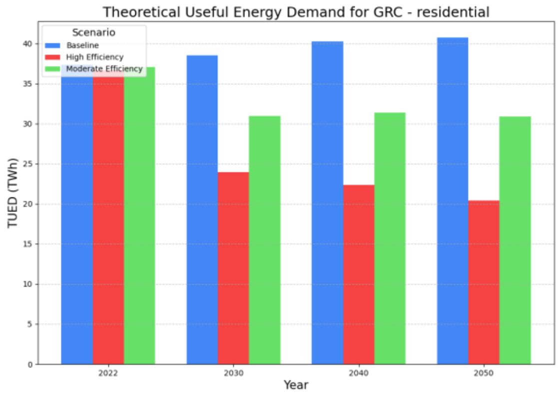
2050
Year

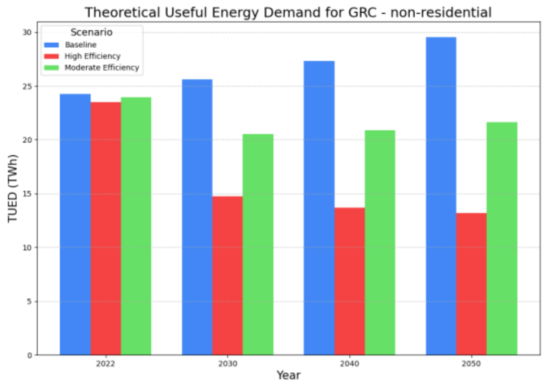

Theoretical Useful Energy Demand for FRA - residential
Scenario
Baseline
High Efficiency
Moderate Efficiency
TUED (TWh)
0
10
20
30
40
50
60
70
80
2022
2030
2040
2050
Year

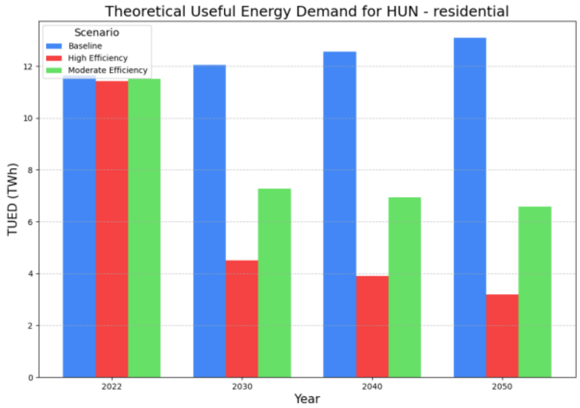

Theoretical Useful Energy Demand for FRA - non-residential
Scenario
Baseline
High Efficiency
Moderate Efficiency
TUED (TWh)
0
20
40
60
80
100
120
140
160
2022
2030
2040
2050
Year

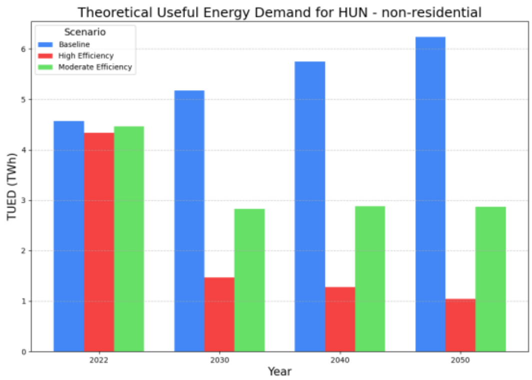

Theoretical Useful Energy Demand for ITA - residential
Scenario
Baseline
High Efficiency
Moderate Efficiency
TUED (TWh)
Year


Theoretical Useful Energy Demand for ITA - non-residential
Scenario
Baseline
High Efficiency
Moderate Efficiency
TUED (TWh)
Year


Theoretical Useful Energy Demand for GRC - residential
Scenario
Baseline
High Efficiency
Moderate Efficiency
TUED (TWh)
Year


Theoretical Useful Energy Demand for GRC - non-residential
Scenario
Baseline
High Efficiency
Moderate Efficiency
TUED (TWh)
Year


Theoretical Useful Energy Demand for HUN - residential
Scenario
Baseline
High Efficiency
Moderate Efficiency
TUED (TWh)
Year


Theoretical Useful Energy Demand for HUN - non-residential
Scenario
Baseline
High Efficiency
Moderate Efficiency
TUED (TWh)
Year