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Home Energy Management Systems Adoption Scenarios: The Case of Italy

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Abstract: The 2030 zero-net emission target in the E.U. demands a significant improvement in the energy performance of the building stock. This study analyses the adoption of connected thermostats and Home energy-management system solutions (HEMS) as an effective means to tackle the residential energy footprint. It reviews the main features of HEMS systems in terms of technology, cross-study performances, and the obstacles to widespread adoption; the study adopts the case-study methodology to examine the impact on the Italian real estate stock at a regional level. A matrix of adoption scenarios assesses the potential benefits of global residential energy savings, weighted by local climatic variations, dimension, number of single dwellings, and average primary energy reduction per household. Results demonstrate that all adoption scenarios dramatically reduce residential energy consumption, outperforming the E.U. targets for Italy by 2030.

Keywords: HEMS; energy consumption; smart building; energy policy; Italian government

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1. Introduction

1.1. EU 2030 Targets on Building Efficiency and Residential Energy Consumption

Vast empirical evidence in single-country and multi-country studies from developed and developing countries found energy consumption to be the primary source of carbon emission [1], showing that energy intensity has a unidirectional [2,3] and bidirectional, casual relationship [4,5] to the rise of per-capita CO_2 emissions.

To tackle this environmental and social issue, the European Union (E.U.) 2030 agenda was set to meet the Sustainable Development Goals (SDGs) with the commitment to reduce energy consumption by more than 20% by 2020 and 32.5% by 2030 [6]. However, energy consumption values Gini coefficients indicate a moderately high concentration in the five largest 27 EU economies: Germany, France, Italy, Spain, and Poland [7].

Among these five countries, the final energy consumption per capita of the three leading European industrial powerhouses are visually displayed in Figure 1.

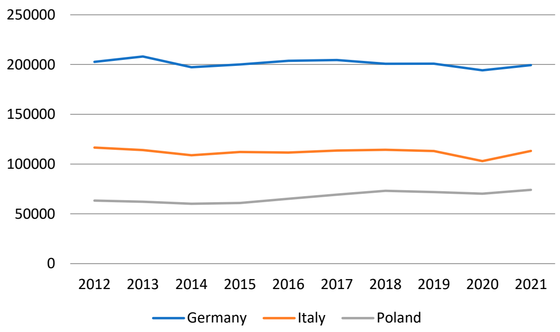

Figure 1. Final energy consumption in thousand tonnes of oil equivalent. Source: own elaboration based on EUROSTAT [8].

In the time series while Germany's economy has seen a stable or slightly declining energy consumption the equally dynamic Polish economy significantly increased energy consumption.

These differences might be explained by the Environmental Kuznets Curve (EKC) hypothesis extensively tested globally. According to the EKC, the relationship between income level and carbon emissions, which is causally linked to energy consumption, presents an "inverted U-shaped" curve [9]. Energy intensity may decrease with economic growth because of the technical changes in energy efficiency that accompany economic development [7].

Urbanisation level is another explaining variable causing a positive correlation between economic growth and ecological footprint [10]. The complex causal relationship between economic growth, energy consumption, urbanisation, and carbon footprint is underlined in the highly urbanised European environment: 40% of energy consumption and 36% of the E.U.'s carbon emissions derive from the building sector [11].

In fact, the European building stock is tending to obsolescence as 75% of it in the E.U. cannot be considered energy efficient as only 3% is classified as "EPC class A" or "very efficient". However, 85–95% of it will last longer than 2050, thus ushering in need for massive continental renovation programs [12].

The 2019 Green Deal program led to a broad Renovation Wave strategy, aiming to revamp 35 million buildings by 2030, bringing an estimated EUR 291bn in environmental, economic, and social benefits related to energy poverty reduction [13]. A complete overhaul of the E.U. stock would necessitate 'deep' renovation, meaning more than 60% savings in energy consumption for 70% of the buildings [14].

The first issue is the cleavage, visually displayed in Figure 2, between Western/Northern EU countries, where energy efficiency programs have been in place for decades, and Eastern/Southern European member states, where the building stock is outdated and highly inefficient.

The Renovation Wave strategy presents significant technical and social obstacles [15] to achieve its ambitious goals, given the need to raise the annual deep renovation rates to 3% by 2030 [13]. Still, the major impediment would be the massive financial burden of such programs, even in affluent countries like Germany [16].

Consequently, enhancing the energetic performance with light and low-cost alternatives to deep renovation works is necessary, especially for late-comer countries forced to catch up on sustainable buildings. European legislative policies have recently backed up this option suggesting Home energy-management system solutions (HEMS) as a viable choice.

The E.U. Directive 2018/844 recommends member countries adopt Smart Readiness Indicators (SRIs) [17], a framework evaluating the capability of buildings to employ information and communication technologies (ICTs), to improve the lives of the tenants and to be integrated into the broader urban grid [18].

The cornerstone of the European legislative framework currently in place is the Energy Efficiency Directive (EED) [19], following which national governments are required to submit and periodically update National Energy Efficiency Action Plans (NEEAPs) [20].

In compliance with art. 7 of the Energy Efficiency Directive, every country has to present a National Energy Efficiency Action Plan. In 2018, the Italian government introduced the National Integrated Plan for Energy and Climate targeting a decrease in final energy consumption to approx. 9.3 Mtoe/year. Most of the forecasted reduction in energy consumption, about 5.7 Mtoe, is planned to be achieved in the civil sector, namely in the residential realm [21].

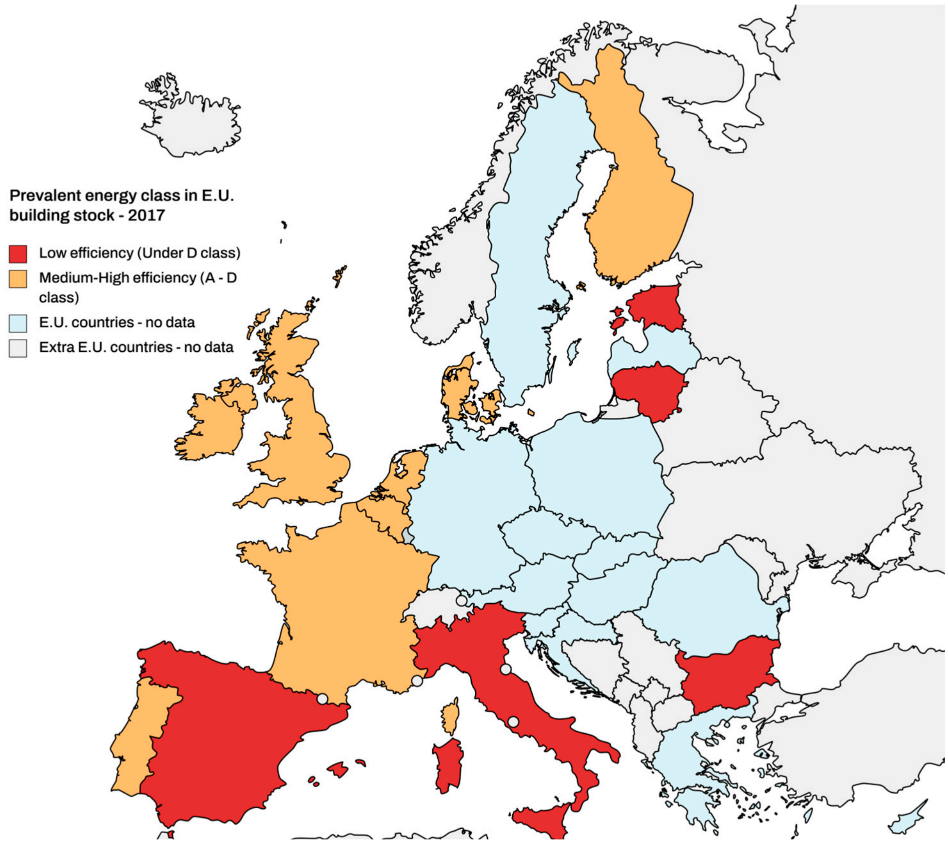

Figure 2. European map with the prevalence of building stock within two categories: low efficiency (under D class) and medium-high efficiency (A–D class). Source: map created by authors with Mapchart.net based on BPIE data [14].

However, decarbonisation technologies, such as transport and heating electrification, are energy intensive. The Italian energy utility Terna projected two national scenarios derived from Italian and European ENTSO scenarios [22]:

(1) Fit-for-55 (FF55): reaching E.U. emission goals for 2030 which imply a significant electrification process in transportation and residential heating.
(2) “Late Transition” scenario: reaching E.U. emission target five years late.

In Italy, energy-saving policies in the residential sector are primarily driven by tax detraction and credit-based government incentives, such as Ecobonus, and, more recently, Superbonus. Ecobonus featured a 65% tax detraction on building automation installations and has a decade-long track record. Therefore, it has been used as a reference in this paper [22].

1.2. Smart Home/HEMS Definition, Components, and Technologies

Several definitions apply to smart-home environments starting from popularising the term in the early 2010s. Smart homes are defined as residences equipped with an IoT-integrated network linking sensors and domestic devices or appliances, whose features can be remotely monitored, accessed, or controlled to provide services to the inhabitants for a better quality of living in terms of safety, comfort, and energy saving [23].

The convergence of technological developments on energy efficiency and heightened ecological sensibility led to the concept of home energy-management systems (HEMS): a network of IoT devices helping to manage energy consumption Connected devices allow users to control appliance usage and schedule power cycles without human intervention, enabling home control and monitoring from afar [24].

Users can control and monitor smart-home appliances remotely through the home energy-management system (HEMS), essentially a remote monitoring system employing telecommunication technology and sensors [25].

The literature on the social dynamics of energy consumption suggests that feedback on usage data enables energy savings through rational behavioural changes [26,27]. HEMS systems include devices ranging from connected thermostats, smart meters, and energy-monitoring tools to automated lighting, heating, and cooling controls.

Blurry boundaries separate the concept of home automation and smart building; therefore, energy efficiency systems can extend to smart plugs and plug load automation [28], connected P.V. panels for renewable energy production [29], smart building controls [30], and building energy assessment [31].

There are hundreds of HEMS devices on the market able to implement energy savings through both behavioural and operational changes [32] but for a functional scope. This research is mainly limited to the benchmark HEMS technologies presented by Urban et al. [33] summarized in Table 1 and implemented in residential housing, but the field is rapidly expanding.

Table 1. Selected HEMS approaches by technology. Source: Urban et al., "Energy savings from five home automation technologies: A scoping study of technical potential." *Boston, MA, Fraunhofer USA Center for Sustainable Energy Systems* (2016) [33].

HEMS Technologies	*Energy Saving Method*
Connected thermostats	Connected thermostats allow occupancy and sleep mode temperature setbacks and monitor energy consumption in real-time.
HVAC zoning control	Automated zoning allows thermally isolated rooms or areas within a home to be conditioned independently.
Automated window covering control	Automated window covering control uses a motorised device to adjust position, limiting energy transfer through the window.
Occupancy-based lighting	Automated lighting control aligns lighting usage with occupant presence, senses when a space becomes occupied, and automatically turns on the lights.
Circuit-level control	Circuit-level controls can intelligently turn off the circuits powering home electric devices to save energy without compromising ordinary functionality.

Most of these technologies optimise the power consumption of heating, ventilation, and cooling (HVAC) appliances, the largest source of residential energy utilisation. A quantitative study conducted by Noro et al. [34] in 2023 on the most effective residential primary energy savings actions confirms that the focus of interventions should be the heating/cooling generation system.

Many interesting developments are taking place in energy efficiency. Integration with artificial intelligence through the deployment of sensors collects data for machine learning techniques [35], allows the algorithm to learn the users' consumption habits, and generates consumption predictions [36]. A.I. allows data-driven predictive control via methods like time-series forecasting (TSF) and reinforcement learning (RL) [30].

As HVAC efficiency improves but the ICT devices' mass diffusion continues, the energy consumption of plug loads is set to become the highest factor. To face this issue, experimental IoT-based occupancy-driven plug load management systems can potentially reduce user burden through smart automation and load monitoring [28].

ICT diffusion can be leveraged by offering innovative digital services interoperable with existing geographic web-service infrastructures, supporting energy efficiency at the urban and building level. These platforms could enable automatic large-scale assessment of building energy behaviour based on data available from public services [31].

The communication protocols connecting the devices are also expanding and evolving. Technology providers employ a range of protocols, such as Z-Wave [37], Zigbee [38], Wi-Fi [39], IPv6 [40], Lorawan [41], and Bluetooth [42–44], combining the features of fast connectivity, low frequency, long-distance communication, and flexibility. Smart building applications use different automation protocols like KNX, En-Ocean, 1-wire, BACnet, C-Bus, CC-link, and DALI [45] but data protection studies also proposed blockchain-based smart homes [46].

1.3. HEMS Social Barriers, ICT Penetration, and Adoption Rate

HEMS systems have been on the market for quite a long time as part of the growing "Internet of Things", but the adoption rate of these technologies is lagging behind expectations, with significant differences among geographies.

A survey on individual adoption in the E.U. countries, illustrated in Figure 3, is evidence of the spread between early adopters in Northern Europe and the rest. Interviews in Denmark, Ireland, Estonia, and Sweden claim an adoption rate nearing or surpassing the 15% threshold, while the Netherlands is a positive outlier with a 65% adoption rate.

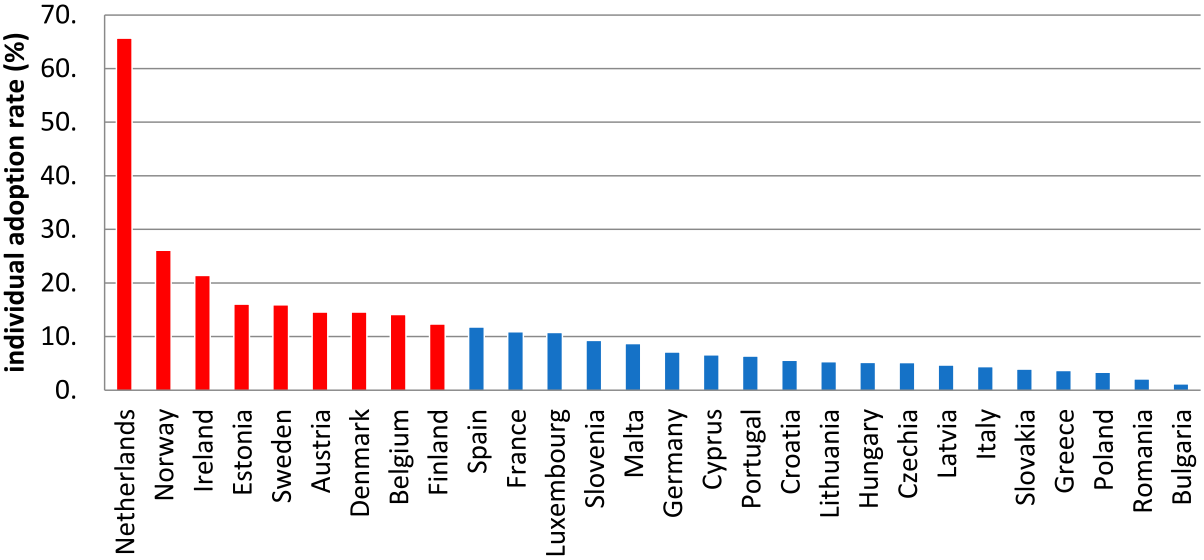

Figure 3. Individuals use internet-connected thermostats, utility meters, lights, plug-ins, or other internet-connected solutions for energy management for their home. Early adopters in Northern and Western Europe are marked in red for didascalic purposes, while late comers in Southern, Central and Eastern Europe are marked in blue. Source: own elaboration based on EUROSTAT [47].

Italy and its peers in Southern and Eastern Europe are positioned among the technological latecomers at the lower end of the adoption spectrum. Data on smart home penetration in the Italian market, which has only seen an acceleration in recent years, as seen in Figure 4, is backing the need for a technological catch-up.

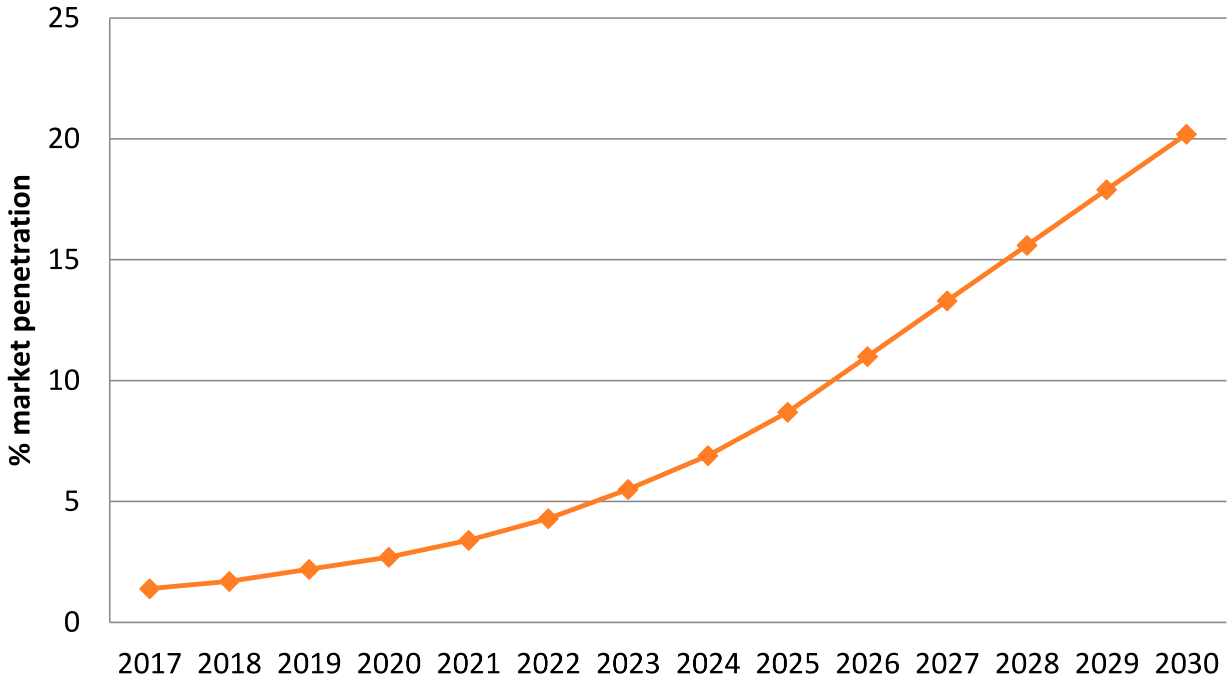

Figure 4. Smart home market penetration projection in the Italian market. Source: own elaboration based on Statista data [48].

This abysmal diffusion of smart homes in Italy could be related to environmental and social factors. Real estate data reports 75.2% of Italian households living in owner-occupied dwellings; therefore, the adoption choice lies in the subjective perception, sometimes conditioned by a lack of awareness of the single tenant, ignoring potential energy benefits [49].

Another decisive factor is the scarce competencies of users and installers (e.g., awareness and technical training), which are essential for any sustainable development initiative to succeed [50]. In a survey interrogating construction companies conducted by Politecnico di Milano, 42% denounced the difficulty of hiring tech-savvy and skilled collaborators as the major obstacle to realizing smart buildings [51].

The COVID effect on technology adoption could explain the increased growth rate detected in a 2021 study asserting that smart home systems' social acceptance heightened as a consequence of the social disruptions, policy changes, and activities of organizations [52]. In this timeframe, data consistently show growing internet access, a critical smart home enabler, facilitating citizens' empowerment for better-informed decision-making on energy management [53].

This global trend is confirmed by Figure 5, displaying drastic improvement in internet access during the COVID years. Rural areas in the Italian South, like Calabria and Molise, saw a considerable 10–15% increase. Still, regions in the North also improved across the board, leading to national ICT coverage per household of up to 91% by the end of 2022.

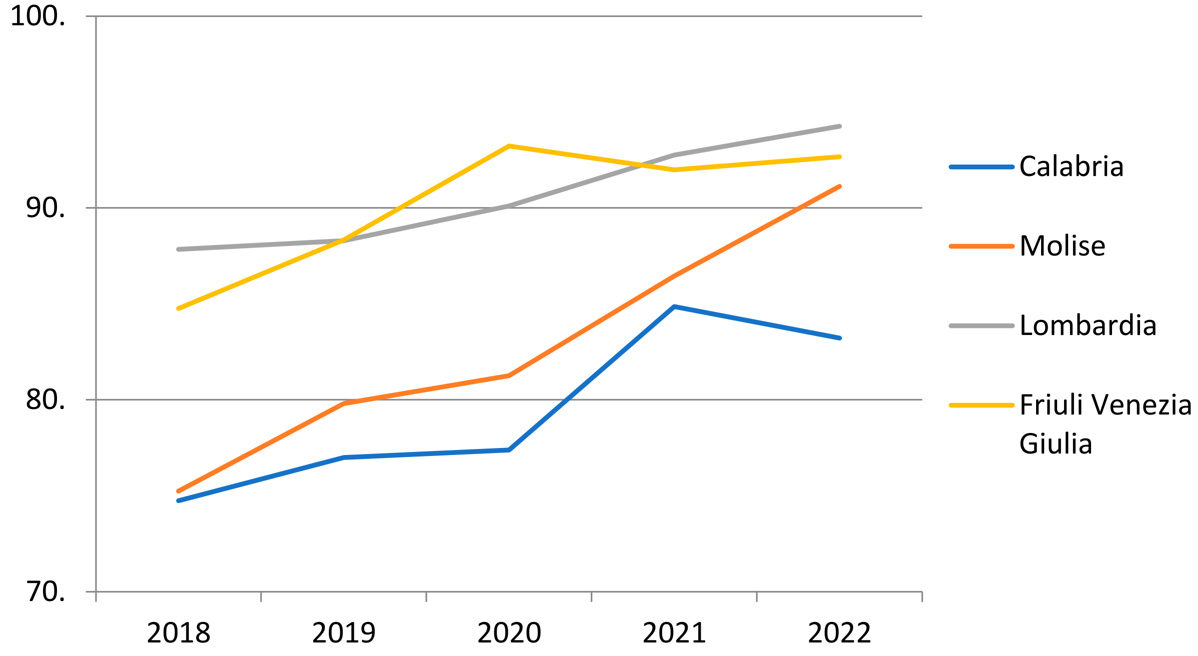

Figure 5. Households with access to the internet at home in selected Italian NUTS 2 regions. Source: own elaboration based on EUROSTAT [54].

Anyhow, effective residential energy management takes much more than simple ICT penetration. Smart homes and buildings require citizens, public administrators, and energy managers, since the attitude towards energy saving in the public sphere, the technical skills and the privacy practices regarding energy consumption and management are as crucial as the technology itself [55]. Without directed policies, the critical variable in future scenarios is the citizens' participation rate, which is strictly connected to IoT acceptance levels in the population [56].

Consumers are aware of the smart home's potential to support energy management. Still, they are not persuaded by the trade-off with benefits like security, comfort, and convenience, which could imply increased energy consumption [57]. Table 2 outlines the literature regarding benefits and risk factors influencing consumers' IoT acceptance and mentions the sociological models proposed to assess the perception of these technologies.

Table 2. Sociological studies and influence factor on IoT acceptance. Source: literature review.

Studies	Sociological Method	Influence Factor
Mulcahy et al. (2019) [58]	Technology readiness index	Consumer engagement, Perceived risks, and trust
Wang et al. (2018) [59]	Net valence model	Performance expectancy, compatibility, privacy risk, performance risk, and time risk
Aldossari et al. (2015) [60]	Unified theory of acceptance and use of technology (UTAUT2)	Performance expectancy, effort expectancy, social influence, hedonic motivation, price value, trust, and security risk
Hong et al. (2020) [61]	Resistance theory and perceived risk model	Performance risk, financial risk, privacy risk, psychological risk, technology uncertainty, and service intangibility
Shuhaiber, A. et al. (2019) [62]	Technology Acceptance Model (TAM)	Attitude, perceived usefulness, trust, lack of awareness, and perceived risks

The matrix of influence factors in Table 2 illustrates that energetic performance expectancy has been mentioned in multiple pieces of research as the leading adoption benefit.

These findings relate to survey data drawn from the U.K., the leading smart home adopter in Europe, by Sovacool et al., where energy management and energy consumption reduction are considered the most important benefit of smart homes [63].

On the other side, privacy, which is the perceived risk directly related to trust, security, and technological uncertainty, emerges as hurting adoption. To operationalize these qualitative findings, we could assume that the perceived risk would cause a 10% refusal to occur in adoption scenarios even if national policies were in place.

However, before delving into the technology's pros and cons, the lack of awareness and the intangibility of services remains a primary obstacle. Interestingly, similar benefits and risk factors also appear when the environment changes: findings from an extensive mixed-methods analysis of the smart energy management systems adoption in the workplace suggest educating employees on the system features as they are unaware of their potential and offer assurances about their data usage [64].

Given the abovementioned theoretical framework, the present research aims to examine the capacity of Home Energy Management Systems adoption to significantly improve the energy efficiency in outdated building stocks enough to reach the Sustainable Development Goals (SDGs) targets. The results are fine-tuned accounting variables such as social impact factors, housing features, and local climatic variations to obtain a more realistic overview of the issue.

Few studies have systematically investigated HEMS adoption at the national level. The only complete field studies available in the literature have been conducted in the USA [34] where IoT penetration is extensive, and the present work would like to enrich the empirical literature with results from Europe.

In Europe, however, cross-country comparative research is undermined by the scattering of data among national agencies. Therefore, the authors consider the case study approach the most effective and innovative to gain insight into energy efficiency policies leaving the possibility to scale up in future investigations with a larger scope.

Extensive energy monitoring data from its building automation intervention in renovation works, significant territorial differences, and regular cadastral updates made Italy a good candidate for a case study in Europe.

2. Methods and Materials

2.1. Building Stock and Energy-Saving Data

Although smart technologies can collect granular use data in real-time, making it possible to precisely determine the energy impact of HEMS systems, validate savings, and set up performance baselines is often challenging [65]. Results fluctuate widely, although not unexpectedly since literature emphasizes the impact of household behaviour responding to energy feedback highly individually [66].

Taking into consideration the smart thermostat, the most typical energy device in households, energy savings estimates range from 5.7% in single-family houses and 7.7% in apartments [16] up to 28% when occupancy-based smart thermostat algorithms are deployed [35]. In a large-scale simulation study on smart thermostat in 40 American cities, with different building foundations, energy classifications, and heating source savings, reaching 30% of energy consumption [67]. Energy-saving claims by smart home industry proponents and academic researchers are criticised, arguing that they are based on trials in carefully controlled laboratory conditions rather than in real-life settings [68].

Given the inconsistency in estimates, this study refers to estimations by the U.S. Department of Energy, where the average savings approximate 10% [69], and a cross-study review conducted by the USA Fraunhofer Institute, indicating 9–13% overall savings [33]. For the Italian case study, the only performance assessment of HEMS performance available is published by Politecnico di Milano, highlighting savings of up to 20% in electricity and 23% in heating on average per household. These assessments are summarised in Table 3 for operational use [51].

Table 3. Reduction in relevant primary energy by technology and average savings. Sources: Urban et al., *"Energy savings from five home automation technologies: A scoping study of technical potential."*, Boston, MA, Fraunhofer USA Center for Sustainable Energy Systems (2016); Politecnico di Milano, L'evoluzione del mercato smarthome nel 2022.

HEMS Technologies	*Yearly Energy-Saving Data*
Connected thermostats	9–13% reduction in primary energy
Total average savings (Italy)	Heating: 23% Electricity: 20% HEMS: 12 kWh per sqm Only thermostats: 6 kWh per sqm ±1 kWh (estimate)

2.2. Climatic Variations Impacting Performance

Micro-climatic variations are critical factors impacting energy performance because they affect user preferences for heating and cooling systems, the most energy-consuming component in households [70]. HEMS system behaviour studies concerning seasonal changes and outside temperatures have been conducted mainly for smart thermostats.

Results are not conclusive; while a study points out hot-humid and cold climate zones to have the highest potential for significant savings [71], another indicates temperate climates to be more energy-efficient because of the low discrepancy between indoor and outdoor temperatures, leading to more substantial reductions in HVAC run times and savings [63].

Italy could be considered an ideal test field to assess these assumptions since its latitudinal extension causes the formation of local micro-climates. This study evaluated the average heating and cooling days as the primary marker to illustrate the Köppen climates dividing the peninsula. With over ~3.500 heating degree days in the northernmost regions of Valle d'Aosta and Bolzano Province down to less than ~1000 in Sardegna and the southern Italian regions; Figure 6 indicates a clear pattern connecting geography and local climate.

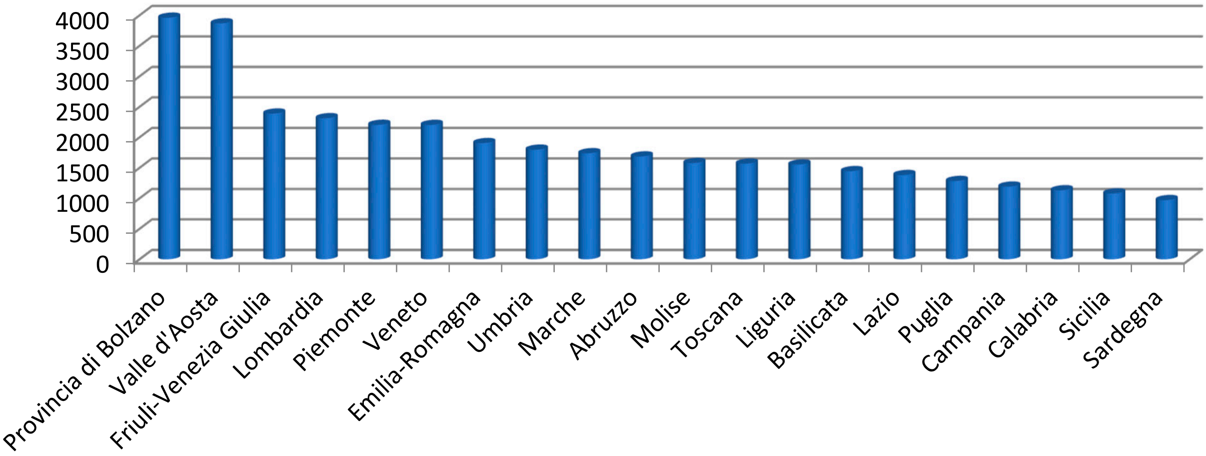

Figure 6. Cooling and heating degree days by NUTS 3 regions—annual data 2020. Source: own elaboration based on EUROSTAT [72].

Then, climatic data can be correlated with the building automation savings drawn from the estimations of renovation works carried out on the Italian building stock between 2014 and 2020, as indicated in Figure 7.

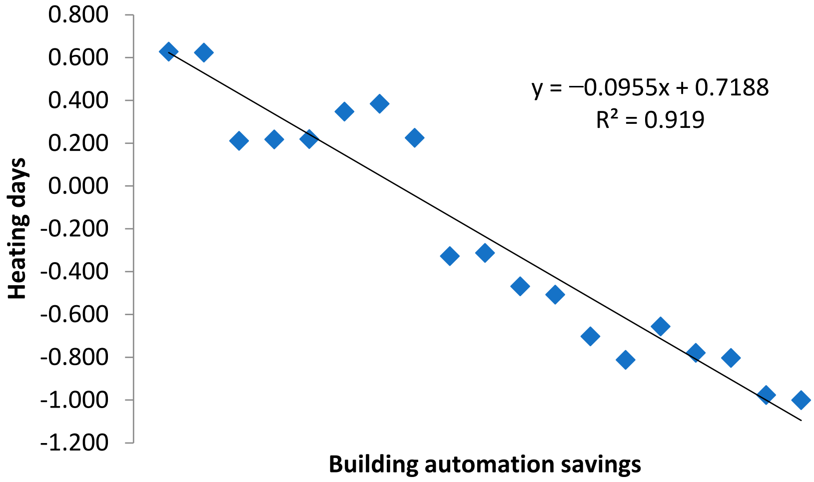

Figure 7. Correlation index between heating days per region and building automation savings per region in 2020 Ecobonus data. Source: own elaboration based on EUROSTAT [72] and ENEA [73] data.

High R^2 indicates that average heating days are strictly correlated to building automation savings, explaining most of the variation in the response variable around its mean. Data about seasonal associations are limited. However, the results are consistent with seminal research by the National Research Council Canada, where Canadian homes exhibit a higher saving of 13% with thermostat setback in winter and set up of 11% in summer [74].

Table 4 estimates HEMS savings based on a regional correlation between building automation installation savings and heating days per year (S_i).

Table 4. Estimated HEMS energy savings by region Source: own elaboration based on Figure 7 data.

Correlation Values	*Regions*	*Estimated HEMS Savings*
≥0.3	Piemonte, Val d'Aosta, Friuli Venezia Giulia, and Trentino Alto Adige	13 kWh
0.3–0	Liguria, Lombardia, Veneto, and Emilia Romagna	12 kWh
0–0.5	Toscana, Umbria, and Marche	11 kWh
≤−0.5	Lazio, Abruzzo, Molise, Campagna, Puglia, Basilicata, Calabria, Sicilia, and Sardegna	10 kWh

These energy savings must be applied to the current Italian building stock's actual condition in terms of ownership, dimension, and number. The gross area of Italian dwellings is about 4 billion square meters; the average dwelling dimension is 117.42 square meters per household [75]. As outlined in Figure 8, the northern regions' dwellings (Valle d'Aosta, Piemonte, Liguria, and Lombardia) tend to be smaller, reducing the heating dispersion and reinforcing the overall energy savings by HEMS.

The average dwelling dimension in sqm is calculated as

$$\mathbf{D_i = A_t/N,} \tag{1}$$

where $\mathbf{A_t}$ presents the total gross area of dwelling; **N** the total number of A group housing units per region.

The real estate stock surveyed in the Italian cadastral archives, as of 31 December 2021, consists of more than 77 million properties [73], of which more than half belong to A Group:

35,379,685. This figure encompasses all kinds of residential properties and offices [76], the spaces more likely to be equipped with smart home solutions, due to the limitations of radio communication technologies to connect long distances.

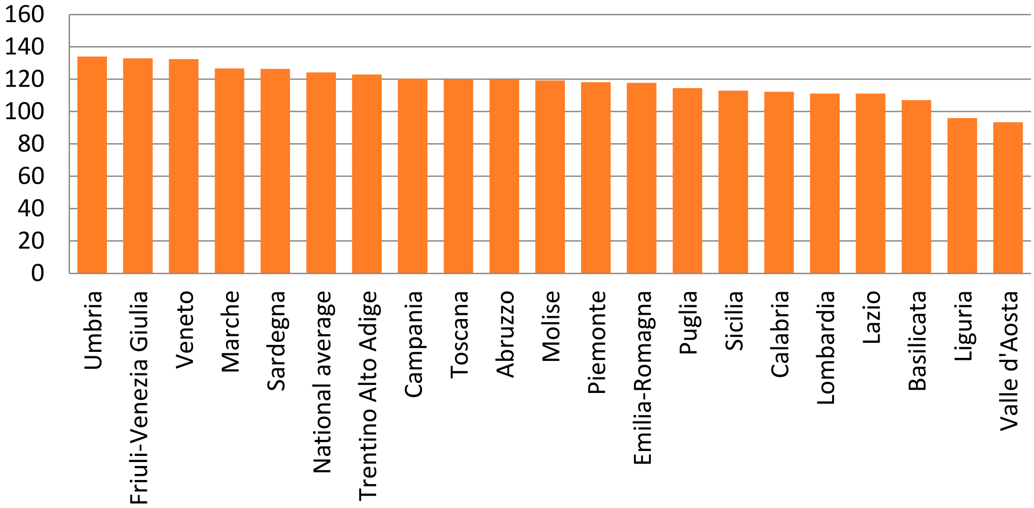

Figure 8. Regional distribution of average area. Source: Own elaboration from Ministery of Finance data [75].

The methodology adopted to estimate the local climatic effect on HEMS saving in the Italian regions can be applied elsewhere to better weigh regional environmental discrepancies in national contexts with high climatic variance, where national averages are not meaningful for policy or research purposes.

To the author's knowledge, it appears to be the first study to weigh into the savings calculation of the average house dimension at the regional level, allowing to assess local discrepancies in the housing stock, e.g., between urban and rural areas.

As most field studies have been carried out in limited areas and cases, this approach could extend the quantitative assessment of HEMS behaviours in larger spatial contexts without losing empirical detail.

3. Results

This study examines a matrix of four possible scenarios to assess the global energy impact of HEMS adoption and their effectiveness in reaching the European emission target, which applies in the framework of residential energy consumption in Italy in 2030, whose trend is outlined in Figure 9.

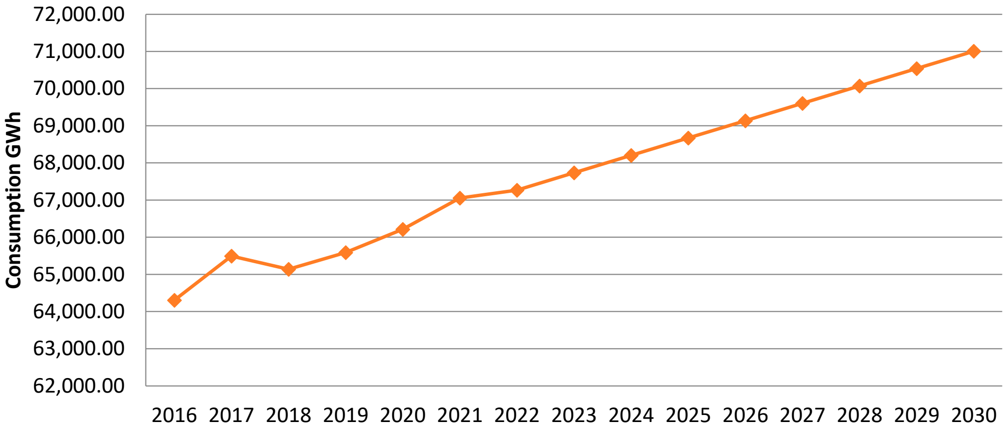

Figure 9. Actual and projected residential consumption in Italy 2016–2030. Source: own elaboration on Terna historical data and linear projection [77].

If the economic environment is not subjected to other external shocks like in 2022, the trend will likely remain steady until 2030. Although the linear projection estimates a significant increase in overall residential consumption, Table 5 shows that Fit-for-55 and Late Transition scenarios forecast an even higher growth rate in energy consumption based on the electrification wave in heating and other related factors.

Table 5. 2030 energetic residential consumption scenarios. Source: own elaboration and ENEA data [73].

Study	*Residential Consumption*
Study simulation	71.004 GWh
F55 2030	83.190 GWh
LT2030	78.500 GWh

Regional energy consumption data is available at TERNA statistical archives using the parameters issued by the Italian statistical institute to analyse the economic activity by different user categories [77].

Given the national and regional residential consumption data, the effect of HEMS and smart-thermostat adoption scenarios can be laid out in these hypotheses:

(1) A high adoption scenario pushed by a hypothetic national policy is limited only by the boundaries of ICT territorial penetration and individual rejection thresholds.
(2) A low adoption scenario follows private households' current adoption trend without governmental intervention.

Then, both scenarios are weighted by adopting full HEMS or smart thermostat-only systems in households, whose values are assessed in Section 2.1. Table 6 visually illustrates the matrix.

Table 6. Adoption and technology scenario matrix Source: own elaboration.

Scenario 1 90% adoption rate full HEMS systems	**Scenario 2** 20% adoption rate full HEMS systems
Scenario 3 90% adoption rate of smart thermostats	**Scenario 4** 20% adoption rate smart thermostats

Given the scarcity of large-scale assessments of HEMS adoption, especially outside the U.S., the analysis was based on the conceptual and operational framework proposed by York et al. (2015), one of the few systematic investigations currently available.

In York et al. (2015), global energy savings were calculated by multiplying the % end use attributable to the technology, average savings, ratio of net savings to gross savings, and participation rate. Subsequently, the resulting savings were divided by the projected 2030 U.S. electricity consumption to estimate how much each measure could reduce total U.S. 2030 electricity usage (end use) on a percentage basis [33].

In this investigation, the compound was prepared by adapting the procedure York et al. (2015) used to include features like climatic variations, housing stock, and dwelling dimension on a regional level and transpose variables such as the end user per technology into the overall residential energy consumption. The formula for the average yearly saving per region in residential electric consumption is as follows.

$$\mathbf{ESP_i = [(S_i) \times (D_i) \times (N_i)].} \quad (2)$$

$\mathbf{ESP_i}$ represents the energy saving potential in GWh per region; $\mathbf{S_i}$ denotes average estimated HEMS savings per sqm weighted by regional disparities; **D** indicates average dwelling dimension in sqm per region; $\mathbf{N_i}$ suggests the number of primary dwellings per region by a scenario where the variable changes according to the various adoption scenarios.

N_1: 90% adoption rate HEMS (Scenario 1) per A group building stock.
N_2: 20% adoption rate HEMS (Scenario 2) per A group building stock.
N_3: 90% adoption rate of smart thermostats only (Scenario 3) per A group building stock.
N_4: 20% adoption rate of smart thermostats only (Scenario 4) per A group building stock.

Calculations on home energy savings refer to 2022 data, while real estate estimates date back to 2016 when a general cadastral survey was carried out. The study assumes that dwelling dimension and the number of primary dwellings per region remain invariant over time, given the declining trend of the Italian demographics, which will lead to lower occupancy rates, even if the overall building stock increases in number, thus decreasing the general HEMS usage [78].

$$\mathbf{RC_i} = \mathbf{RC_p} - \mathbf{ESP_i}. \tag{3}$$

RC_i represents the 2030 residential consumption projection in GWh per region and per adoption scenario, and **RC_p** stands for the 2030 residential consumption projection in GWh per region, giving the projected 2030 saving per region (**S_p**):

$$\mathbf{S_p} = \mathbf{ESP_i/RC_p} \times \mathbf{100}. \tag{4}$$

Figure 10 illustrates the impact of energy savings on each Italian region's projected 2030 residential primary energy consumption in the four scenarios concerning different adoption degrees and technologies.

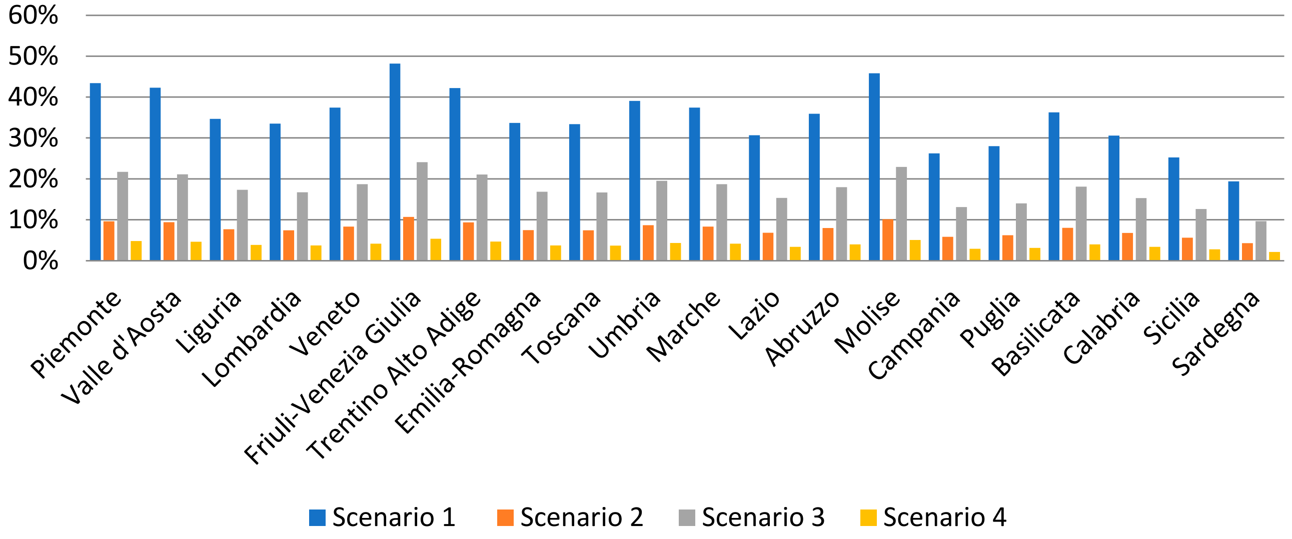

Figure 10. Regional energy savings percentage by the scenario in 2030. Source: own elaboration.

Finally, Figure 11 provides a visual overview of the national HEMS adoption scenarios and compares them to the European energy consumption target scenarios: $\sum \mathbf{R.C._{(i)}}$.

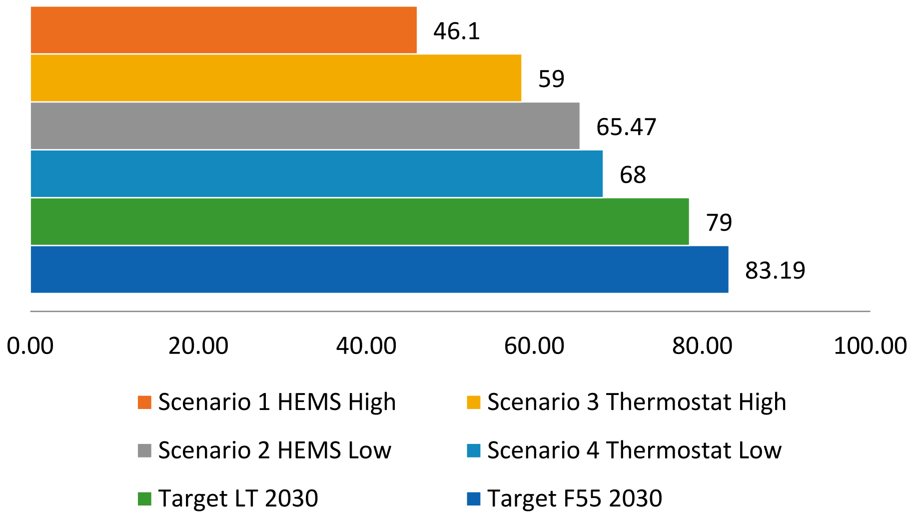

Figure 11. 2030 Global residential consumption in Italy by the scenario in TWh. Source: own elaboration.

4. Discussion

This study set out to assess the importance of HEMS in energy consumption reduction, and the findings broadly support the work of other studies in this area linking the HEMS adoption rate to effective global energy consumption reduction.

Although in a simulation study in Sweden during the early days of the pandemic, the building energy (lighting and appliances) slightly surpassed the HVAC energy consumption [79], the findings by Noro et al. (2023) [34] and the effectiveness of thermostat-only interventions to slash residential energy consumption confirm that HVAC efficiency is the primary enabler of home energy management.

Moreover, the results have practical implications for various players: policy-makers, energy and telecom utilities, manufacturers, and end users. Provided that technical prerequisites are needed to get the full potential of HEMS technology.

Telecom and Energy public utilities would need to integrate single HEMS into Smart city projects with different layers of the Internet of Things communicating by 5G technologies, allowing energy-saving operations on a large scale and complete interconnection with the broader infrastructure [80].

The widespread deployment of Smart home technologies would allow the adoption of a new strategy for energy trading in distributed energy systems [81].

The user's worry about compatibility and technological uncertainty means that manufacturers, infrastructure providers, and public stakeholders should consider interoperability between their systems and networks. As many players converge towards the Matter platform in the smart home segment, creating a coherent IoT infrastructure is necessary to ensure that hardware and software are externally compatible with communications providers, energy suppliers, or system operators, especially during peak usage [82].

Interconnectedness is crucial to maximizing benefits but privacy risks as a significant impediment to HEMS and smart home adoption. All those single risk points converge to the general lack of trust in this technology or, more likely, the perceived unwillingness by manufacturers and providers to face the users' concerns convincingly.

Generally speaking, to bring forward technology acceptance in late-comer countries, much higher cooperation among the industry stakeholders is required, as problems such as trust, regulations, lack of technical competencies, and product awareness need different actors' concerted efforts to overcome.

Throughout the literature, the main perceived utility of HEMS adoption is energy performance and the risks/expectations connected to it. Stakeholders should clarify the value proposition with more real-world estimations of energy saving per device or system installation, providing concrete case studies to the public.

Regarding this factor, perhaps the most critical finding of the study was the positive correlation between building automation energy savings and heating days, consistent with the analysis of seasonal energy efficiency fluctuations by Manning et al. (2007) [74].

This finding implies that policymakers could plan targeted energy renovation interventions according to the local climatic conditions rather than adopting country-wide, inefficient, and costly solutions. Following this direction, there is ample room for further progress in determining which HEMS technology is more cost-effective in each climatic condition.

For this goal, urban-scale "ecomaps" suited for planning activities and large-scale energy pre-certification purposes can be created by transforming HEMS digital platform into a smart service platform accessible from both a web-based client and Apps [31].

Digital technologies might mitigate the lack of perceived usefulness and service intangibility for end users outlined by Hong et al. (2020) [61] and Shuhaiber et al. (2019) [62]. Young users can be effectively engaged by appealing to social influence and hedonic values. A study among Millennials and Gen Zers on energy-efficient app usage intentions found the positive effect of adopting energy-saving attitudes developed during COVID-19 and heightened environmental knowledge [83].

For a more mature audience, policymakers creating energy conservation plans for the residential sector could leverage the demonstrated strong association between energy saving and the intelligence of the built environment [84].

From an assessment of COVID-19's impact on energy consumption and CO_2 emissions, it is evident that the path between households and other economic sectors diverged both in comparative multi-country studies and single-dwelling case studies. While residential consumption increased, industry, services, and transport energy footprint declined [85]. Similarly, an agent-based model tested in a Canadian building showed that the "during COVID-19 scenario energy consumption was higher by 29% compared with the "before COVID-19″scenario [86].

Therefore, the overall reduction effect on energy consumption does not affect the trajectory in the long run [87], and to enforce an effective sustainability policy [88–90], policymakers should continue implementing energy management measures horizontally from civil construction to transportation [91,92] and industry [93–95].

5. Conclusions

The present research suggests that the widespread adoption of HEMS technologies would play a significant role in achieving 2030 European energy targets. Even in the worst-case scenario (thermostat-only, low adoption rate), the residential energy consumption in Italy would largely remain under the threshold of European targets. In the best-case scenario, full-scale adoption would lower by 44.5%.

The data collection process emerged, energy and housing data are more likely to be accurate and reliable at the national level in Europe. Therefore, only the single-country case-study approach can effectively be scientifically employed to estimate the HEMS system adoption scenarios.

Given this assumption, this methodology presents significant drawbacks to generalizing its conclusions. Sources of uncertainty like the features of national databases (e.g., time and space discrepancies of cadastral surveys), the measurements of microclimatic variations potentially affecting the device's performances, and the technological differentiation on the consumer market, made possible only a partial generalization of the results.

Another impediment is the relative shortage of real-world experimental studies because industry-standard savings calculation methods are not unanimously established and compare the single estimations is troubling [33]. If simulation-based analyses could oversimplify user behaviour, large-scale randomized field studies are only possible in early adopter countries in North America and Western Europe. On one side, technological evolution, user behaviour, location, and device category could highly impact the results but on the other side, small-scale studies provide only general indications.

In conclusion, the present study aims to lay the groundwork for future research on energy performance data across device categories, climatic regions, and household types. To the best of our knowledge, it is the first effort to evaluate the impact of HEMS adoption scenarios on overall energy consumption in a European context. However, to determine if HEMS performances and global energy savings forecasted for the Italian case also apply on a European scale further modelling work will have to be carried out in future assessments.

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