D2.2. Energy Demand Assessment

Cool LIFE

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List of Acronyms

AC	Air Conditioning
CAC	Centralized Air Conditioner
CDD	Cooling Degree Days
CV	Coefficient Of Variation
DC	District Cooling
EED	Energy Efficiency Directive
EER	Energy Efficiency Ratio
EFLH	Equivalent Full Load Hours
ETS	Emissions Trading System
EU	European Union
FEC	Final Energy Consumption
GHG	Greenhouse Gas
H&C	Heating And Cooling
HVAC	Heating, Ventilation, Air Conditioning
kWh	Kilowatt Hours
M	Million
m^2	Square Meter
PC	Process Cooling
PEC	Primary Energy Consumption
RAC	Room Air Conditioners
RES	Renewable Energy Sources

SC	Space Cooling
SH	Space Heating
SEER	Seasonal Energy Efficiency Ratio
TWh	TeraWatt Hours
UED	Useful Energy Demand
VC	Vapour Compression
VRF	Variable Refrigerant Flow

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Keywords list

- Space Cooling
- Space Cooling Market
- Energy Demand Quantification

Disclaimer

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Executive summary

This research delves into the domain of space cooling energy within Europe. The objective is to evaluate the useful energy demand for space cooling in the European Union, considering both residential and service sectors, using 2021 as a reference point. A comprehensive review of literature encompassing datasets and journal papers has been undertaken to bridge any gaps in knowledge pertaining to this energy sector. Within the European space cooling market, vapour compression (VC) technologies reign supreme. This study categorizes them into room air-conditioners (RACs) and centralized air-conditioners (CACs) for analysis. Parameters such as installed capacities, equivalent full load hours (EFLHs), and the quantity of space cooling units installed have been examined as crucial factors in determining useful energy demand for space cooling. The culmination of this assessment reveals that the total useful energy demand for the European space cooling sector, encompassing both residential and service domains, amounts to about 545 TWh/year.

The objective of this study is to address the existing gaps in understanding within the European space heating and cooling market. While considerable research exists on space heating, there is a notable scarcity of information regarding air-conditioning. Employing a bottom-up methodology, we gather and analyse data pertaining to the current space cooling market. Subsequently, we adopt a top-down approach to obtain and contrast air-conditioning market data with the information acquired through the bottom-up method.

The approach integrates bottom-up and top-down procedures, alongside leveraging data from specialized tools developed by consortium members (Invert/EE-Lab and Smart-E). The first bottom-up approach involves gathering space cooling equipment data and information from various sources, including scientific literature and projects such as the IEE TABULA project Webtool. Utilizing this data, calculations are performed to determine the useful energy demand per equipment type, sector/subsector, and country for the reference year 2021.

The second bottom-up approach focuses on collecting specific useful energy demand data for space cooling purposes from scientific literature and multiplying it by the cooled buildings' floor area. This approach enables the retrieval of total useful energy demand for different sectors/sub-sectors and countries. Additionally, data on Europe's building stock useful space cooling demand are collected from various scientific literature sources and undergo a thorough vetting process to ensure accuracy and reliability.

The outcomes of the bottom-up approaches are compared with those obtained through the top-down approach, sourced from projects like Tender ENER/C2/2014-641 and the IEE Stratego project and the tools Invert/EE-Lab and Smart-E. Statistical quality control measures are applied to the assembled data to enhance robustness, including using the coefficient of variation (CV) as a statistical indicator of uncertainty. Furthermore, the comparison and data sharing aim to ensure consistency between the tools implemented in the study. By analysing divergences and methodologies employed, the most reliable approach is selected.

1. Introduction

Renewable energy sources (RES) and energy efficiency have emerged as key focal points for the European Union (EU) in transitioning from fossil fuels to meet energy objectives by 2020. These objectives encompass a 20% reduction in greenhouse gas (GHG) emissions, a 20% enhancement in energy efficiency, and a 20% increase in RES shares compared to 1990 levels. EU Member States established these targets in 2009 through the RES Directive legislation [1,2].

The Energy Efficiency Directive (EED), initially instituted in 2002 and revised in 2018 (EDDII), elevated the energy efficiency target from 20% to 32.5%. The EDDII revisions primarily aimed to enhance energy efficiency, leading to reduced costs and decreased reliance on fossil fuels within the EU [3-4].

Furthermore, the RES-Directive underwent revisions in 2018. The REDII raised the mandatory target to achieve a 32% RES share in final energy consumption (FEC) by 2030 for the EU. Achieving this target necessitates increasing production by up to 2.5 times the current levels. Additionally, the Emissions Trading System (ETS) is a tool overseeing GHG emissions, aiming for cost-effective reduction in pollutants from large-scale industries in the energy sector [4-7].

As per the REDII, specifically addressing the heating and cooling (H&C) sector, EU Member States are required to raise yearly RES shares by an average of 1.3 percentage points from 2021 to 2030. This increase is primarily driven by the fact that the H&C sector accounted for the most significant share of EU primary energy consumption (PEC) in 2018, making it the largest contributor to environmental emissions [4, 6-8].

The H&C sector encompasses space heating (SH), domestic hot water (DHW), space cooling (SC) for building comfort, and process cooling (PC) for industries. In 2016, EU H&C PEC was approximately 800 Mtoe/y, while the total EU PEC was around 1600 Mtoe/y [8]. Notably, about 85% of H&C generation is sourced from fossil fuels, with only the remaining 15% from RES. However, there is an expected increase in RES production to meet cooling needs in the EU in the coming years.

The term "cooling" refers to heat removal against the second law of thermodynamics. In this study, "cooling" denotes SC. SC ensures thermal comfort in enclosed spaces and finds applications in various sectors, particularly tertiary and residential. For the purposes of this study, we will focus solely on SC within the residential and service sectors. Process cooling, typically associated with industrial processes, will not be taken into consideration. This allows us to concentrate specifically on the cooling needs and technologies relevant to residential and service-oriented spaces. The full nomenclature list of acronyms used in the text is provided in the ‘List of Acronyms’ table.

In this investigation, a clear distinction has been made between useful energy demand (UED) and final energy consumption (FEC). Specifically, UED represents the net heat extracted from the space or process intended for cooling, while FEC for cooling denotes the energy input of the cooling generators. Consequently, these two measures differ due to distinct conversion factors. Electrically driven cooling equipment exhibits an energy efficiency ratio (EER) greater than 1, leading to lower results in cooling FEC compared to cooling UED. This work focuses specifically on useful energy demand. Hereafter, UED is indicated as energy demand (SC demand).

Importantly, while the energy demand for SC in the EU27 market is on the rise, there has been minimal exploration of the subject in scientific literature. Consequently, information and data are scarce, particularly in the residential and service sectors of the SC domain. In contrast, scientific literature predominantly delves into the space heating (SH) sector.

Despite the sensitivity of SC in the context of sustainable energy, this study encountered significant challenges, especially during the phase of information and data retrieval. Consequently, it is crucial to acknowledge that a substantial portion of the data regarding the EU27 SC market in this study is based on approximations.

The overarching goal of this study is to evaluate the SC demand of the EU27, encompassing both residential and service sectors, using the year 2021 as the baseline. The choice of 2021 as the baseline is driven by data and information availability considerations.

An integral aspect of this research involves the creation of a comprehensive and reliable dataset for SC in the EU27. To achieve this objective, various factors such as data inventory, data reliability, and data definition and comparability were carefully considered before undertaking the analysis:

1.1. Data Inventory

Initiating an inventory of data for the EU27 region commenced with gathering current information. Utilizing data and information gathered at the EU27 level offers a significant advantage due to its comprehensive perspective (e.g., EurObserv'ER [20], EUROHEAT&POWER [5], and EHPA [21]). It's important to note that achieving data completeness proved challenging. Efforts to fill data gaps involved extrapolation and compilation from extensive online datasets (e.g., EUROSTAT [22], EU Buildings Database [23], and ENERGY PLUS [24]), as well as scrutinizing scientific journal papers to ensure rigor (e.g., Jakubcionis et al., 2017 [26], Jakubcionis et al., 2018 [27], Dittmann et al., 2017 [28], Fleiter et al., 2016 [29], Werner et al., 2016 [30]). Estimates on the space cooling units sold in the recent years have also been extracted from JRAIA reports [31].

Notably, scientific journal papers highlighted the topic of SC, estimating EU SC demand potential mainly using United States (US) data as a proxy. These studies indicate a projected increase in SC demand in the coming years, potentially straining energy supply systems. Additionally, Werner et al., 2016, emphasized the necessity of location-specific information about SC demands for planning district cooling (DC) systems [30]. Estimations for EU DC demand were based on cold deliveries, identified as lower compared to estimations based on electricity inputs and assumed performance ratios for service sector buildings. Jakubcionis et al., 2017 and 2018 estimated residential and service sectors' SC demands, termed as the aforementioned SC demand [26,27]. However, the current research, focusing on SC demand, incorporates energy efficiency of the SC system into its calculations. Therefore, the current study identifies the breakdown of SC market technologies as essential, aiming to include parameters such as installed capacities, energy efficiencies, and number of units installed categorized by types and sectors. Dittmann et al., 2017, provide a comprehensive overview of different vapour compression (VC) technology types in the EU market [28], while Fleiter et al., 2016, serve as a primary source of crucial parameters essential for SC demand computation, including information on SC power peak capacities and correlated energy efficiencies for major SC technologies in the EU market.

Moreover, ensuring comprehensibility, interpretability, and usability of data and information by any user when needed is crucial. Therefore, clear metadata representation, contextual information, documentation, and annotations are essential. Documentation including creator, time references, title, access circumstances, restrictions, and terms of data usage has been provided.

1.2. Data Verification

Various sources were scrutinized and evaluated for reliability and related data. Extensive investigations helped fill a number of gaps discovered. Unreliable, misleading, or uncertain data and information were excluded from the study.

While the space heating (SH) sector of the EU27 market has been extensively researched, gaps, uncertainties, and unreliable information regarding the SC EU27 market were identified. It can be concluded that much of the information in scientific literature is based on estimations.

Based on the above, all data collected on SC concerning residential and service sectors were adequately processed and statistically assessed, including installed capacities, equivalent full-load hours, quantity of operative units, and energy efficiency coefficients per technology type and country. Synchronizing data from various sources to ensure consistency posed a significant challenge due to the disaggregated nature of the information. Section Materials and Methods, provides detailed insight into the methodology adopted to achieve the objectives, while study's results are presented in the Results section.

1.3. Data Definition and Standardization

Despite most data providers utilizing standard formats and units, not all collected data are comparable. Enhancing data comparability has been imperative, necessitating adjustments for differences, gaps, and inconsistencies due to various methods, assumptions, specifications, time-references, measures, and information providers.

2. Bottom Up Approach

2.1. Materials and Methods

For evaluating the energy demand regarding SC applications across various technologies and countries within the EU27, the categorization of vapour compression (VC) technologies suggested by Dittman et al., 2017 (Horizon 2020 Heat Roadmap Europe 4-HRE4 project) has been adopted as it stands out as one of the most precise scientific literature sources identified [28]. Additionally, this source furnishes data pertinent to both residential and service sectors. In comparison to the VC technology breakdown offered by the Heat Roadmap Europe 4 (HRE4) project, this study differs only in the section concerning movable and window units, with window units excluded due to their negligible presence in terms of sales numbers and installed stock. Hence, the classification for the current investigation regarding the SC component is as follows:

RACs:

- *Moveables*
- *Small split (<5 kW)*
- *Big split (>5 kW, inclusive ducted technologies)*

CACs:

- *VRF (Variable refrigerant flow) system Rooftop system + Packaged*
- *Chiller (air-to-water) < 400 kW*
- *Chiller (air-to-water) > 400 kW*
- *Chiller (water-to-water) < 400 kW, Chiller (water-to-water) > 400 kW*

Based on data availability outlined in Section 1.1, various types of centralized air-conditioner (CAC) have been consolidated into a unified category—combining rooftop systems and packaged units. Furthermore, the collection of data and information on split systems allowed for distinguishing sales based on capacity, although not categorizing them into different types—split or multi-split systems.

It is notable that VC systems fulfill the vast majority (almost 100%) of Europe's cooling requirements. In contrast, the market penetration of thermally driven heat pumps (TDHPs) is minimal compared to VC technologies. However, EUROVENT data indicate that thermally driven heat pumps (TDHPs) represent approximately 1% of the EU's SC market [38]. Other SC technologies have minimal presence in the EU27 SC market and were not considered in this study.

Additionally, utilizing the provided breakdown of VC technologies, an analysis of the SC market was conducted. Among other aspects, the authors primarily investigated the following data per technology and country:

- *Quantity of installed units for SC*
- *Equivalent full load hours (EFLHs)*
- *Capacity installed*

- *Energy efficiency levels (SEER)*

The energy input for each SC type was determined by calculating the average capacities per SC type and dividing them by their respective SEER means. Ensuring reliability within the bottom-up approach necessitated a thorough investigation of a broad range of information sources, solely relying on technical documentation for data collection. The gathered data underwent amalgamation and assessment. To ensure robustness, sources deviating more than one standard deviation from the mean of a specific information pool were excluded. Combined estimates were then used to derive a more solid average. However, in specific cases, it was not feasible to gather at least two pieces of information for each investigated scenario, resulting in the absence of factual elaboration. Ultimately, the SC demand for each EU27 country was computed. To determine the yearly energy demand for each technology and country within the EU27, the number of SC units was multiplied by their respective mean EFLHs over a year, along with their average installed capacity and divided by the SEER value, as per Equation (1) provided below.

$$\text{Energy demand cooling} = Nr_{.\text{Units}} \times T_{\text{equivalent full load hours}} \times W_{\text{electricity}} / SEER \quad (1)$$

where

- Nr_{units} is the number of units installed for space cooling for a certain technology, sector, and European Member state.
- $T_{\text{equivalent}}$ full load hours is the equivalent full load hours.
- $W_{\text{electricity}}$ is the work input of the SC system. Electricity is the energy input that allows the cold as output.
- SEER is the Seasonal Energy Efficiency Ratio

Additionally, the subsequent text elucidates the process by which the EFLHs, crucial for the aforementioned calculations, were determined.

2.1.1 Calculation of Equivalent Full Load Hours

The calculation of Equivalent Full Load Hours (EFLHs) is an approach to estimate the operational demand for SC in residential and service sectors. It considers various factors like indoor and outdoor temperatures, building occupancy, and population density.

In residential settings, EFLHs are calculated with normalized load curves that capture electricity demand variations throughout the year. These curves are linked to outdoor temperature fluctuations, with Cooling Degree Days (CDD) and Heating Degree Days (HDD) used to gauge the need for cooling and heating. The calculations use typical hourly weather data from Meteonorm software v7.1, spanning from 2000 to 2009, with a reference temperature of 18°C. For countries with varying climates, such as France, Italy, and Spain, data is weighted by building floor areas to account for different regional climates [40, 41, 42].

In the service sector, the approach adjusts to different building types and their characteristics, such as size, geometry, internal loads, ventilation rates, and thermal properties. Simulations using the Smart-E platform model the SC needs for 2000 buildings across various sectors, like offices, retail, hospitals, hotels, and restaurants. These simulations, based on specific climate zones, consider unique building parameters and occupancy patterns.

The analysis finds that starting air conditioning in the morning can lead to significant demand peaks. Internal and solar heat gains are also crucial, emphasizing the need for accurate modeling. Hospitals, hotels, and offices tend to have the highest SC demand due to their larger surface areas.

The final EFLHs values for various EU27 countries are weighted to create representative figures based on the distribution of building types. The analysis considers several factors, including city-specific data, climate variations, and constructed area. Weighted values from the H2020 HotMaps project are used to derive single EFLHs values for each country. This detailed approach accounts for the diversity within the EU27 countries and provides a comprehensive understanding of SC demands across residential and service sectors.

2.2. Results

As there were numerous values for each individual EU27 country, the following figures present the key findings in aggregated form for the entire EU27. Figure 1 illustrates number of installed units across each country.

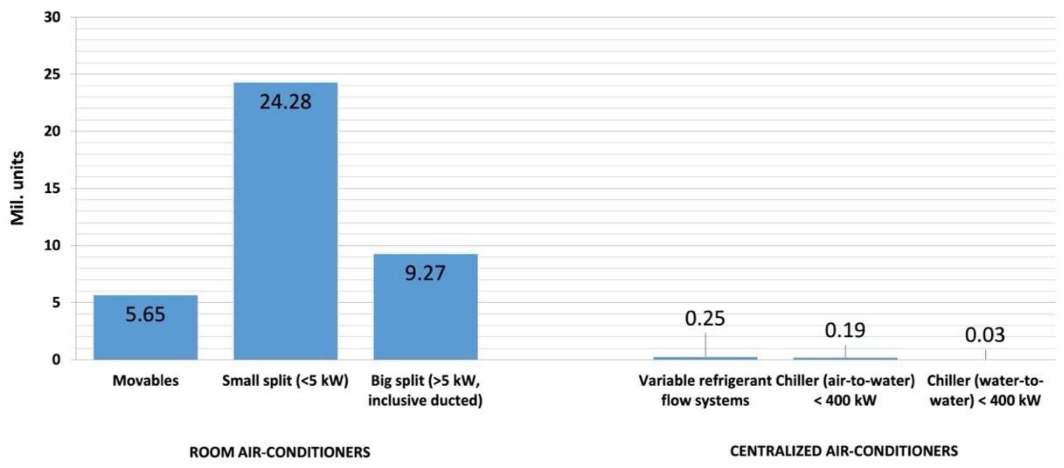

Figure 1. Number of installed units per space cooling type in the residential sector, EU27, the reference year 2021.

The majority of SC units per type consist of small split systems (<5 kW), totaling over 24 million installed devices. Following closely are big split systems (>5 kW, including ducted systems) with over 9 million units. Room air-conditioning (RAC) systems, categorized as moveables, account for approximately 5.65 million units. Additionally, the installed quantity of centralized air-conditioning (CAC) systems includes around 0.25 million variable refrigerant flow (VRF) systems, about 0.19 million air-to-water chillers (< 400 kW), and approximately 0.03 million water-to-water chillers (< 400 kW).

It's important to note that rooftop and packaged units, as well as air-to-water chillers (> 400 kW) and water-to-water chillers (> 400 kW), are not present in the residential sector. However, it should be noted that the presence of such SC technologies in the residential sector may be limited.

Next, Figure 2 indicates the average installed capacity per SC type in kW.

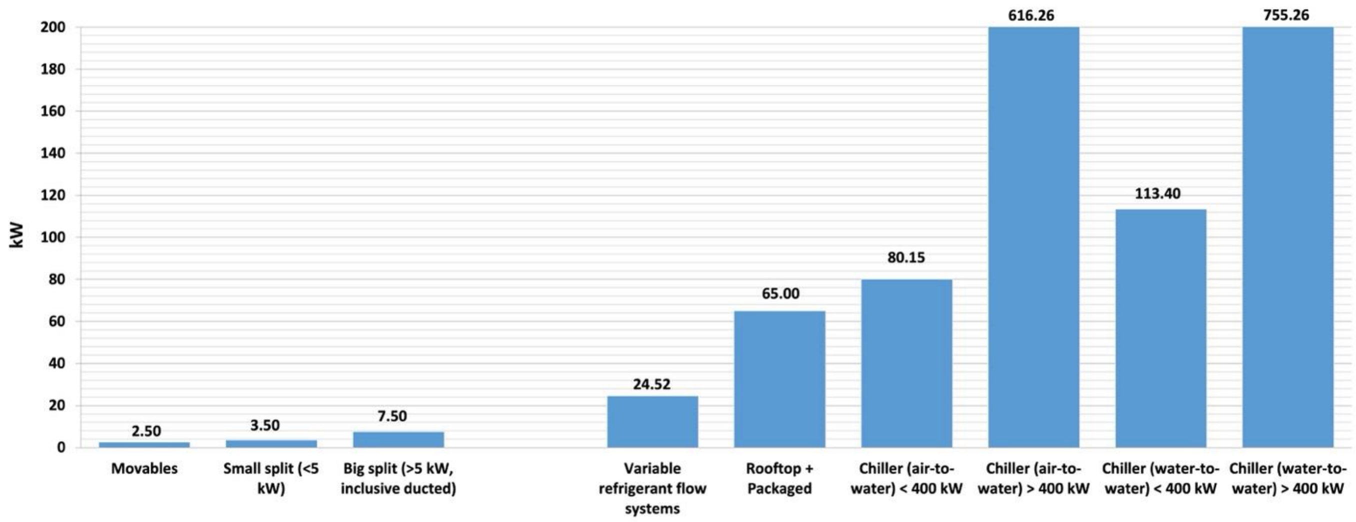

Figure 2. Average installed capacity per space cooling type in the residential sector, EU27, the reference year 2021.

The highest average installed capacity is observed in water-to-water chillers (> 400 kW), exceeding 750 kW. Following closely are air-to-water chillers (> 400 kW) with approximately 620 kW. Subsequently, water-to-water chillers (< 400 kW) follow with an average capacity of about 115 kW, while air-to-water chillers (< 400 kW) have an average installed capacity of around 80 kW. Among CACs, variable refrigerant flow (VRF) technologies exhibit an average capacity of about 25 kW. Finally, rooftops with packaged units have an average capacity of around 65 kW.

Additionally, Figure 4 provides insights into the SEER. It's noteworthy that no installed units of rooftop with packaged units, air-to-water chillers (> 400 kW), and water-to-water chillers (> 400 kW) were found in the residential market. Figure 3 emphasizes details concerning these SC technologies.

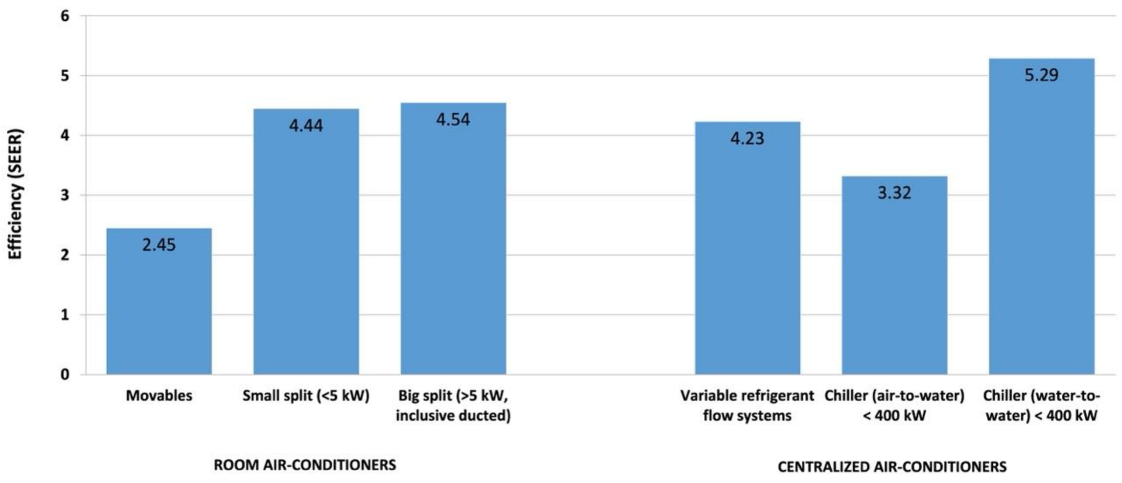

Figure 3. Seasonal energy efficiency ratio per space cooling type in the residential sector, EU27, the reference year 2021.

The most efficient SC type emerges to be chiller (water-to-water) < 400 kW with a SEER of over 5. Small split (>5 kW inclusive ducted) systems follow a SEER value of more than 4. VRF Small split (<5 kW) and VRF systems come next with a SEER of around 4. Chiller (air-to-water) < 400 kW come next, associated with a SEER of about 3.5. Moveables are last, with a SEER of over 2. Using the assembled mean capacity and SEER values per SC type, the relative electricity input in kW has been computed.

Integrating the data obtained above in Equation (1) results in Table 1.

Table 1. Energy demand for space cooling per type of technology in the residential sector, EU27, the reference year 2021.

TECHNOLOGIES		ENERGY DEMAND [TWh/y]
ROOM AIR-CONDITIONERS		
	Movables	6.05
	Small split (<5 kW)	59.02
	Big split (>5 kW, inclusive ducted)	48.72
CENTRALIZED AIR-CONDITIONERS		
	Variable refrigerant flow systems	2.12
	Rooftop + Packaged	0.00
	Chiller (air-to-water) < 400 kW	5.78
	Chiller (air-to-water) > 400 kW	0.00

	Chiller (water-to-water) < 400 kW	1.15
	Chiller (water-to-water) > 400 kW	0.00

As depicted in Table 1, small split systems (<5 kW) emerge as the most energy-demanding SC model, accounting for 59 TWh/y of the total energy demand recorded. This is followed by big split systems (>5 kW, including ducted systems) with nearly 49 TWh/y. Moveables rank next with 6 TWh/y, while air-to-water chillers (< 400 kW) follow closely with over 5.7 TWh/y. VRF systems and water-to-water chillers (< 400 kW) are positioned in the penultimate and last places, respectively, with 2.12 TWh/y and 1.15 TWh/y each.

Consequently, room air conditioner (RAC) types constitute the bulk of the EU27 residential sector's SC demand, representing over 90% of the total. The aggregate amount exceeds 122 TWh/y. Finally, Table 2 and Figure 4 delineate the demand shares per country.

Table 2. Energy demand for space cooling per country in the residential sector, EU27, the reference year 2021

State	TWh/y	%
Austria	0.44	0.35
Belgium	0.12	0.09
Bulgaria	0.82	0.66
Croatia	1.01	0.81
Cyprus	3.58	2.91
Czech Republic	0.16	0.13
Denmark	0.05	0.04
Estonia	0.00	0.00
Finland	0.05	0.04
France	4.28	3.48
Germany	4.28	3.48
Greece	19.10	15.55
Hungary	0.89	0.72
Luxembourg	0.00	0.00
Ireland	0.01	0.01
Italy	57.21	46.56
Latvia	0.00	0.00
Lithuania	0,00	0.00
Malta	1.03	0.83
Netherlands	0.12	0.09
Poland	0.24	0.19
Portugal	2.36	1.92
Romania	2.46	2.00
Slovenia	0.18	0.14

Slovakia	0.13	0.10
Spain	24.24	19.73
Sweden	0.07	0.05
EU27	122.85	100

As shown in Table 2 and Figure 4, there are five countries (Italy, Spain, Greece, Germany, and France) accounting for more than 90% of Europe’s SC demand. Thus, the remaining 23 countries account for the left 10%.

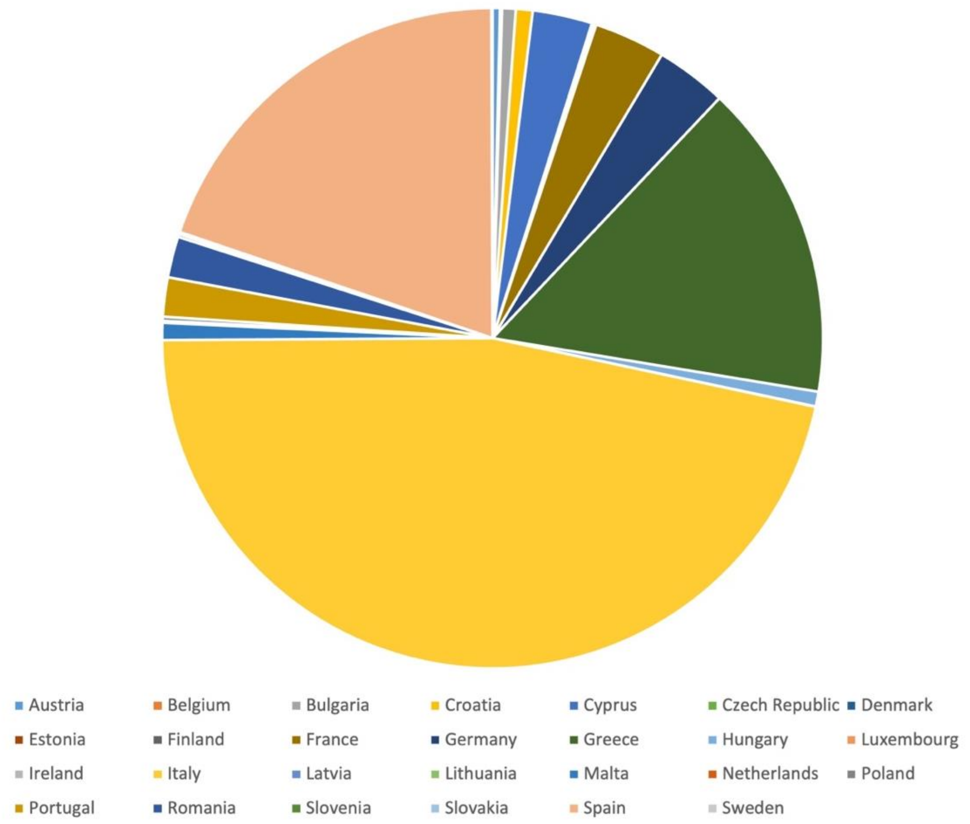

Figure 4. Share of energy demand for space cooling per country in the residential sector, EU27, the reference year 2021.

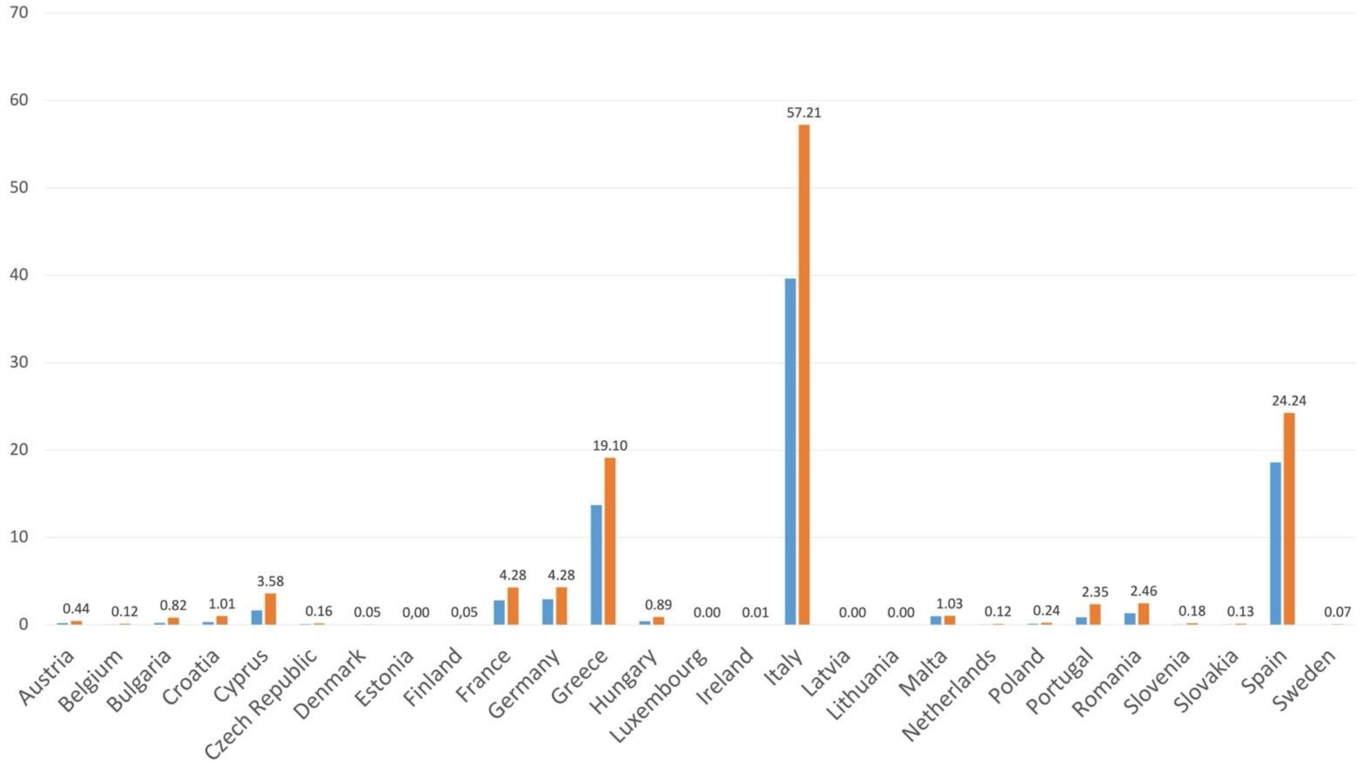

Figure 5. Energy demand for space cooling per country in the residential sector, EU27, the reference year 2021 (Orange) compared with year 2016 (Blue)

2.2.2. Service Sector

In contrast to the residential sector, in this case, the big split (>5 kW, inclusive ducted systems) systems are ranked first, with over 21 mil. units. Small split (<5 kW) systems follow with over 11 mil. units. In the third position, VRF units are allocated with over 2.5 mil. units. Rooftop plus packaged units come next, with about 1.7 mil units, followed by chiller (air-to-water) < 400 kW with around 0.46 mil. units. Movables follow with more than 0.30 mil. units. The remaining chiller types show solely minor values: 0.13 mil. chiller (water-to-water) < 400 kW, 0.09 mil. chiller (air-to-water) > 400 kW, and finally 0.05 mil. chiller (water-to-water) > 400 kW.

The average setup capacity per SC type for the service sector corresponds to these households - please see Figure 5.

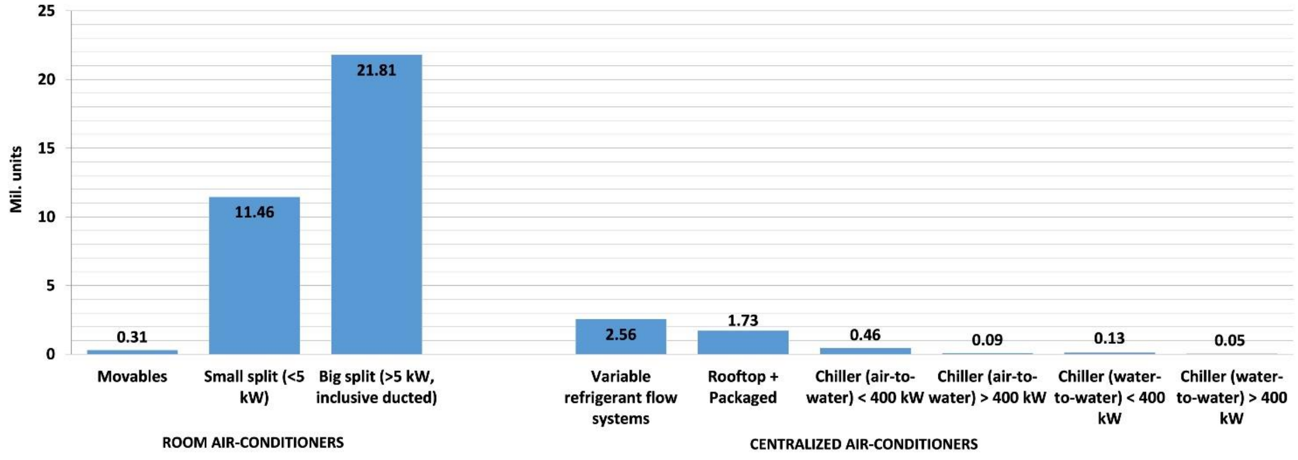

Figure 6. Number of installed units per space cooling type in the service sector, EU27, the reference year 2021.

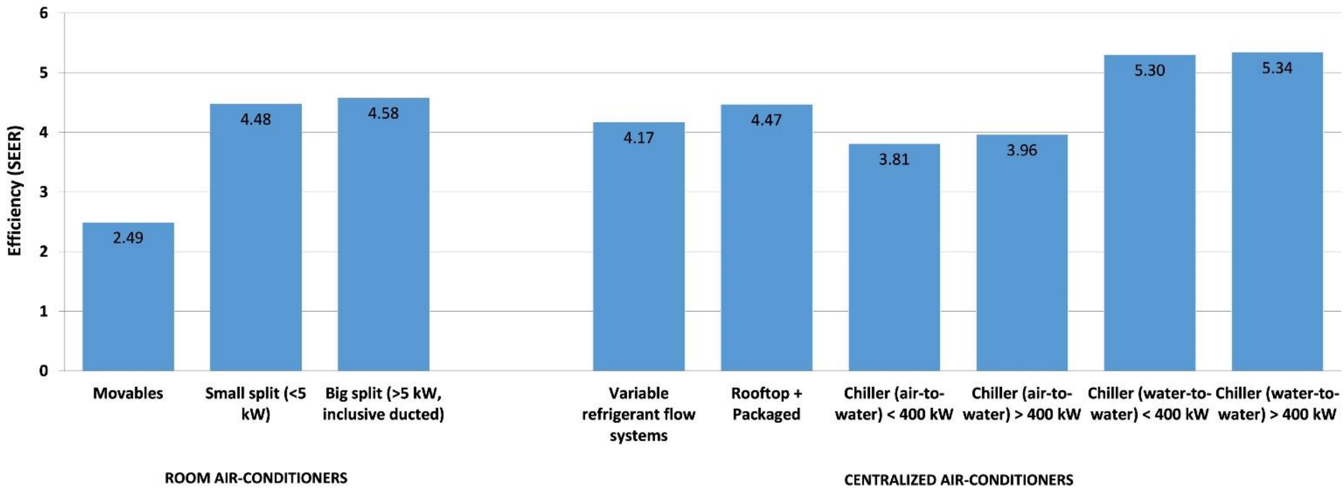

Figure 7. Seasonal energy efficiency ratio per space cooling type in the service sector, EU27, the reference year 2021.

Furthermore, Figure 7 highlights details concerning the SEER.

The most efficient SC types emerge to be chiller (water-to-water) > 400 kW and chiller (water-to-water) < 400 kW with a SEER value of more than 5, respectively. Big split (>5 kW) follows with a SEER value of more than 4. VRF, rooftop plus packaged units, and small split (<5 kW, inclusive ducted) technologies come next with a SEER of about 4. Chiller (air-to-water) < 400 kW and chiller (air-to-water) > 400 kW come next with SEER values of more than 3. Movables are in the last position with a SEER of more than 2.

Again, through the collected average capacity and SEER values per SC type, the corresponding energy demand in TWh/y has been calculated.

Integrating the data obtained above in Equation (1) results in Table 3.

Table 3. Energy demand for space cooling per type of technology in the service sector, EU27, the reference year 2021.

TECHNOLOGIES		ENERGY DEMAND [TWh/y]
ROOM AIR-CONDITIONERS		
	Movables	0.55
	Small split (<5 kW)	31.83
	Big split (>5 kW, inclusive ducted)	140.03
CENTRALIZED AIR-CONDITIONERS		
	Variable refrigerant flow systems	52.76
	Rooftop + Packaged	96.47
	Chiller (air-to-water) < 400 kW	24.10
	Chiller (air-to-water) > 400 kW	36.93
	Chiller (water-to-water) < 400 kW	9.48
	Chiller (water-to-water) > 400 kW	30.53

Table 4 shows that the most energy-demanding SC type are big split (>5 kW, inclusive ducted) systems with more than 140 TWh/y. Rooftop plus packaged units come next with more than 96 TWh/y. Variable refrigerant flow systems follow with more than 52 TWh/y. Chiller (air-to-water) > 400 kW and small splits come next with almost 37 TWh/y and 32 TWh/y, respectively. Chiller (water-to-water) > 400 kW and chiller (air-to-water) < 400 kW follow with over 30 TWh/y and 24TWh/y, respectively. Chiller (water-to-water) < 400 kW comes with more than 9 TWh/y, and movables are positioned last with 0.55 TWh/y.

Thus, in contrast to the residential sector, CACs prevail with around 60% of the final SC demand. The total amount of final SC demand in Europe's service sector comes out to be 422.67 TWh/y. Finally, Table 4 and Figure 6 show the final cooling demand shares per country.

Table 4. Energy demand for space cooling per country in the service sector, EU27, the reference year 2021

State	TWh/y	%
Austria	5.42	1.28
Belgium	6.52	1.54
Bulgaria	2.67	0.63
Croatia	2.12	0.50
Cyprus	1.89	0.44
Czech Republic	4.68	1.10
Denmark	2.12	0.50
Estonia	0.72	0.17
Finland	4.98	1.17
France	81.81	19.35
Germany	9.92	2.34
Greece	12.22	2.89
Hungary	4.68	1.10
Luxembourg	0.83	0.19
Ireland	12.28	2.90
Italy	74.30	17.57
Latvia	0.77	0.18
Lithuania	0.79	0.18
Malta	0.86	0.20
Netherlands	7.84	1.85
Poland	9.05	2.14
Portugal	4.99	1.18
Romania	6.02	1.42
Slovenia	1.17	0.27
Slovakia	2.00	0.47
Spain	157.70	37.31
Sweden	4.30	1.01
EU27	422.67	100

Just like the residential sector, the majority of the EU27 SC demand amount is attributed to five states. Specifically, Spain, France, Italy, Greece, and Germany contribute over 80% of the final SC demand for the service sector in Europe, leaving the remaining 22 countries to account for the remaining 20%.

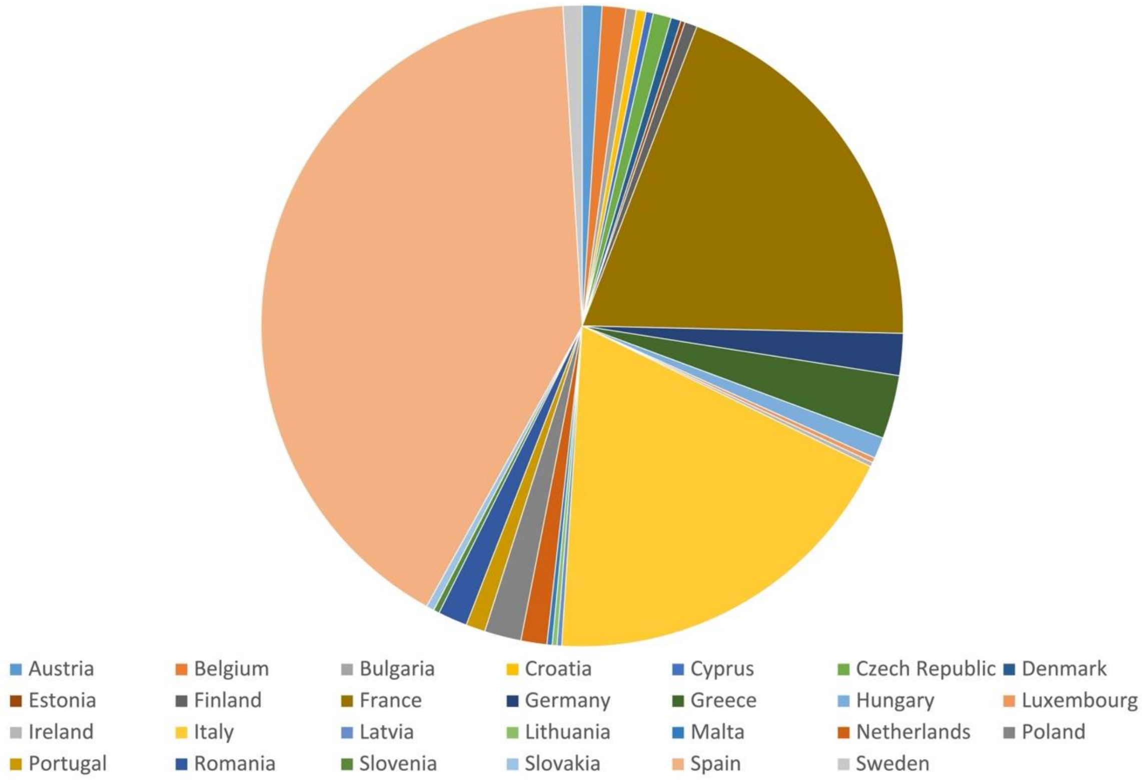

Figure 8. Share of energy demand for space cooling per country in the service sector, EU27, the reference year 2021.

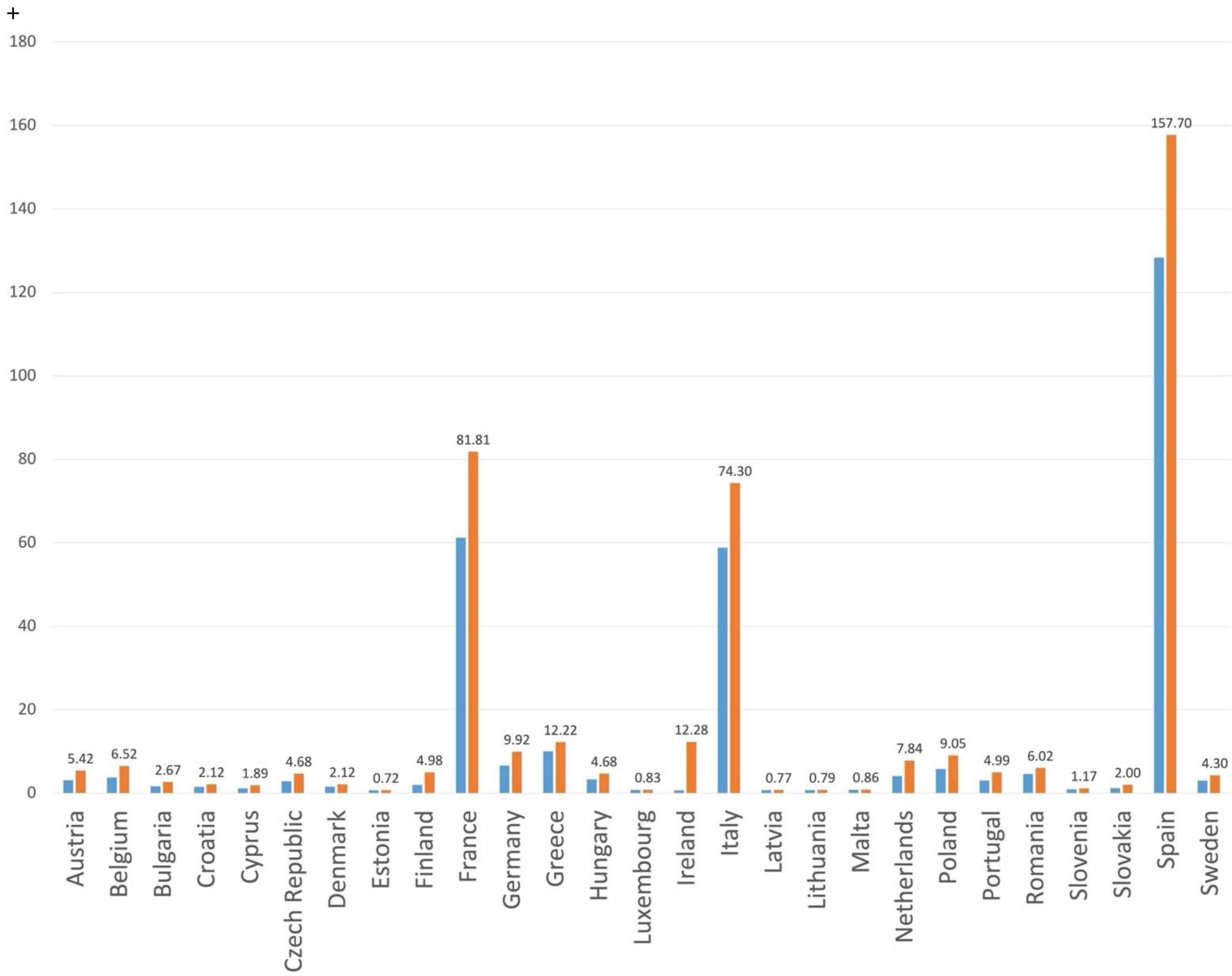

Figure 9. Energy demand for space cooling per country in the service sector, EU27, the reference year 2021 (Orange) compared with year 2016 (Blue)

2.2.3. Residential and Service Sectors

Table 5 results from aggregating the outcomes of Table 1 and Table 3.

Table 5. Energy demand for space cooling per type of technology in the residential and service sector, EU27, the reference year 2021.

TECHNOLOGIES		ENERGY DEMAND [TWh/y]
ROOM AIR-CONDITIONERS		
	Movables	6.60
	Small split (<5 kW)	90.85
	Big split (>5 kW, inclusive ducted)	188.75
CENTRALIZED AIR-CONDITIONERS		
	Variable refrigerant flow systems	54.89
	Rooftop + Packaged	96.47
	Chiller (air-to-water) < 400 kW	29.88
	Chiller (air-to-water) > 400 kW	36.93
	Chiller (water-to-water) < 400 kW	10.63
	Chiller (water-to-water) > 400 kW	30.53

As depicted in Table 5, the highest energy-demanding SC types are primarily big split systems (>5 kW, including ducted) with an annual demand of nearly 190 TWh/y. Following closely are rooftop plus packaged units, totaling over 96 TWh/y annually, while small split systems rank third with almost 90 TWh/y. VRF systems and chillers (air-to-water) greater than 400 kW each contribute more than 54 TWh/y and 37 TWh/y, respectively. Chillers (air-to-water) below 400 kW trail behind with almost 30 TWh/y, and chillers (water-to-water) greater than 400 kW follow suit with over 30 TWh annually. Movables need nearly 7 TWh yearly, while chillers (water-to-water) below 400 kW represent the lowest need at over 10 TWh annually.

Combining the quantities from both the residential and service sectors, the total EU27 SC demand amounts to 545,5 TWh per year. Regarding the overall SC demand encompassing both sectors, RACs and CACs contribute roughly equal proportions, each representing approximately 50% of the total EU27 demand.

In summary, Table 6 presents a consolidation of the findings from Tables 3 and 5.

Table 6. Energy demand for space cooling per country in the residential and service sector, EU27, the reference year 2021

State	TWh/y	%
Austria	5.86	1.073795

Belgium	6.64	1.217991
Bulgaria	3.49	0.639522
Croatia	3.13	0.573209
Cyprus	5.47	1.002581
Czech Republic	4.85	0.888358
Denmark	2.17	0.397893
Estonia	0.72	0.132099
Finland	5.03	0.922961
France	86.09	15.78167
Germany	14.20	2.60389
Greece	31.33	5.742616
Hungary	5.57	1.021667
Luxembourg	0.83	0.152925
Ireland	12.30	2.254451
Italy	131.50	24.10613
Latvia	0.77	0.141404
Lithuania	0.79	0.145605
Malta	1.89	0.346407
Netherlands	7.96	1.458427
Poland	9.29	1.702645
Portugal	7.35	1.347037
Romania	8.49	1.555588
Slovenia	1.35	0.247255
Slovakia	2.13	0.390552
Spain	181.94	33.35291
Sweden	4.37	0.800421
EU27	545.51	100

Once more, only a handful of countries contribute to the majority of the SC demand within the EU27. Spain, Italy, France, Greece and Germany collectively represent over 85% of Europe's SC demand across residential and service sectors. Consequently, the remaining 22 countries contribute to the remaining 15%.

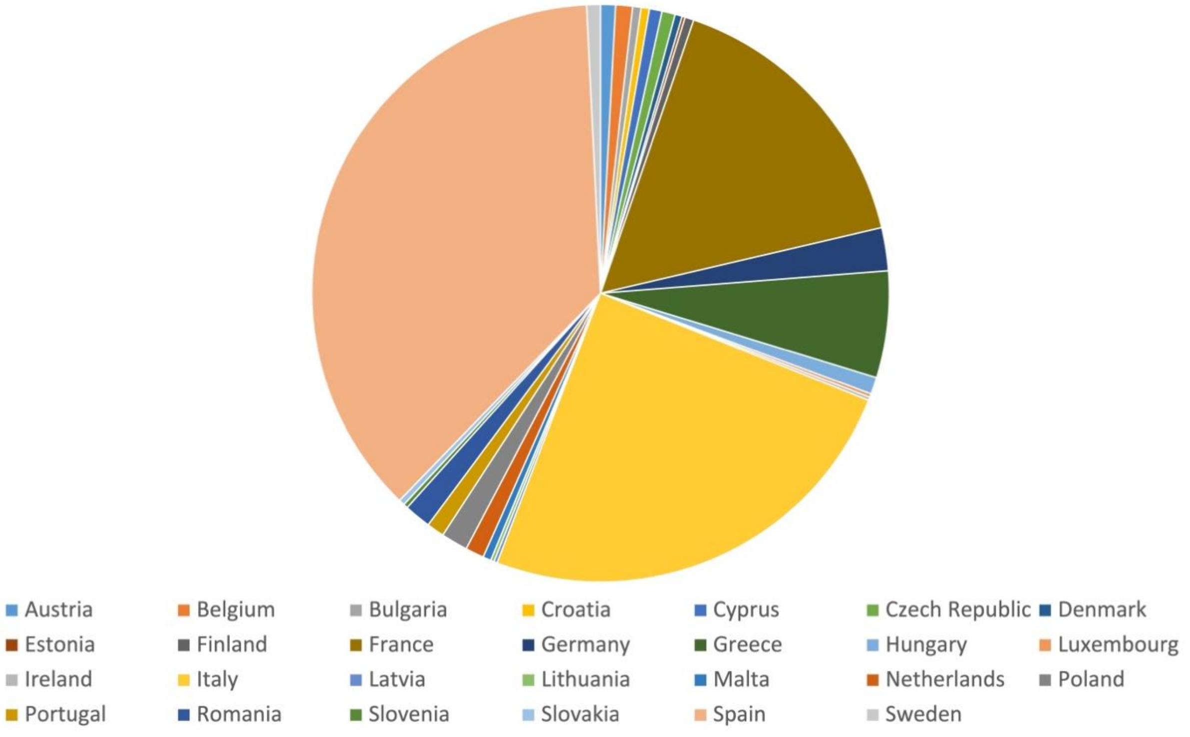

Figure 10. Share of energy demand for space cooling per country in the residential+service sector, EU27, the reference year 2021.

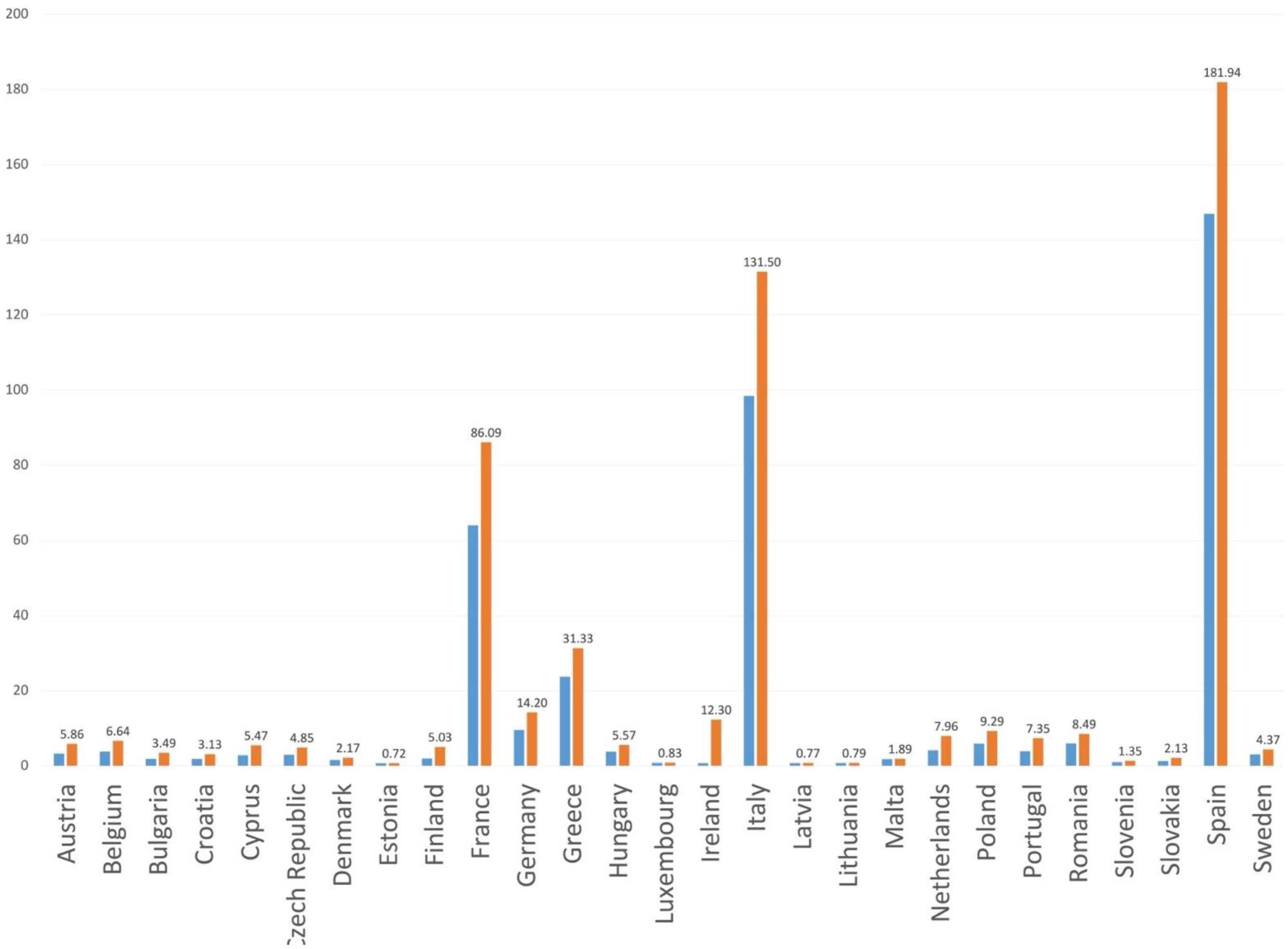

Figure 11. Energy demand for space cooling per country in the residential and service sector, EU27, the reference year 2021 (Orange) compared with year 2016 (Blue)

This study utilized 2021 as the baseline for assessing the EU27 demand for the SC sector. It's noteworthy that while SH in the H&C sector is extensively studied in scientific literature, SC remains largely unexplored. During the initial literature review phase, limited information was found, with key sources such as EurObserv'ER [20], EUROHEAT&POWER [5], and EHPA [21] providing essential territorial views and data crucial for calculating EFLHs. Additionally, the EU Buildings Database [23] and EHPA's Online Stats Tool [21] offered fundamental building data for Section 2.

Dittmann et al.'s study in 2017 [28], part of the H2020 HRE4 project, proved to be the most precise and reliable source for installed data on SC units in the EU27+UK. SEER values were obtained following the computation practice recommended in European Standards EN 14825 [49].

In both residential and service sectors, SC equipment such as moveables, small split (<5 kW), and big split (>5 kW, including ducted systems) are grouped under RACs, while VRF systems, rooftop systems + packaged units, and various types of chillers are categorized as CACs. RAC types dominate the residential sector, accounting for approximately 90% of EU27 SC demand, whereas CACs contribute about 60% in the service sector. Together, RACs and CACs represent around 50% each of the total EU27 SC demand.

The study observed that big split systems (>5 kW, inclusive ducted) are the most energy demanding SC types in the EU27, accounting for 188.75 TWh/y of the total SC demand. Rooftop plus packaged units follow with over 96 TWh/y, and small split systems come next with over 90 TWh/y. All other VC systems collectively need circa 160 TWh/y.

The input data from the mentioned sources fed into Equation (1), resulting in an estimated SC demand of around 545.51 TWh/y in 2021 for both residential and service sectors. Italy, Spain, France, Greece, and Germany represent over 85% of EU27 SC demand, with the remaining 22 member states contributing the remaining 15%.

Enhanced accessibility to reliable datasets of SC equipment parameters from producers is crucial. However, challenges may arise in accessing data from private companies. Nonetheless, improved accessibility to research and development (R&D) resources is hoped for in the near future.

3. Comparison of Results and Top Down Approach

3.1. Materials and Methods

To evaluate the outcomes from our bottom-up analysis and the effectiveness of the tools utilized for estimating SC per square meter, we employed a methodical approach. Initially, we collected data from two distinct tools: SmartE and InvertEE, renowned for their ability to estimate SC requirements [43, 44, 45, 46, 47, 48, 49]. Subsequently, we meticulously compared the values obtained from these tools with those derived from the bottom-up analysis across three reference countries in Southern Europe, Central Europe, and Northern Europe. Our aim in this comparative analysis was to identify any differences, similarities, or trends between the estimations provided by the tools and those derived from the bottom-up approach. By systematically evaluating the outputs across different regions, our goal was to assess the accuracy and reliability of the tools in estimating SC needs per square meter. This comprehensive evaluation process enabled us to draw meaningful conclusions regarding the performance and suitability of the tools across diverse geographical contexts within Europe.

In Central Europe, our evaluation focused on gathering and comparing data primarily from France, utilizing datasets from both SmartE and InvertEE to ensure a comprehensive analysis. For Southern Europe, we examined data provided by SmartE for Greece and data from InvertEE for Italy, allowing us to assess the performance of both tools across the region. Similarly, in Northern Europe, we used datasets from both SmartE and InvertEE, with InvertEE providing data for Sweden and SmartE for Finland. Despite the use of different reference countries within the same European regions, our comparison centered on the common metric of kWh per square meter for SC estimation, facilitating insightful conclusions regarding the effectiveness and reliability of the tools across diverse geographical contexts.

Due to data availability, our comparison specifically focused on energy demand per square meter within the residential sector, ensuring consistency and accuracy in our evaluation process. This metric is crucial for assessing SC requirements as it provides a standardized measure facilitating meaningful comparisons across regions and tools. Concentrating on energy demand per square meter in the residential sector allowed for a direct and relevant assessment of the tools' performance, aligning with industry practices and research methodologies.

To provide a comprehensive analysis, we conducted average calculations across various parameters including different years and typologies of dwellings. This step was essential to mitigate potential fluctuations and variations within the data, capturing underlying trends while reducing year-to-year variability. Considering different dwelling typologies enabled us to account for residential building diversity, enhancing the accuracy of our representation of energy demand. Overall, averaging data across multiple parameters enhanced the robustness and reliability of our analysis, facilitating more meaningful conclusions regarding SC requirements and tool performance.

3.2. Results

Table 7. Values from different tools for energy demand per m^2 for space cooling in the residential sector, EU27.

Energy Demand – Residential (kWh/m² y)			
	Northern Europe	Central Europe	Southern Europe
InvertEE	30.40	14.14	25.197
SmartE	2.60	9.05	42.42
Bottom Up Approach CoolLife	24.14	27.92	48.83

For each of these approaches, the table shows the corresponding energy demand values (in kWh/m² per year) for the three European regions.

Some key observations from the data:

For Northern Europe, the Invert/EE-Lab approach has the highest energy demand at 30.40 kWh/m² y, while the Smart-E approach has the lowest at 2.61 kWh/m² y. In Central Europe, the results from the bottom approach show the highest value at 27.92 kWh/m² y, closer to Invert/EE-Lab. For Southern Europe, the we obtained the highest energy demand at 48.84 kWh/m² y, similar to the values of Smart-EE.

In our evaluation, we found that Invert/EE-Lab provided more accurate data for Central Europe and for Northern Europe. This accuracy could potentially be attributed to Invert/EE-Lab having local access to more reliable data sources, particularly in the case of France. Local access to data sources often enhances the accuracy of estimations due to a better understanding of regional factors and nuances.

On the other hand, for Southern European countries, Smart-E emerged as the tool providing more accurate and robust results. This may be because Smart-E has specialized data sources or algorithms tailored to the specific conditions and characteristics of Southern European climates and building structures. The tool's focus on Southern European contexts might contribute to its ability to provide more precise estimations for countries in this region.

Overall, these findings highlight the importance of considering the regional expertise and data access of each tool when assessing their accuracy. Localized data sources and specialized algorithms can significantly enhance the reliability of estimations, particularly in regions with distinct climatic and building characteristics.

4. Conclusions

The key findings of the present study regarding European space cooling demand, using 2021 as the baseline, are outlined below for both the residential and service sectors.

Overall, space cooling demand for both sectors combined exceeded 54.51 TWh/y in 2021. The following sections detail the main characteristics of space cooling technology types and the distribution of energy demand across European member states for each sector.

Residential Sector

The most energy-intensive space cooling technologies in the residential sector are small split (<5 kW) systems, accounting for circa 59 TWh/y of total space cooling demand. Big split (>5 kW, inclusive ducted) systems follow closely with almost 49 TWh/y, and moveables come next with circa 6 TWh/y. Chiller (air-to-water) < 400 kW accounts for 5.78 TWh/y, while variable refrigerant flow systems and chiller (water-to-water) < 400 kW rank lower with 2.12 TWh/y and 1.15 TWh/y, respectively.

Room air conditioner types represent the vast majority of European space cooling demand, exceeding 90%, while centralized air conditioner types make up the remaining 10%. The total European space cooling demand in the residential sector exceeds 122 TWh/y.

Only five countries—Italy, Spain, Greece, Germany, and France—account for over 90% of European space cooling demand in the residential sector, with the remaining 22 countries contributing the remaining 10%.

Service Sector

The most energy-demanding space cooling technologies in the service sector are big split (>5 kW, inclusive ducted) systems, totaling more than 140 TWh/y. Rooftop plus packaged units follow with over 96 TWh/y, and variable refrigerant flow systems contribute more than 52 TWh/y. Chiller (air-to-water) > 400 kW and small split systems follow closely with more than 36 TWh/y and 31 TWh/y, respectively. Chiller (water-to-water) > 400 kW and chiller (air-to-water) < 400 kW come next with almost 30 TWh/y each, while chiller (water-to-water) < 400 kW demand over 9 TWh/y, and movables are last with 0.55 TWh/y.

Centralized air conditioner types dominate European space cooling demand in the service sector, surpassing 60%, while room air conditioner types make up the remaining 40%. The total European space cooling energy demand in the service sector amounts to 422,67 TWh/y.

Residential and Service

Across both sectors, the most energy-demanding space cooling type is big split (>5 kW, inclusive ducted) systems, needing almost 189 TWh/y. Rooftop plus packaged units follow with more than 96 TWh/y, and small split systems contribute over 90 TWh/y. Variable refrigerant flow systems and chiller (air-to-water) > 400 kW each need more than 54 TWh/y and 36 TWh/y, respectively. Chiller (air-to-water) < 400 kW follows with over 29 TWh/y, while chiller (water-to-water) > 400 kW demand almost 31 TWh/y. Movables account for almost 7 TWh/y, and chiller (water-to-water) < 400 kW require more than 6 TWh/y.

Room air conditioners and centralized air conditioners each represent approximately 50% of European space cooling demand across both sectors. The total European space cooling demand, encompassing both residential and service sectors, amounts to 545.51 TWh/y.

Once again, a small number of European member states— Spain, France, Greece, Italy, and Germany—account for over 80% of European space cooling demand, with the remaining 22 countries contributing the remaining 20%.

In conclusion, the study faced significant challenges in data retrieval due to data unavailability, fragmentation, and obsolescence. Despite its significant contribution to European energy demand, the space cooling sector remains underexplored in scientific literature. Thus, greater attention from both the private and public sectors is crucial to support the European Union's efforts in meeting climate and energy requirements.

The rising temperatures, evolving building designs, and increasing demand for thermal comfort have led to a rise in space cooling needs. Space cooling is no longer a minor consumer of electricity but has become a significant sector, contributing between 5% and 20% of overall electricity demand in various European countries. Consequently, the European Union and its Member States are working on implementing renewable cooling methodologies to align renewable energy sources with the space cooling sector, as mandated by Article 7(3) of the 2018 Renewable Energy Directive.

The study aimed to shed light on the underexplored topic of space cooling in scientific literature to better inform decisions regarding future sustainable pathways in the European Union. The comparison of the different tools SmartE and InvertEE for the value of energy demand per square meter in the residential sector for three countries reveals important insights into the regional variations in energy use across Europe. The InvertEE model appears to be the most accurate for Northern Europe, capturing the highest energy demand at 30.40 kWh/m² y. In Central Europe, both the InvertEE and Bottom Up Approach CoolLife models provided reliable results, with the latter showing the highest value at 27.92 kWh/m² y. Interestingly, for Southern Europe, the SmartE approach emerged as the most accurate, estimating the highest energy demand at 48.84 kWh/m² y. These findings highlight the importance of considering the regional expertise and data access of each modeling tool when evaluating their accuracy. Localized data sources and specialized algorithms can significantly enhance the reliability of energy demand estimations, particularly in regions with distinct climatic and building characteristics. Understanding the strengths and limitations of different modeling approaches is crucial for policymakers and energy planners to make informed decisions and improve the energy efficiency of residential buildings across Europe.

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