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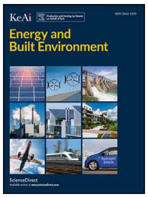

Decomposing the drivers of residential space cooling energy consumption in EU-28 countries using a panel data approach

Andreas Andreou[a,*], John Barrett[a], Peter G. Taylor[a,b], Paul E. Brockway[a], Zia Wadud[b,c]

[a] *Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK*
[b] *Low Carbon Energy Research Group, School of Chemical and Process Engineering, University of Leeds, Leeds, LS2 9JT, UK*
[c] *Spatial Modelling and Dynamics Research Group, Institute for Transport Studies, University of Leeds, Leeds, LS2 9JT, UK*

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ABSTRACT

While space cooling currently represents less than 1% of final energy use in the residential sector of the European Union (EU-28), it was the fastest growing end-use during the 2000-15 period with a mean annual growth rate of 6% per year. Currently, little is known about factors which have driven regional air-conditioning (AC) energy consumption over time, since the literature is limited to cross-sectional studies that lack differentiation between climatic and non-climatic influences. Future projections for the EU's electricity sector may therefore neglect the potential implications of rapidly growing AC demand. We develop a novel decomposition framework, which breaks down residential space cooling energy consumption in EU-28 countries into the effect of different components from 2000 to 2015. Decomposition is extended to panel data models identifying specific drivers of space cooling's climate-sensitive components. Finally, we explore scenarios of residential AC energy consumption up to 2050 and evaluate their impact on summer time peak loads. AC diffusion was found to be the key driver of space cooling energy consumption, but this effect was partly counterbalanced by efficiency gains. While weather influences AC equipment ownership rate in EU-28 households, personal income has a larger marginal effect. In baseline scenarios, AC diffusion saturates by 2050, while modestly increasing sectoral final energy use. Still, our range of scenario values for space cooling energy consumption in 2050 exceed the majority of those originating from recently published projections. In a future renewables-driven electricity system, energy security risks may emerge from a scenario of fast AC up-take in new and renovated buildings, especially for colder European countries where modelled peak cooling electricity demand is shown to outgrow the projected expansion of solar capacity. These findings have important implications for the EU's strategy to decarbonise energy supply.

1. Introduction

Global energy consumption for space cooling has increased threefold between 1990 and 2016 and has been accompanied by a tremendous growth in air-conditioning (AC) sales [1,2]. The diffusion and use of air-conditioning across the globe has been strongly linked to changing climatic and economic conditions [3]. In the European Union (EU-28), while residential space cooling currently forms a minor share of sectoral final energy use (0.6% in 2015) it was the fastest growing household end-use during the time period 2000-15, recording an average consumption growth rate of 6.3% per year (Fig. 1) [4]. Residential air-conditioning also has an enormous future growth potential in the EU-28 as less than 10% of household floor area is currently cooled [5]. Since space cooling in EU-28 households is usually supplied through electric room air-conditioners (RACs) [6], the expected growth of residential AC markets across Europe [7] will intensify pressure on national electricity sectors. This translates into a need for additional generating capacity and more effective management of summer time peak loads; issues which are already evident in Mediterranean EU-28 countries [8].

In the absence of granular household end-use consumption data, studies analysing the EU's current space cooling energy use involve estimates obtained mostly through bottom-up technology-based energy models. These in turn depend on technical parameters gathered over tiny time frames, overlooking past variation of AC use [5,9]. These models provide limited value to the policy making process as they do not facilitate a broader discussion about the relative importance of the various factors driving air-conditioning use in different EU Member States. These historical estimates are subsequently mixed with crude assumptions about the future development of modelled parameters, such as a 100% AC technology saturation rate [10,11] or using current diffusion data from United States as a proxy [12,13], to define ceiling values for EU-28 space cooling energy consumption. The adoption of such simplified methodologies limits understanding about the potential trajectories residential AC markets could follow in the near-future and how different

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[*] Corrresponding author.
E-mail address: eeaan@leeds.ac.uk (A. Andreou).

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Nomenclature

FEU	Final energy use (TWh/y)
A, S, I	Activity, Structural, Intensity parameters
Hou	Number of households (hh)
Diff	Air-conditioning diffusion (%)
Qspec	Useful specific cooling demand (useful kWh/hh•y)
Eff	Efficiency indicator of air-conditioning systems
Sat	Air-conditioning saturation (%)
X	Predictor variables of air-conditioning diffusion
Pop	Population
INC	Personal income (2011$/pop PPP)
TMP	Mean outdoor temperature (°C)
t	Time trend
$\alpha, \beta, \gamma, \delta$	Estimated model parameter coefficients
ε	Residual error
AREA	Useful household area (m^2/hh)
CDD	Cooling degree days (°C•d)
SSP	Shared socio-economic pathway
RCP	Representation concentration pathway
Peak	Potential peak electricity demand (GW)
Cap	Rated capacity (kW)
SEER	Seasonal energy efficiency ratio
w	Share of air-conditioning technologies (%)
NrAC	Number of air-conditioning units
new	New and renovated households
old	Old households
AC	Air-conditioning
y	Year
c	Country
NUTS	Nomenclature of Territorial Units for Statistics
n	Number of NUTS regions
JJA	June-July-August
d	Day
tech	Type of air-conditioning technology
warm	Warm group of EU-28 countries
cold	Cold group of EU-28 countries

factors, including climate change and economic growth, could affect its evolution. Even if the impact of these two factors is taken into consideration, projections of AC diffusion are based on functions which were not calibrated using historical data for the EU-28 region only [14–16].

This paper uses the novel Integrated Database of the European Energy Sector (IDEES), published by the European Commission's Joint Research Centre (JRC) in 2018, which provides consistent and detailed data about the residential space cooling sector of EU-28 countries over an extended time period (2000-15) [4]. This permits the development of a multi-method modelling framework for studying historical trends of space cooling energy consumption, which is inclusive of the broader non-technology factors. We use the term 'space cooling (or AC) energy consumption' to equate to the 'electricity-based final energy use for space cooling' from this point onwards in the paper. Moreover, it adopts a more scenario-based approach to evaluate potential future pathways of residential AC energy consumption for different EU-28 countries. More specifically, this paper tackles the following research questions:

i. What was the main driving force of EU's residential space cooling energy consumption in the time period 2000-15? This question is tackled with index decomposition analysis (IDA), which helps link the variation of household air-conditioning energy consumption to relevant activity, structural and intensity components.
ii. Which are the specific drivers of the climate-sensitive components of space cooling energy consumption? This objective is achieved by extending decomposition analysis to a set of panel data econometric models aiming to explain the influence of climatic and non-climatic factors on national AC penetration rates and households' useful space cooling demand.
iii. What are the impacts of future AC diffusion trajectories on electricity-based final energy use for space cooling in the EU-28 residential sectors and potential peak cooling electricity demand, as projected up to 2050? This paper develops baseline AC diffusion scenarios incorporating projections of socio-economic and climatic data, while alternative policy cases consider unit efficiency targets and AC installation rates in new and renovated buildings.

The rest of the paper is organised as follows: Section 2 describes the novel modelling framework adopted in this study and summarises the data requirements. Section 3 presents the results of the historical analysis (2000-15) and the future scenario modelling (2016-50). Section 4 then discusses potential areas for EU policy intervention, while section 5 concludes.

2. Methodology

2.1. General modelling framework

The analysis is performed across two overlapping layers, as shown in Fig. 2: (A) Traditional decomposition analysis [17–19] is first

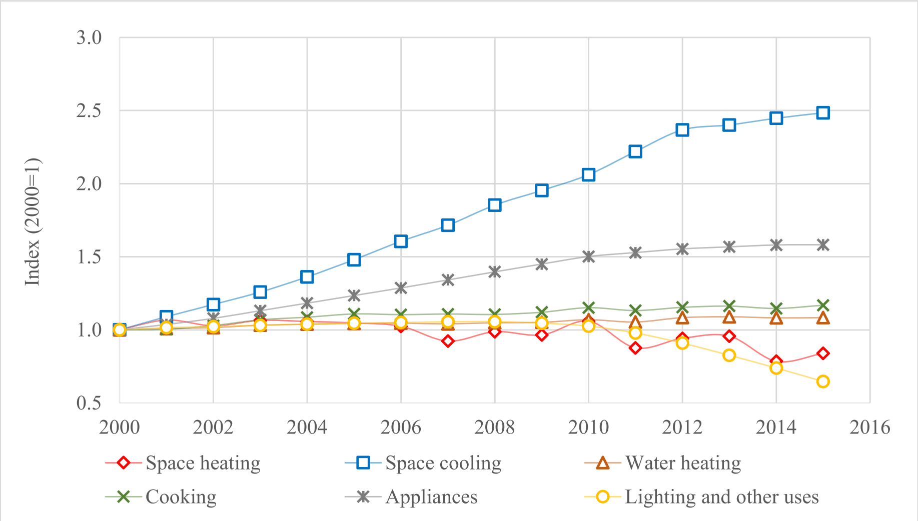

Fig. 1. Indexed evolution of EU-28 residential final energy use by end-use (2000-15) [4]

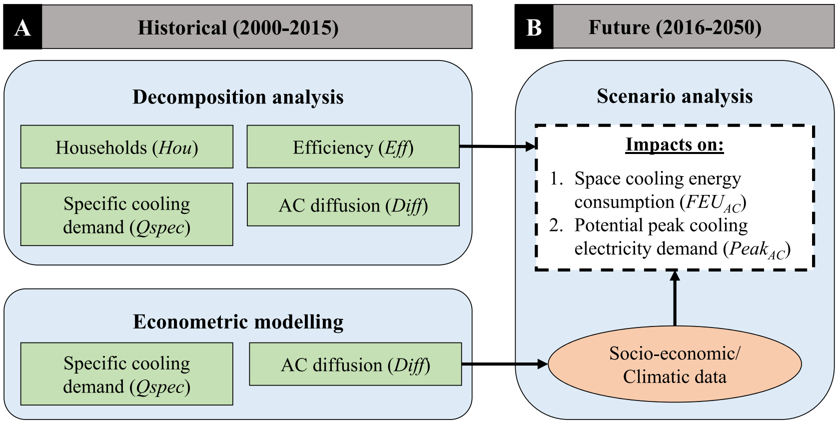

Fig. 2. General modelling framework

employed to quantify the effect of changes in different components (i.e. household numbers, unit AC efficiency, useful specific cooling demand and AC diffusion) on historical variation (2000-15) of EU-28 residential AC energy consumption. Panel data models are then utilised to study the sensitivity of AC penetration rates and useful specific cooling demand to climatic and non-climatic influences. (B) Finally, scenarios are developed to analyse the impact of distinct AC diffusion trajectories on EU-28 sectoral space cooling energy consumption in the time period 2016-50, as well as on potential peak cooling electricity demand. Future baseline AC diffusion estimates are derived from the econometric model developed in (A), when enacted with country-level projections of climatic and socio-economic data. These are benchmarked against two policy cases concerning unit efficiency improvements and diversified installation rates, for which the assumptions are presented in the following sections.

2.2. Decomposition analysis (2000-15)

Sectoral-level decomposition analysis is a very useful tool for energy policy-making, especially in the context of residential sector mitigation strategies where it has been applied to understand the temporal dynamics of energy consumption and the corresponding carbon emissions [20]. This approach offers the advantage of attributing changes of final energy use to a set of pre-specified factors which can be unique for each end-use service, thus facilitating the design of more tailored energy reduction policies. In its simplest form, index decomposition analysis (IDA) is performed via Eqn. (1):

$$FEU = A \times S \times I \tag{1}$$

where *FEU*, final energy use of a sector or for a specific end-use, is expressed as the product of Activity (*A*), Structure (*S*) and Energy Intensity (*I*). The first component, namely *A*, denotes the primary driver of final energy use, while *S* captures additional parameters having an impact on its size. On the other hand, factor *I* represents energy consumed per unit of activity, which is influenced by weather, building and AC technology characteristics, as well as lifestyle patterns [21]. In the case of residential space cooling energy consumption, the number of households and diffusion rate of AC equipment is respectively ascribed to the activity and structural parameter [12]. The intensity indicator is then defined as space cooling energy consumed per air-conditioned household. Space cooling energy consumption (FEU_{AC}) in EU-28 countries is therefore expressed in annual steps (TWh/y) between 2000 and 2015, using Eqn. (2):

$$FEU_{AC} = Hou \times Diff \times Qspec \div Eff \tag{2}$$

where *Hou* is the number of households (hh) and *Diff* the share of residential buildings equipped with air-conditioning (%), conforming to the adopted framework. Moreover, useful specific cooling demand (useful kWh/hh), captured through *Qspec*, is converted into units of specific space cooling energy consumption (kWh/hh) via the cooling system's efficiency indicator, *Eff*.

Log Mean Divisia Index – method I (LMDI-I) is the preferred tool to explain the year-to-year variation of residential AC energy consumption via the contribution of the 4 pre-selected components, due to its theoretical and methodological advantages [22]. These advantages include leaving no residual term since absolute annual FEU_{AC} changes over time can be completely decomposed to individual components, in an additive fashion through Eqn. (3):

$$\Delta FEU_{AC} = \Delta FEU_{AC}^{Hou} + \Delta FEU_{AC}^{Diff} + \Delta FEU_{AC}^{Qspec} - \Delta FEU_{AC}^{Eff} \tag{3}$$

where differences in FEU_{AC} between a specific year, *y*, and base year, 0, equates to the sum of partial temporal effects arising from changes in household numbers, AC appliance ownership, useful specific cooling demand and efficiency improvements. Given the logarithmic form of the decomposition, the impact of individual components on FEU_{AC}, such as that of the housing stock is calculated via Eqn. (4):

$$\Delta FEU_{AC}^{Hou} = \frac{FEU_{AC_y} - FEU_{AC_0}}{lnFEU_{AC_y} - lnFEU_{AC_0}} \times \left(lnHou_y - lnHou_0\right) \tag{4}$$

2.3. Panel data econometric modelling (2000-15)

Diffusion (*Diff*) of residential air-conditioners in EU-28 countries during the baseline period is studied in a panel data setting through an "s-shaped" logistic curve; a common functional form first adopted by *McNeil and Letschert* [23,24] to construct a global AC diffusion curve. Similar to [25], we modify the logistic function via Eqn. (5) to account for intra-country data variation:

$$Diff_{c,y} = \frac{Sat_c}{1 + \alpha_c \exp\left(\beta X_{c,y}\right)} \tag{5}$$

Saturation (*Sat*) represents the maximum attainable up-take level of air-conditioning in residential buildings which is invariant with time, measured in years (*y*), and can be unique for each EU-28 country (*c*). Without imposing any ad-hoc restrictions, *Sat* can theoretically vary between 0 and 100%. The horizontal position of the logistic curve is adjusted by the constant *α*, while its slope is controlled by *X*, an array of variables expected to have a positive or negative temporal impact on AC diffusion rates.

Besides local climate, a number of studies have concluded that growing personal income has been a strong determinant of worldwide AC up-take ([25] for China; [26] for United States; [27] for Mexico). Evidence has also shown that energy efficiency improvements and reduction in equipment prices has a reinforcing effect on consumer purchasing decisions with respect to air-conditioners [28]. Bringing these elements together, our model explicitly accounts for weather and income changes and implicitly controls for evolving energy efficiency standards and AC prices through a time trend, *t*. Rearranging Eqn. (5) and taking logarithms on both sides produces the following linear model given in Eqn. (6):

$$\ln\left(\frac{Sat_c}{Diff_{c,y}}-1\right)=\ln\left(\alpha_c\right)+\beta_1 t+\beta_2 INC_{c,y}+\sum_{k=0}^{K}\beta_{3y-k}TMP^{JJA}_{c,y-k}+\varepsilon_{c,y} \quad (6)$$

where *INC* denotes annual personal income in individual EU-28 countries, as approximated by per capita GDP which is adjusted to represent between-country price-level differences based on purchasing power parity (PPP). The response of AC diffusion to weather variation is captured through TMP^{JJA} which accounts for mean outdoor temperature in the summer months June-July-August (JJA), while a TMP^{JJA} lag (K=1) is subsequently added to control for the delayed impact of extreme heat events on ownership rates [25]. Since the impact of a unit change of temperature is expected to be stronger in areas with larger population [3], we adjust TMP^{JJA}, through Eqn. (7), to account for the heterogeneous distribution of residents across each EU-28 country, by applying weights corresponding to 2014's population count of "Nomenclature of territorial units for statistics – level 3" (NUTS-3) sub-regions:

$$TMP^{JJA}_{c,y}=\frac{\sum^{n}_{NUTS=1}TMP^{JJA}_{NUTS,y}Pop_{NUTS,c}}{\sum^{n}_{NUTS=1}Pop_{NUTS,c}} \quad (7)$$

where *n* is the number of NUTS-3 sub-regions in each EU-28 country.

Instead of estimating Eqn. (6) through Ordinary Least Square (OLS) regression, which would yield 28 unique sets of model coefficients corresponding to each EU-28 country, the effect of weather and income on residential AC diffusion is more accurately identified via fixed-effects (FE) panel data estimation. Unlike OLS, panel data models can handle a data structure involving both a temporal and spatial dimension, thereby recognising the heterogeneity of behaviours observed in individual countries. Moreover, panel data estimators control for time-invariant, country-specific characteristics (αs) which can be correlated with explanatory parameters, thereby reducing omitted variable bias [29]. In the FE case, generated model coefficients resemble the effect on the dependent variable – on average across EU-28 countries – from a unit change in the independent variable along the temporal dimension. A Hausman test is also performed to confirm the superiority of the FE estimator to the random-effects (RE) one [30].

Matching future *Sat* levels in EU-28 countries with present-day AC diffusion rates observed in regions of United States with similar climatic conditions – the so called "Climate Maximum" [12,21,23] – would cloud analysis with strong assumptions about the pace of evolution of regional AC markets. Instead, a different approach is followed to determine these ceiling values empirically. EU-28 countries are first split in two groups according to long-term (1995-2015) cooling degree days (*CDDs*), measured in °C•d, each of them assumed to reach a unique saturation point: countries with higher than average *CDDs* are labelled as warm, while the rest of them are named as cold. The performance of the *Diff* model is iteratively evaluated (at steps of 10%) for various group-level *Sat* values through the adjusted-R^2 criterion. Sat_{cold} is constrained to be always smaller or equal to Sat_{warm}, while both are set to vary above the highest current AC diffusion level in each region. A combination of saturation points that maximise the model's goodness-of-fit are finally adopted.

Useful demand for space cooling per unit of activity has been previously econometrically estimated based on cross-sectional models using climatic variables, in the form of CDDs, and economic development indicators, such as personal income [21] and household expenditures [31,32]. In a cross-sectional setting, the positive effect of income on specific cooling demand was demonstrated to diminish in wealthier countries, as occupants choose to use their AC equipment irrespective of their financial status [33]. Since the vast majority EU-28 nations are high-income economies a different model specification, described in Eqn. (8), has been chosen to study the within-country variation of *Qspec*:

$$Qspec_{c,y}=\gamma_c+\delta_1 AREA_{c,y}+\delta_2 AREASQ_{c,y}+\delta_3 CDD_{c,y}+\varepsilon_{c,y} \quad (8)$$

Useful floor area (*AREA*) is selected as a more straightforward explanatory parameter of *Qspec*; in larger households, containing more rooms and communal areas, maintaining desired indoor temperature level demands either more intense use of existing space cooling equipment or acquisition of additional AC units, both having a significant effect on *Qspec* [34]. Moreover, past research has shown that household floor area is strongly connected with personal income [3] and so the inclusion of both variables in the FE panel data model has been avoided. A quadratic floor area term (*AREASQ*) is also included to capture any additional non-linear effects.

Cooling degree days (*CDDs*) characterize the climate-sensitive part of useful specific cooling demand. They quantify the annual sum of daily deviations of mean outdoor air temperature from a pre-specified fixed threshold [35], in line with Eurostat's definition[1], below which no mechanical space cooling is needed to restore thermal comfort in households. Using a high temperature threshold (here set at 24 °C) ensures that days with low average temperature, when building energy demand is essentially climate-insensitive, are excluded from *CDD* calculations. *CDDs* in essence capture the cumulative effect of warm temperatures on specific AC demand more effectively than using an absolute measure of temperature, which was the approach used in the AC diffusion model. As in the standard FE model specification, γs refer to country-level factors and ε to the residual error term.

2.4. Scenario analysis (2016-50)

Future pathways of space cooling energy consumption (FEU_{AC}) and potential peak cooling electricity demand ($Peak_{AC}$) in the EU-28 region are evaluated though a scenario modelling process which extends the analysis to the period 2016-50. The scenarios focus on incorporating anticipated changes in the stock and efficiency of residential air-conditioners in accordance with the specifications of a baseline and two policy cases. In the baseline case, country-level AC penetration rates are projected in annual steps up to 2050 via the diffusion model in Eqn. (6), for combinations of personal income (*INC*) and mean summer temperature (TMP^{JJA}) trajectories.

Future personal income is derived from the Intergovernmental Panel on Climate Change's Shared Socio-economic Pathways (SSPs), which provide plausible narratives for the long-term evolution of various socio-economic drivers [36]. Baseline AC diffusion scenarios adhere to 3 SSPs which cover the full spectrum of projection uncertainty, including a "middle-of-the-road" trajectory (SSP2) and a fast vs. slow economic growth case (SSP5/SSP3). With respect to increasing summer temperatures across Europe, Representative Concentration Pathway (RCP) 8.5 was selected since it describes the high-end of projected climate change, whereby radiative forcing is boosted up to 8.5 Wm^{-2} in 2100 due to unmitigated greenhouse gas emissions [37].

The sensitivity of country-level FEU_{AC} to growing AC up-take is assessed in 2016-50 by adjusting the *Diff* factor in Eqn. (2) to match the respective scenario's value, while holding household count (*Hou*), AC efficiency (*Eff*) and useful specific cooling demand (*Qspec*) constant at the level in 2015. Future residential AC energy consumption is therefore estimated using Eqn. (9):

$$FEU_{AC\,c,y}=FEU_{AC\,c,2015}\times\frac{Diff_{c,y}}{Diff_{c,2015}} \quad (9)$$

We define potential peak cooling demand as the maximum theoretical load which a national electricity system would have to sustain if

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[1] $CDD_y=\sum^{d}_{i=1}\begin{cases}(TMP^d-21°C), & TMP^d>24°C\\ 0, & TMP^d\le 24°C\end{cases}$, where d is the number of days in year, *y*, and $TMP^d$is daily mean outdoor temperature [59].

Table 1
Composition and technical parameters of buildings RAC stock at the EU-15 level [6]

AC technology	w (%)	Cap (kW)	SEER
Split systems	61.8	3.50	3.22
Multi-split systems	5.3	16.0	2.12
Single-duct systems	15.7	10.5	4.75
Packed units	17.2	4.75	2.12

the full residential AC stock in a given year was operating at nameplate capacity; a condition which is more likely be fulfilled during periods of high extreme temperature. Maximum peak cooling demand ($Peak_{AC}$) is then calculated as the product of total annual AC stock in a country and full space cooling (electric) load. Stock size is first obtained as a percentage from the projections performed through the AC diffusion model (Eqn. (6)) in the 2016-50 period and then converted into number of units (*NrAC*) using the number of houses in 2015. The latter parameter is estimated with the help of EU-15 inventory data obtained from Pezzutto *et al.* [6], including different RAC systems' rated capacity (*Cap*) and seasonal energy efficiency ratio (*SEER*), as well as their respective share (*w*) in total buildings' sector stock. Estimation of potential peak cooling demand is given in Eqn. (10):

$$Peak_{AC\,c,y} = NrAC_{c,y} \times \frac{\sum_{tech=1}^{4} w_{tech} \times Cap_{tech} \div SEER_{tech}}{\sum_{tech=1}^{4} w_{tech}} \tag{10}$$

where *tech*= split, multi-split, single-duct and packed systems; which are currently the technologies with highest diffusion in the household sector. Amongst available room systems (Table 1), split AC units form the largest portion of the installed RAC stock (~60%), while they have the smallest average capacity size and highest conversion efficiency factor. Given the absence of data about the future composition of residential AC stock, peak cooling electricity demand scenarios in 2050 are built based on the assumption that the relative share of individual technologies remains unchanged.

We subsequently devise two policy case scenarios, whose aim is to assess the sensitivity of future AC energy consumption trajectories to varying assumptions for factors which can be tackled by policy makers, namely the level of unit efficiency improvements and diffusion rates in new and renovated buildings. In this way, we demonstrate the wide range of possible outcomes in 2050 under various policy regimes, instead of attempting to quantify the possibility of each scenario being realised in the future.

Case 1 - Unit Efficiency Improvement: We explore the size of energy savings which could be achieved due to significant increases in AC equipment efficiency. Tighter minimum energy performance standards (MEPS) and stricter labelling schemes are the main mechanisms which currently enforce improvements in the performance of air-conditioners in EU-28 markets [1,3]. These measures along with technological change are expected to have a major contribution in alleviating the foreseen pressure on electricity systems exerted by peak AC demand [38,39].

This scenario adopts the 20% and 30% general efficiency goals endorsed through the EU's mid-term energy strategy for 2020 and 2030, while it assumes that super-efficient units dominate the market by the end of mid-21st century, increasing average AC efficiency by 40% in 2050, relative to 2015. Based on JRC-IDEES data, the efficiency parameter (*Eff*) of residential AC systems at the EU-28 level is equal to 3.0 in 2015. Incremental technical improvements, imposed in the future through this policy scenario, result in assumed EU-level *Eff* factors of 3.6, 3.9 and 4.2 in 2021-30, 2031-40 and 2041-50, respectively for our study. While our assumed average AC efficiency of 4.2 in 2050 is slightly higher than the one adopted by JRC in [40] (~4.0), this is a feasible target since it is still lower than the *Eff* value of the best available technology currently marketed in the EU-28 region [1] Electricity-based final energy use for space cooling in 2016-50 is calculated via Eqn. (11), after expanding Eqn. (9) to incorporate changes in space cooling efficiency:

$$FEU_{AC\,c,y} = FEU_{AC\,c,2015} \times \frac{Diff_{c,y}}{Diff_{c,2015}} \times \frac{Eff_{c,y}}{Eff_{c,2015}} \tag{11}$$

A similar approach is followed in obtaining modified potential peak cooling electricity demand ($Peak_{AC}$) estimates through applying efficiency improvements on the current SEER values of individual RAC technologies in Table 1.

Case 2 - New Buildings AC Rates: About 3% of housing stock across the EU-28 region every year (2000-15) consists of new and renovated buildings, which generally display higher AC diffusion rates than existing, non-renovated, ones [4]. In 2015, 17.1% of new and renovated EU-28 households were equipped with an air-conditioner, while only 8.9% of old residential buildings had one installed. Future developments in the construction industry could facilitate easier installation of air-conditioning in the former group of buildings, as shown by the experience of the USA [26]. A drop in installation costs could work as an incentive for investing in room AC units; an economic behaviour which if mimicked by more and more newly-constructed households could abruptly transform the EU's residential space cooling market.

This "bad case" scenario is assumed to have an additive effect on baseline residential AC diffusion trajectories. The diffusion parameter is modified each year (*Diff'*) to account for the growing number of new and renovated units, $NrAC'_{new}$, in total air-conditioning stock, added to the previous year's stock, $NrAC'_{y-1}$, as well as to old households' AC equipment replacements and additions, $NrAC'_{old}$, as demonstrated by Eqn. (12):

$$Diff'_{c,y} = Diff_{c,y} + \frac{\left(NrAC'_{new} - NrAC_{new}\right) + \left(NrAC'_{old} - NrAC_{old}\right) + \left(NrAC'_{y-1} - NrAC_{y-1}\right)}{Hou_{c,2015}} \tag{12}$$

Our assumptions for this high penetration scenario is that diffusion rates for air-conditioning in new and renovated buildings, $Diff'_{new}$, increase from around 17% in 2015, in 10-year time steps, from 80% in 2021-2030, to 90% in 2031-40, and eventually reach full saturation (100%) in 2041-50. These values are benchmarked against baseline $Diff_{new}$ projections constructed to 2050 by means of linear extrapolation based on historical diffusion data (2000-15). The fraction of new and renovated buildings in the total housing stock per year in EU-28 countries is assumed to remain constant at 3% in the future; which equals the ambitious building stock renovation target set in the EU's Directive on Energy Performance of Buildings [41] and lies within the range of renovation rates selected in [42] for Germany's household sector. Since this set of rules does not affect AC purchasing decisions in old households, the $NrAC_{old}$ terms can be removed from Eqn. (12) as they cancel each other. Based on these assumptions, the modified AC diffusion parameter can be calculated under this scenario using Eqn. (13):

$$Diff'_{c,y} = Diff_{c,y} + 3\% \times \left(NrAC'_{new} - NrAC_{new}\right) + \frac{\left(NrAC'_{y-1} - NrAC_{y-1}\right)}{Hou_{c,2015}} \tag{13}$$

2.5. Data requirements

For the purposes of index decomposition analysis, the JRC-IDEES database was accessed to obtain information regarding space cooling energy consumption (FEU_{AC}), household numbers (*Hou*), air-conditioning stock and efficiency status of AC systems (*Eff*) [4]. Based on these data, response variables of panel data models (i.e., useful specific cooling demand (*Qspec*) and AC diffusion (*Diff*)) were derived. Moreover, econometric modelling required the input of PPP-adjusted GDP data which

Table 2
Descriptive statistics of country-level variables during the historical period 2000-15

Variable	Symbol	Mean	Std. Dev.	Max	Min
AC energy consumption (TWh/y)	FEU_{AC}	0.40	1.07	7.84	0
Useful specific cooling demand (useful kWh/hh•y)	Qspec	1,656	1,070	5,241	333
AC diffusion (%)	Diff	6.4	9.3	48.6	0
Number of households (hh)	Hou	7,459,383	9,998,632	40,558,210	134,669
AC system efficiency	Eff	2.18	0.48	3.62	1.40
Personal income (2011$/pop PPP)	INC	32,684	14,914	98,646	8,811
Household floor area (m^2/hh)	AREA	89.9	21.9	142.6	41.8
Mean JJA temperature (°C)	TMP^{JJA}	19.35	3.35	29.19	13.19
Cooling Degree Days (°C•d)	CDD	108	174	781	0

were obtained from the World Bank [43], expressed in constant international dollars for the year 2011. National and NUTS-3 EU-28 population statistics, as well as annual (1995-2015) cooling degree days (*CDDs*) were sourced from Eurostat [44,45].

Monthly mean, near-surface, temperatures during the historical period (2000-15) were retrieved for every EU-28 country from Climatic Research Unit's (CRU's) time-series dataset, which is available in 0.5°x0.5° resolution [46]. For this task, the geographic centroid of each NUTS-3 sub-region was previously matched to the 4 nearest grid points and grid temperatures were aggregated to the NUTS-3 level via inverse distance weighting (IDW) interpolation. The coordinates of these geographic centres were extracted from shapefiles depicting the geometries of NUTS-3 regions in 2013 [47].

Descriptive statistics for all variables in the 2000-15 period are presented in Table 2. In absolute terms, Italy is the country with by far the largest residential AC energy consumption having mean annual FEU_{AC} levels of 5.4 TWh/y, which is 4 times larger than the quantity consumed by either Spain or Greece. Italy, Spain and Greece were collectively responsible for 70% of EU-aggregate residential space cooling energy consumption in 2015. Small northern EU-28 countries such as Estonia and Latvia had negligible FEU_{AC} levels in 2015 (<0.001 TWh/y).

In per household terms, Cyprus and Malta, which are the two hottest EU-28 countries according to the long-term CDD criterion (1995-2015), recorded the highest levels of useful specific cooling demand, with *Qspec* values of 4974 useful kWh/hh•y and 3977 useful kWh/hh•y, respectively, when averaged over the 2000-15 period. On the other hand, EU-28 countries found on the low-end of the annual *Qspec* distribution - Latvia (364 useful kWh/hh•y) and Lithuania (392 useful kWh/hh•y) - do not coincide with those having the lowest number of long-term *CDDs*, namely Ireland and Sweden. Finally, the highest residential AC diffusion rates in 2015 were recorded in Croatia (48%), Greece (33%) and Italy (30%). Croatia's exceptionally high penetration rates is unexpected, given its milder summer seasons and lower consumer affluence levels.

In order to devise baseline scenarios of AC penetration rates in EU-28 households, long-term projections regarding the annual growth of GDP per capita (PPP-adjusted) were collected for 3 SSP storylines from the database of International Institute for Applied Systems Analysis [36] and then averaged over the time period 2015-50. Daily mean, near-surface, temperatures were extracted for the same timeframe from 19 regional climate projections, which have been performed under the EURO-CORDEX downscaling experiment and simulate the effects of an extreme climate change scenario (RCP8.5) [48]. These projections were then translated into monthly, country-level, temperature statistics following the same aggregation procedure as in subsection 2.2. Table 3 provides a summary of climatic and non-climatic assumptions governing AC diffusion projections under the baseline case.

Table 3
Long-term mean (2015-50) annual growth rates of baseline variables in the EU-28 region

Category	Variable	Annual growth rate (%)		
		Low-Range	Mid-Range	High-range
Socio-economic	INC	1.1	1.2	2.2
Climatic	TMP^{JJA}		n/a (RCP8.5)	

3. Results

3.1. Decomposition analysis of FEU_{AC} (2000-2015)

During the time period 2000-15, EU-28 residential space cooling energy consumption increased from 6.4 to 15.8 TWh/y. Fig. 3 displays the results of the additive decomposition for all 1-year time bands, whereby the annual variation in EU-aggregate FEU_{AC} levels, represented by diamond markers, is broken down into the contribution of single components (*Hou, Diff, Qspec, Eff*), illustrated by the uniquely coloured column bars. As an example of this method, the +0.88 TWh/y change in FEU_{AC} observed between 2007 and 2008 comprises the 0.12, 1.23 and 0.08 TWh/y positive impact attributed respectively to housing stock, AC diffusion and specific cooling demand, and to the 0.55 TWh/y negative effect from efficiency improvements.

Fig. 3 shows that the diffusion of AC units in residential buildings had the strongest increasing impact on EU-28 space cooling energy consumption across all 15 time bands, having a mean effect (2000-15) on FEU_{AC} of +1.02 TWh/y. The second largest contribution to FEU_{AC} variation is attributed to AC system efficiency, with an average decreasing effect being half the size of diffusion-related one (-0.51 TWh/y). Useful specific cooling demand and housing stock size had smaller influences on annual AC energy consumption levels in the EU-28 region, with an average impact amounting to +0.04 and +0.08 TWh/y, respectively. This highlights the significance of studying "extensive margins" in more detail [40], relating partly to understanding the role climatic and non-climatic factors play in residential AC adoption.

Moreover, the largest diffusion effect on FEU_{AC} (+1.5 TWh/y) is found for the 2011-12 time band, which co-occurs with a 49.3% relative increase in EU-wide cooling degree days, whose annual change is also plotted in Fig. 3. One would expect that the *Diff* effect would have peaked in 2002-3, as a result of the severe heatwave which struck the European continent; however, this is not evident from EU-aggregate data. On the other hand, useful specific cooling demand influences FEU_{AC} the most in the 2010-11 time band, during which mean *CDDs* across the EU dropped by 19.2%. While this finding is counterintuitive, one should also note that this effect peaks due to a sharp increase in *Qspec* levels across Italy, which indeed faced increasing *CDDs* in 2010-11. It is therefore vital to evaluate the specific drivers of *Diff* and *Qspec*, while accounting for the heterogeneous behaviour of EU-28 countries; an objective which is tackled next.

3.2. Panel data modelling of Diff and Qspec (2000-2015)

EU-28 countries qualifying in the warm group, exceeding the region's average long-term annual *CDDs* (102 °C•d), are Croatia (121 °C•d), Bul-

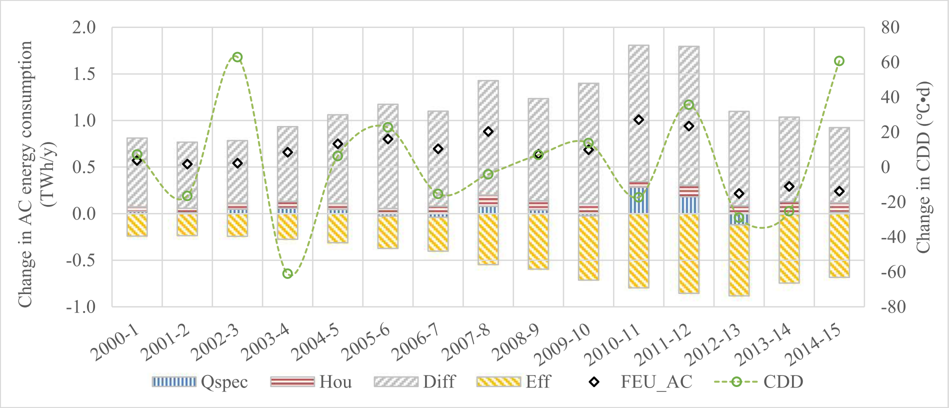

Fig. 3. Decomposition of residential space cooling energy consumption at the EU28-level with comparison to change in cooling degree days [LHS: Decomposition of 4 drivers of annual residential AC energy consumption (FEU_{AC}): Useful specific cooling demand (Qspec); Number of households (Hou); AC diffusion (Diff); AC system efficiency (Eff)
RHS: Annual change in cooling degree days (CDD)]

Table 4
FE estimation results of AC diffusion model with Sat_{warm}=60% and Sat_{cold}=30%

Variables	(1)	(2)	(3)
INC (000$/pop)	-0.086***(0.033)	-0.078**(0.031)	-0.150***(0.046)
TMP_{y}^{JJA} (°C)	-0.043***(0.014)	-0.034*(0.019)	-0.030***(0.009)
TMP_{y-1}^{JJA}(°C)		-0.025*(0.014)	
Trend	-0.137***(0.011)	-0.142***(0.012)	-0.152***(0.013)
$\overline{\ln(\alpha_c)}$	7.503***(1.117)	7.570***(1.095)	3.964***(0.110)
Observations	448	420	448
F-test	128.5***	130.8***	
Hausman test	18.0***	11.5**	
R^2 (adj.)	0.753	0.745	0.727

Statistically significant * at the 10%, ** at the 5% and *** at the 1% confidence level. Note: Standard errors in the parenthesis are clustered by country (a la Arellano covariance matrix).

Table 5
FE estimation results of specific cooling demand model

Variables	
AREA (m^2/hh)	-36.595# (23.465)
AREASQ	0.339** (0.145)
CDD (°C•d)	0.103* (0.062)
$\overline{(\gamma_c)}$	2004.117** (907.279)
Observations	432
F-test	440.2***
Hausman test	8.3**
R^2 (adj.)	0.394

Statistically significant at # at the 12%, * at the 10%, ** at the 5% and *** at the 1% confidence level.

garia (145 °C•d), Portugal (170 °C•d), Italy (201 °C•d), Spain (205 °C•d), Greece (300 °C•d), Malta (606 °C•d) and Cyprus (678 °C•d), which together represented 26.2% of total EU-28 housing stock in 2015 (57.7 million units). The rest 20 EU-28 countries (i.e., Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Ireland, Latvia, Lithouania, Luxembourg, Netherlands, Poland, Romania, Slovakia, Slovenia, Sweden and United Kingdom) were assigned to the cold group. The residential AC diffusion model in Eqn. (6) is run initially without a lagged temperature variable, while the obtained R^2 (adj.) statistic is compared for all potential combinations of Sat_{warm} (50-100%) and $Sat_{cold.}$ (20-100%). Model diagnostics which involved application of an F-test for country-level effects and a Hausman test demonstrated the suitability of fixed-effects over the pooling and random-effects panel data estimator, accordingly. The optimal model fit is achieved when the saturation parameter for warm countries is set at 60%, while that for cold ones at 30%.

Table 4 reports FE estimator's output following implementation of the empirically-derived saturation levels. Column (1) includes generated coefficients, along with their robust standard errors. Results show that both personal income (*INC*) and contemporaneous mean summer temperature (TMP^{JJA}) exhibited a highly statistically-significant ($p<0.01$) positive effect on AC up-take in households during the time period 2000-15, while a strong trend is also present[2]. Overall model performance is deemed very good, as independent variables collectively explain 75% of observed variation in data.

Delayed temperature effects are assessed by re-running the AC diffusion model with a summer temperature variable lag (Column (2)). Interestingly, the coefficient of TMP_{y-1}^{JJA} also turns out to be statistically significant, albeit at lower confidence level ($p<0.1$). This finding suggests that EU-28 households respond to warmer weather through purchasing AC units at two time steps, one occurring the same year during which a heat event took place and another the year after. The marginal impact of lagged temperature on the response variable is however smaller than the one attributed to contemporaneous TMP^{JJA}. One should also note that inclusion of a lagged TMP^{JJA} term in the model does not come without a cost, as model parameter estimation is less accurate and resulting R^2 (adj.) statistic is smaller compared to the basic specification.

Comparing the size of temperature and income marginal effects on AC diffusion requires a standardization procedure which puts both predictors on the same measurement scale. Re-scaling variables effectively harmonizes FE regression coefficients as they now represent the response of dependent variable due to a standard deviation of either TMP^{JJA} or *INC* (Column (3)). The new income estimate is about 5 times larger than the one for temperature, implying that growing household affluence levels have larger influence on AC purchasing decisions in the EU-28 region, compared to increasing outdoor temperatures. The greater importance of income versus temperature on AC diffusion is reflected in the ratio of *INC* to TMP^{JJA} effect on penetration, which we obtain as around ~5 in this paper, being roughly similar to a study reported for Chinese provinces (~6) [25].

The model of useful specific cooling demand in Eqn. (8) is run after ensuring the suitability of the FE estimator via the same confirmatory tests. Ireland is the only EU-28 country with zero cooling degree days for all years in the sample (2000-15), thus it is excluded from the analysis. The estimated FE model generally has less explanatory power relative to the AC diffusion one, with an R^2 statistic close to 0.4 (Table 5). Parameter estimation shows the presence of a non-linear relationship between useful specific cooling demand and household floor area, since the *AREASQ* term has a statistically-significant coefficient. The marginal effect

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[2] Due to the transformation of the logistic model, a negative change in one of the variables on the right-hand side of the equation results in an increase of *Diff* variable, when other terms are kept constant.

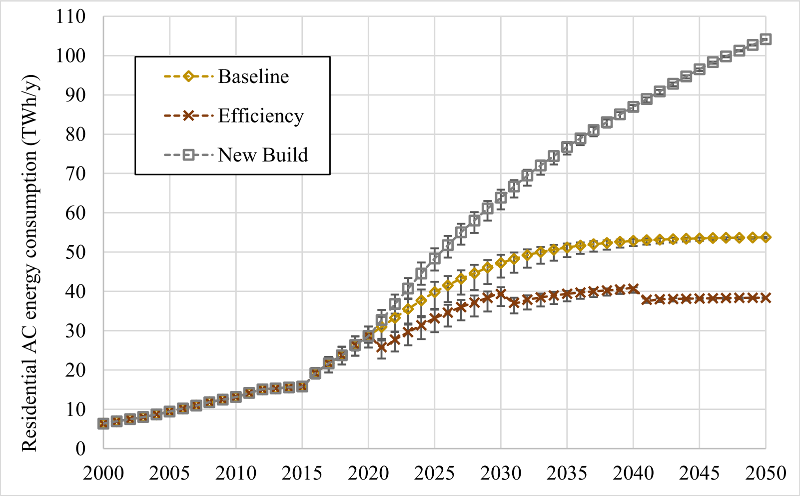

Fig. 4. Past and future residential AC energy consumption at the EU-28 level under different scenarios. Note: Error bars represent the range of uncertainty in RCP and SSP projections

of *AREA* on *Qspec* $(\delta_1 + 2\delta_2 AREA)$ becomes positive when household floor area exceeds 54 m^2/hh. This is much lower than the EU's average household area recorded in the 2000-15 period (89.5 m^2/hh).

On the other hand, the temporal effect of weather on useful specific cooling demand is less evident. Although the estimated *CDD* coefficient exhibits the correct (+) sign, it is only marginally significant ($p \approx 0.097$), while its inclusion has a minor impact on model performance. Nevertheless, the soft link between *Qspec* and *CDD* demonstrated through our results supports the argument brought forward later in peak cooling electricity demand calculations that simultaneous AC use across multiple households would more likely occur during extreme heat conditions.

3.3. Future scenarios of residential AC energy consumption (2016-2050)

This section explores the range of potential FEU_{AC} and $Peak_{AC}$ outcomes under different trajectories of air-conditioning market development in the 2016-50 period. AC diffusion levels are projected in the future using the basic *Diff* model specification (without a TMP^{JJA} lag). In the baseline case, residential air-conditioning markets across warm and cold countries reach almost full saturation by the end of the projection period, increasing EU-aggregate, mid-range, AC diffusion from 9.2% in 2015 to 37.6% in 2050. Saturation is virtually reached under all personal income and summer temperature projections in 2050, albeit at varying paces. A steeper AC diffusion curve at intermediate market development stages, arising from a high-income (SSP5) and extreme temperature trajectory (maximum of multi-model ensemble), would result in a higher amount of cumulative energy consumption over the period (2016-50).

Penetration levels of residential air-conditioning deviate significantly from the Baseline scenario in the "New Buildings AC rates" case, with the largest impact observed in cold countries where new and renovated buildings have low installation rates during the historical analysis period. Under mid-range trajectories, residential AC ownership rate in cold countries reaches 87.5% in 2050 without any signs of saturation, while diffusion in warm countries stagnates at 78.5%. Overall, aggregate space cooling diffusion in the EU-28 region reaches 85.1% in 2050 under this "bad case" scenario.

Residential space cooling energy consumption is calculated at one-year time steps from 2016-50, under each of the 3 scenarios (Fig. 4). In the baseline case, mid-range FEU_{AC} across the EU increases by a factor of 3.4 in 2050 (53.7 TWh/y) relative to 2015. The contribution of cold countries to total FEU_{AC} levels rises from 21.9% in 2015 to 39.5% in 2050, whereas that of warm states declines from 78.1% to 60.5% in the same time period. Italy and Spain together represent the largest portion of EU-28 space cooling energy consumption (46.4% compared to 59.8% in 2015). Despite its growth, AC energy consumption in the baseline case still accounts for a modest share of EU's residential total (1.9%) and electricity-based (6 %) final energy use in 2050, as projected by the International Energy Agency (IEA) in their Reference Technology Scenario (RTS) [2].

As expected, the sharpest increase of EU-28 residential AC energy consumption in the future is estimated under the "New Buildings AC rates" scenario (104.1 TWh/y in 2050 for the mid-range trajectory). Due to the radical transformation of national AC markets, the cold group of countries account for the largest share of household space cooling energy consumption in 2050 (60.1%), with Germany and France having a combined contribution of 54.7% to total FEU_{AC}, as opposed to 11.5% in 2015. On the other hand, the future share of Spain, Italy and Greece in FEU_{AC} drops to a third. Under this scenario, space cooling in 2050 represents about 3.7% of final residential energy and 11.7% of electricity use at the EU level.

With respect to capacity-related impacts, potential peak cooling electricity demand in the EU-28 household sector increases from 43.3 GW in 2015 (26.7/16.6 GW in warm/cold countries) to 177.7 GW in 2050, under the mid-range baseline projection, with 103.7 GW attributed to cold countries. Moreover, in agreement with FEU_{AC} findings, $Peak_{AC}$ is affected the most under the extreme AC diffusion scenario, recording a 9-fold increase by 2050 (401.9 GW, of which 304.9 GW is in cold countries). As anticipated, the smallest change in peak cooling electricity demand is projected for the strong unit efficiency case (127 GW in 2050, of which 74.1 GW is in cold countries).

While knowledge about the future size of potential peak cooling demand is essential for electricity capacity upgrades, what is also of principal value for electricity network operators is the timing of integration of new plants to the grid. Given the fast-growing residential AC markets and ambitious EU plans to decarbonise electricity grids by 2050, adequate provision of renewable capacity will be required to manage peak loads emerging during summer, mostly in the form of solar which has high seasonal output potential. Fig. 5 benchmarks the growth of $Peak_{AC}$ under the 3 scenarios against the projected expansion of solar-based generating capacity [49], separately for warm and cold EU-28 countries. Potential peak residential AC demand across cold countries is shown to outgrow forecasted expansion of solar capacity during most of the projections period. This is especially the case for "New buildings AC rates" scenario, whereby aggregate $Peak_{AC}$ increases by as much as twice ($\sim$1.9) the size of total solar capacity in cold countries, highlighting potential risks of electricity system failure if other sources of generating capacity are not added to meet peaking demand and alternative cooling options are not provided. In contrast to cold Member States, growth in solar capacity in warm countries catches up with that of potential peak

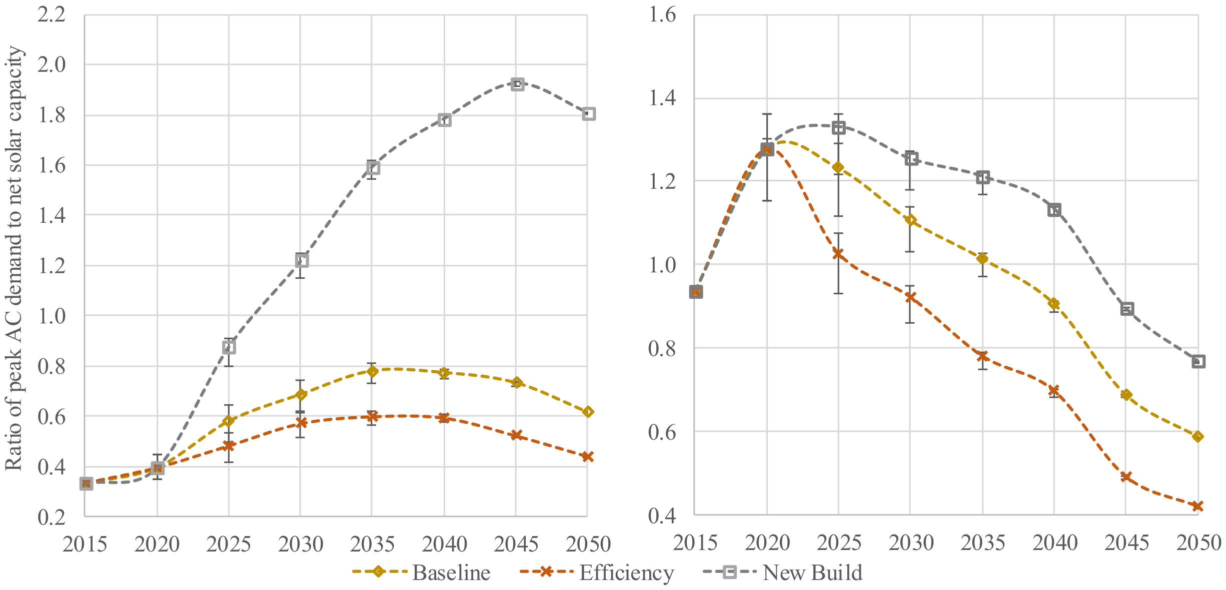

Fig. 5. Ratio of potential peak cooling electricity demand to solar-based capacity for cold (left) and warm (right) EU-28 countries

cooling demand much earlier in the 2016-50 period, with the latest turning point occurring by 2025 under the extreme AC diffusion scenario.

4. Discussion

4.1. Comparison with previous studies

Our findings agree with the general trend found in previous studies, which predict a significant increase of electricity-based final energy use for space cooling in the EU's residential sector [3]. However, discrepancies arise between projections about the exact level of AC energy consumption in 2050. Our baseline FEU_{AC} estimate for the EU-28 region in 2050 is roughly 2.5 times as large as the IEA's RTS projection for space cooling energy consumption (21.8 TWh/y) [2]. The latest FEU_{AC} estimate for 2050 for the EU-28 region is found in the JRC POTEnCIA central scenario (42.5 TWh/y) [40], which compares well with our strong unit efficiency projection (38.4 TWh/y). Unlike this study's modelling approach, these assessments did not examine potential implications of climate change on future residential AC energy consumption.

Our paper generally finds important differences from other studies which also accounted for the effects of temperature and income on AC diffusion and useful specific cooling demand. The JRC projected EU-28 residential AC energy consumption to reach 33 TWh/y by 2050, without the influence of climate change, and to increase up to 78 TWh/y under an RCP8.5-like set of climate simulations [14]. While the JRC's highest FEU_{AC} estimate lies within the range of values obtained in this paper (38-104 TWh/y), they predict a much stronger impact on the growth of AC penetration rates for southern European countries in 2050 than our baseline case. These were shown to exceed the 80% diffusion level by 2050 and continue to ascend thereafter, due to higher assumed saturation rates and the determinant role of climate. On the other hand, mid-21st century's AC ownership rates across northern European countries in [14] were found to remain well below the 30% saturation point adopted in this paper.

Dittmann *et al.* [9] presented similar trends to [14] about the spatial heterogeneity of future climatic impacts on the share of residential cooled areas in southern and northern EU-28 countries. For a moderate climate change trajectory (RCP4.5), their EU-level estimate of FEU_{AC} in 2050 amounts to 31 TWh/y, which is lower than the range of our estimates. Mima and Criqui [15,16] were the only studies which projected a significantly larger increase of future levels of space cooling energy consumption. They estimated EU-27 residential final electricity use for space cooling to reach 129-233 TWh/y [16] and 634-754 TWh/y [15] in 2050. Each range represents the difference in predicted AC energy consumption levels for a constant climate case and a medium-high greenhouse emissions scenario in 2050.

4.2. Policy recommendations

In general, our findings highlight the expected important contribution of future space cooling diffusion trajectories to the increasing stress felt by regional power systems, particularly through requiring additional capacity to meet summer time AC loads. A number of energy policies could therefore be promoted to limit the growth of EU-28 residential electricity use from AC growth to 2050:

(i) Effective promotion of passive cooling designs: Passive cooling comprises all those natural or passive techniques that can help maintain indoor thermal comfort, while requiring minimal or zero energy input [3]. These can be split into processes preventing solar heat gains (e.g. better shading systems, roof and glazing properties), those modulating heat through utilisation of buildings' thermal mass and those dissipating heat (e.g., natural ventilation and evaporative cooling) [50]. Passive cooling needs to receive further support in the Energy Performance of Buildings Directive [41], as a tool which can not only enhance energy conservation efforts in residential buildings, but more importantly can help minimise the chance of mass penetration of mechanical space cooling technologies in the future.

(ii) Encouraging further efficiency improvements: Our scenario analysis results show that increasing the efficiency of RAC systems by 40% in 2050 significantly reduces EU-28 space cooling energy consumption and potential peak cooling electricity demand. In the baseline case, faster diffusion of residential air-conditioners in the medium term results in higher annual growth rates of space cooling energy consumption relative to those observed in the 2041-50 period, when AC markets have approached saturation (Fig. 4). Earlier action to enforce stricter minimum AC performance standards could therefore reduce the excess space cooling loads which electricity systems will have to sustain over successive years in the medium term. Achieving faster penetration of highly-efficient AC units in the EU-28 residential sector should not only rely on strengthening regulatory measures, such as mandatory MEPS. It will also require that national governments increase funding towards cooling-related research, prioritise consumer information programmes about the benefits of using energy efficient AC units and provide financial incentives which increase the market availability of these products [1].

(iii) Amendment of renovation strategies: EU-28 Member States are obliged, under the Energy Efficiency Directive [51], to publish long-term renovation strategies with a description of current housing stock and cost-effective approaches to achieve deep renovation. While the majority of countries were found to be compliant with this requirement [52], there is still not a unifying approach towards curbing demand for space cooling. Moreover, the growing role of air-conditioning in achieving renovation goals has been overlooked by many of cold countries. Updated strategies should parameterise anticipated changes in local climate characteristics, and also address other risk factors, such as increased consumers' thermal comfort expectations [53].

(iv) Diversification of cooling supply: While residential space cooling is usually supplied through electric room air-conditioners, decentralised, small-scale, production sites are emerging as alternative cold providers. Amongst available technologies, district cooling (DC) is considered by the EU as an integral part of a future highly-efficient space cooling sector [51], as it offers substantial environmental and primary energy savings benefits [54]. Installing decentralised DC plants in urban areas with high cold demand density can more importantly increase flexibility of cooling supply by reducing the stress on European electricity systems.

However, the size of DC systems in terms of peak demand capacity is presently limited to 1.7 GW in cold EU-28 countries and 0.5 GW in warm ones [55], which we estimate represents only 10% and 2% of the cold and warm sub-regions' potential peak cooling electricity demand in 2015 respectively. Furthermore, local authorities need to design a combination of fiscal incentives and bonus mechanisms for DC suppliers in order to overcome market obstacles and increase this technology's share in EU-28 space cooling supply. In addition to minimising market risks, innovation in building engineering could facilitate easier connection of buildings to nearby decentralised systems.

5. Conclusions

This paper has developed and applied new approaches to deciphering drivers of past and future trends of electricity-based final energy use for air-conditioning in EU's residential sector; an end-use characterised by tremendous growth potential. A novel multi-method modelling framework was constructed, which used index decomposition analysis as a reference point for understanding the drivers of past space cooling energy consumption, then extended this to a set of panel data models estimating climatic and non-climatic effects on AC components. Finally, a combination of the two methods led to the creation of scenarios of residential AC energy consumption and potential peak cooling electricity demand in EU-28 countries up to 2050.

First, index decomposition analysis showed that penetration of air-conditioning and technical efficiency improvements, to a lesser extent, shaped past trends (2000-15) of space cooling energy consumption in EU-28 households. AC diffusion was by far the key driver in the past, contributing to the annual increase of EU-28 space cooling energy consumption on average by 1 TWh each year. This increasing effect was only partly counterbalanced by AC unit efficiency gains over the same time period. Econometric analysis also suggested that both the diffusion of air-conditioning in households and useful specific energy demand depend on temperature variation. However, personal income was found to be the most important determinant of past AC diffusion, having a five times larger marginal effect compared to mean summer temperature.

Second, through scenario analysis we devised three potential trajectories of AC diffusion and unit efficiency, based on which EU-28 aggregate residential space cooling energy consumption grows from 16 TWh/y in 2015 to 38-104 TWh/y in 2050. This represents an increase in the share of space cooling in EU-level residential final electricity use from 2% in 2015 to 4-12% in 2050. Our baseline estimate of household AC energy consumption in 2050 (54 TWh/y) is 32 TWh/y and 11 TWh/y higher than projections from IEA [2] and JRC [40], respectively, which do not forecast potential temperature-driven increases of AC usage in the future. When compared to other climate change impact assessments, our study generally finds important differences regarding the degree of north-south polarisation of AC diffusion in the EU-28 region [9,14] and the aggregate level of residential AC energy consumption in 2050 [15,16].

Third, our study showed that electricity systems will have to sustain a higher level of peak cooling demand in the future if met by mechanical air-conditioners, which could challenge generation and network performance, subject to the size of electrical capacity installed [56]. This could be a particular issue in EU-28 countries whose power infrastructure is currently designed to face the highest loads during the winter season [57]; a potential seasonal shift of peak electricity demand to summer months, as a result of increased AC usage, would have implications for improved inter-seasonal storage of renewable electricity, which could be then transmitted across the EU to places with high peak cooling demand. Future work could focus on devising future projections of actual peak cooling demand in EU-28 countries, which are based on functions that explain the variation in number of residential AC units being active in a region according to a set of climatic and non-climatic conditions, similar to [58].

Declaration of competing interest

The authors declare no conflict of interest.

CRediT authorship contribution statement

Andreas Andreou: Conceptualization, Formal analysis, Methodology, Data curation, Investigation, Writing - original draft, Visualization, Software, Validation, Writing - review & editing. **John Barrett:** Conceptualization, Supervision, Visualization, Project administration, Resources. **Peter G. Taylor:** Conceptualization, Supervision, Visualization, Writing - review & editing, Funding acquisition. **Paul E. Brockway:** Conceptualization, Supervision, Visualization, Writing - review & editing, Funding acquisition. **Zia Wadud:** Conceptualization, Supervision, Visualization, Methodology.

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Data Repository

A complete set of input and results datasets for this paper have been deposited at the University of Leeds Data Repository at doi:10.5518/821.

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