COST-EFFECTIVE DECARBONISATION OF THE EUROPEAN HOUSING STOCK:

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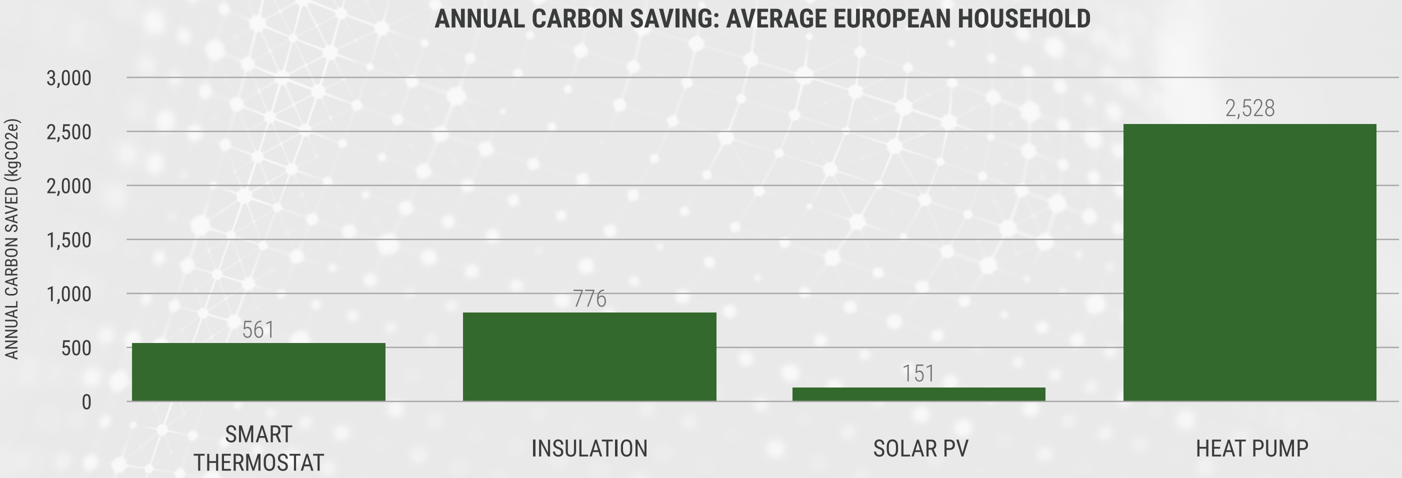
EXECUTIVE SUMMARY

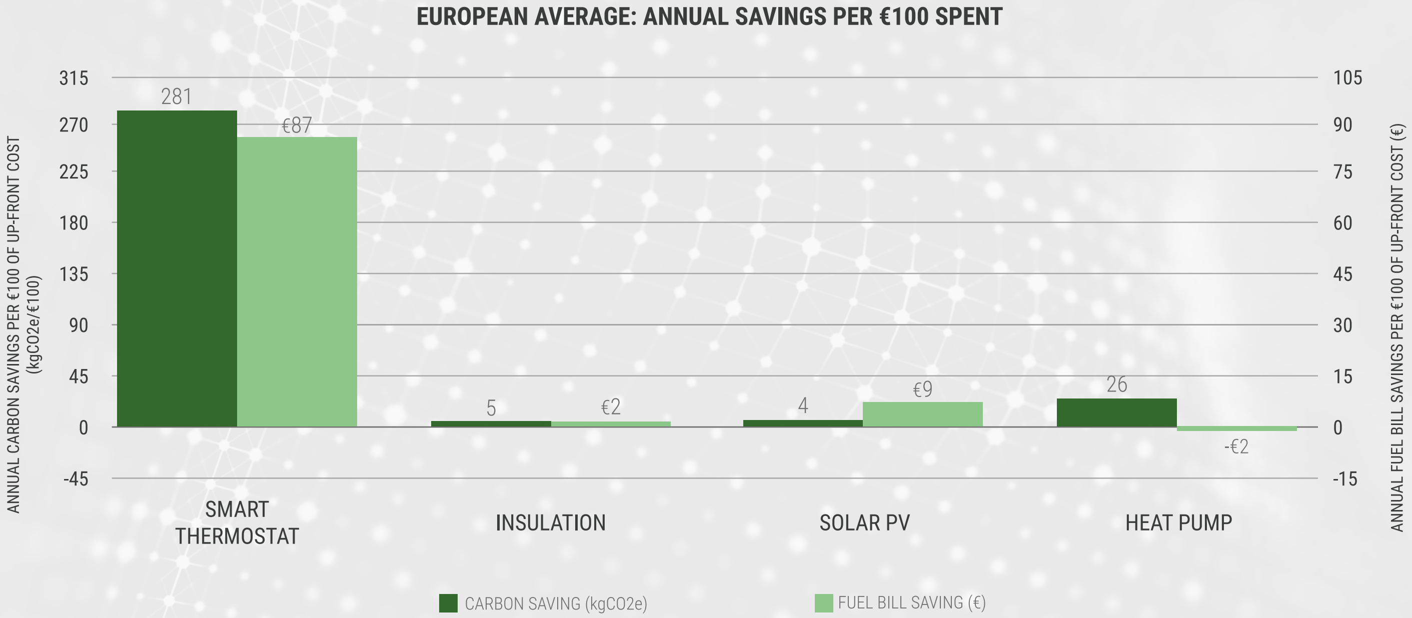
Buildings across Europe account for roughly 40% of total energy consumption, and 36% of greenhouse gas emissions from energy use[1]. A large proportion of this energy consumption and emissions comes from heating and cooling domestic properties; across Europe, this accounts for around 21% of total energy consumption, and in the UK, domestic heating and cooling contributes around 14% of total greenhouse gas emissions[2]. This represents a high proportion of emissions that require attention if the EU and UK are to meet their carbon reduction targets of net-zero by 2050. Recognising this, the EU has launched a buildings Renovation Wave, aiming to double annual energy efficiency renovations in the next decade. The strategy follows the principles of prioritising energy efficiency, affordability, and tackling the twin challenges of the green and digital transitions together. The UK Government is also expected to outline a similar recognition for existing buildings in its impending Heat and Buildings Strategy. In this context, this report evaluates the relative performance of carbon and energy-saving measures available in existing domestic buildings, including smart thermostats, heat pumps, insulation packages and solar photovoltaic (PV) installations. Whilst some combination of solutions will likely be needed for a home to reach net-zero, gaining a better understanding of their relative individual performance will also help in establishing economically efficient and prompt decarbonisation.

Figure 1: Annual Carbon Saving: Average European Household



This study has been commissioned by tado° and evaluates these measures individually across three representative housing archetypes. These are selected for their prevalence in the European housing stock, representing a range of building ages and local climates, amongst other factors. The measures are assessed in isolation due to the scope of analysis agreed, and to present clear findings on the "first step" approach to decarbonisation. To ascertain cost-efficiency and the return on investment, total carbon saved, carbon saving costs and energy saved have been calculated for each measure. This evaluation was completed excluding any financial incentives from policy in the selected countries to ensure that results are applicable across similar archetypes and climates, regardless of the origin country and support that may be in place.

Figure 2: European Average: Annual Savings per €100 of Up-Front Cost.



The results in this report indicate that heat pumps deliver excellent carbon saving potential, with insulation packages and smart thermostats performing well. With the expected continuation of the decarbonisation of electricity grids across Europe, a transition to heat-pump driven heating is clearly important for meeting net-zero. With a rapid transition required to decarbonise in time to meet the net-zero targets, consumer uptake and decision making will be crucial to consider. This makes the cost of the measures an important factor, changing the picture considerably, as seen below.

When up-front cost is considered, the smart thermostat pulls ahead of the alternatives – offering the most cost-effective route to reducing emissions. This view highlights the financial returns of solar PV, something to be expected given their widespread uptake to date. Importantly, further examination of lifetime costs (discussed in the results section of the report) repeats the message seen above. The focus on up-front costs is extremely important for consumer uptake, particularly given their tendency towards shorter-term intertemporal preferences. Ultimately, smart thermostats present a compelling case for any decarbonisation programme – particularly as a cost-effective and more affordable first step. On average a smart thermostat from tado° saves 22% of energy used in homes across Europe, based on data provided by over 1 million connected thermostats. If all homes in Europe were equipped with smart thermostats, the total carbon emissions across Europe would fall by 4.75%, almost one fifth of the 2030 target of lowering emission. Further research should focus on the compound potential that can be achieved with the installation of different combinations of these measures – in particular, smart thermostats and heat pumps in tandem could have a compelling potential for cost-effective decarbonisation.

CONTEXT

The UK was the first major economy to pass net-zero emissions into law in 2019, requiring the country to reach net-zero by 2050. Similarly, the European Union (EU) has a greenhouse gas emissions reduction target of at least 55% by 2030, as part of a broader drive to reach net-zero emissions by 2050. This signals a clear recognition across the continent of the need to rapidly decarbonise to address the challenges presented by the climate crisis. Buildings currently account for around 40% of Europe's total energy consumption and 36% of greenhouse gas emissions from energy[3]. A large proportion of this energy consumption and emissions come from heating and cooling domestic properties, in the UK for example, around 14% of total greenhouse gas emissions can be attributed to heating and cooling in domestic properties[4]. As such, decarbonising domestic buildings is a key priority for Europe and the UK as they look to meet their respective climate obligations.

Action to date on existing building stock has been slow. Despite an acknowledgement that improvements lead to significant energy and carbon savings, fewer than 1.2% of buildings are renovated each year. In addition, 85% of the European building stock, more than 220 million buildings, was built before 2001, and up to 95% of these may remain standing over the next 50 years[5]. Of the buildings still expected to be around by 2050, 75% are deemed to be energy inefficient. These must therefore be addressed as part of the green transition.

There has been a growing recognition of the need to drive the decarbonisation of buildings via policy. The European Commission has laid out an ambitious proposal, detailing plans for a "Renovation Wave" across Europe[6]. The plan aims to:

- Promote wide-scale renovations to the housing stock.
- Create and support jobs associated with renovation installations.
- Generate social benefits related to cost-efficient housing.

The Renovation Wave strategy seeks to double annual building renovation rates over the next ten years, in recognition that the pace of delivery must be increased to meet climate targets. The guiding principles of the Renovation Wave include:

- **Energy efficiency first:** this principle primarily ensures that energy demand is more efficiently managed, without limiting the scope of measures to those that are prevalent in renovations today.
- **Affordability:** the financial burden of energy bills can be alleviated through the reduction in energy use that efficiency measure installations bring, having significant benefits for lower-income households.
- **Tackling the twin challenges of the green and digital transitions together:** promoting the incorporation of smart technology into buildings, development of smart buildings, and the efficient production and use of renewable energy at the house, district, or city level.

It is also clear that this strategy must be delivered in a cost-optimal manner. It has been shown that a cost-optimal method comprises *"a cost-efficient equilibrium between the reduction of final energy consumption and the decarbonisation of energy supply."*[7] Given the housing sector's proportion of overall greenhouse gas emissions, these goals must be pursued in tandem with promoting low-carbon emission energy supply and domestic heating methods.

While smart thermostats may not be considered a "traditional" energy-efficiency measure, they aim to manage energy demand more efficiently, whilst tackling the digital and green transitions simultaneously. Compared to more traditional measures, smart thermostats are a relatively recent innovation, with the first one launched in 2007[8]. Their capabilities have been refined considerably since then, and continue to be so, particularly considering the recency of the technology.

This recency may be the primary reason that information failure exists regarding the comparative benefits of the technology. Whilst other efficiency measures are well established and accepted, there is perhaps less awareness of the benefits that smart thermostats may bring. This report therefore aims to contribute information regarding the performance of smart thermostats, establishing how they can impact typical dwelling types across Europe, better informing the debate about efficient decarbonisation.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METHODOLOGY

The main estimates for the cost-effectiveness of smart thermostats (and alternative measures) are primarily given as costs per tonne of carbon saved (also known as the marginal abatement cost). We began by first designing three separate housing archetypes. Featuring differing sizes, heating systems, and overall energy usage profiles, these were selected to represent the key housing archetypes across Europe to make the results as applicable as possible. The impact of each carbon-saving measure (as described in the technology overview below) was then modelled for each archetype over 30 years – with measures being intermittently replaced as required.

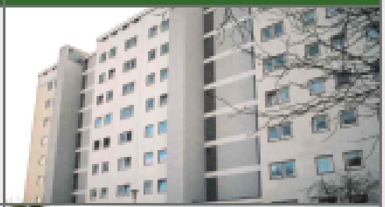
When evaluating the performance of any carbon-saving measure, the cost per tonne of carbon saved (also known as the marginal abatement cost) is one of the quickest ways to rank cost-effectiveness of decarbonisation. However, in instances with negative costs (a positive financial return) per carbon saved, the metric fails to accurately rank options[9]. Therefore, it makes sense to further break down and analyse its components individually. In particular, the financial, energy, and carbon emissions savings through implementation:

- Annual financial return (€)
- Total carbon saved (kgCO2e)
- Carbon saving cost (€/tCO2e)
- Energy savings (kWh)
- Equivalent annual return (€)

HOUSING ARCHETYPES

The following archetypes are used as the basis for our analysis, based on datasets available from the EU's TABULA web tool[10]:

Table 1: Housing Archetypes

	COUNTRY	CONSTRUCTION YEAR	BUILDING TYPE	CLIMATE	HEATING SYSTEM	REPRESENTATIVE PICTURE
1	Germany	1969 - 1978	Apartment	Continental	Gas boiler	
2	United Kingdom	1945 - 1964	Semi-Detached	Moderate	Oil boiler	
3	Italy	≥ 2006	Detached	Mediterranean	Gas Boiler	

These three archetypes give a relatively broad perspective of the European housing stock. Germany, the UK, and Italy combined represent more than 40% of total dwellings in Europe[11], and, further to this, provide suitable representation of the most populous European climates. Germany accounts for almost 18% of European housing stock, of which, flats/apartments comprise ~ 70%[12]. The use of the United Kingdom and Italy as the locations of the other two archetypes present two of the largest remaining markets[13], whilst also providing variation covering the predominant climate types. We have elected to use the other two most common dwelling types, with the UK market's most reflective type as a semi-detached house, and the Italian archetype taking its second most common archetype of a detached house, ensuring that the three most common dwelling types are covered by the analysis. The construction year intervals utilise the TABULA database categorisation and are some of the most frequently occurring.

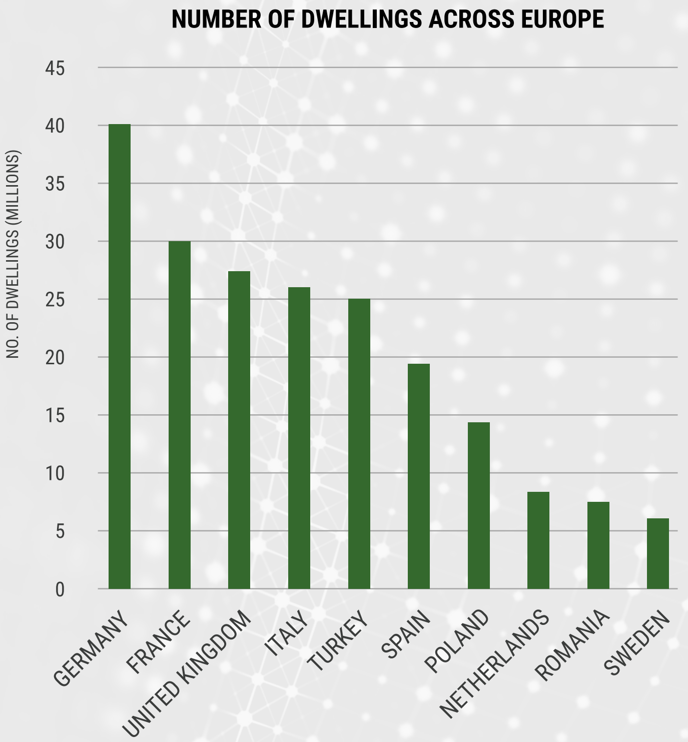


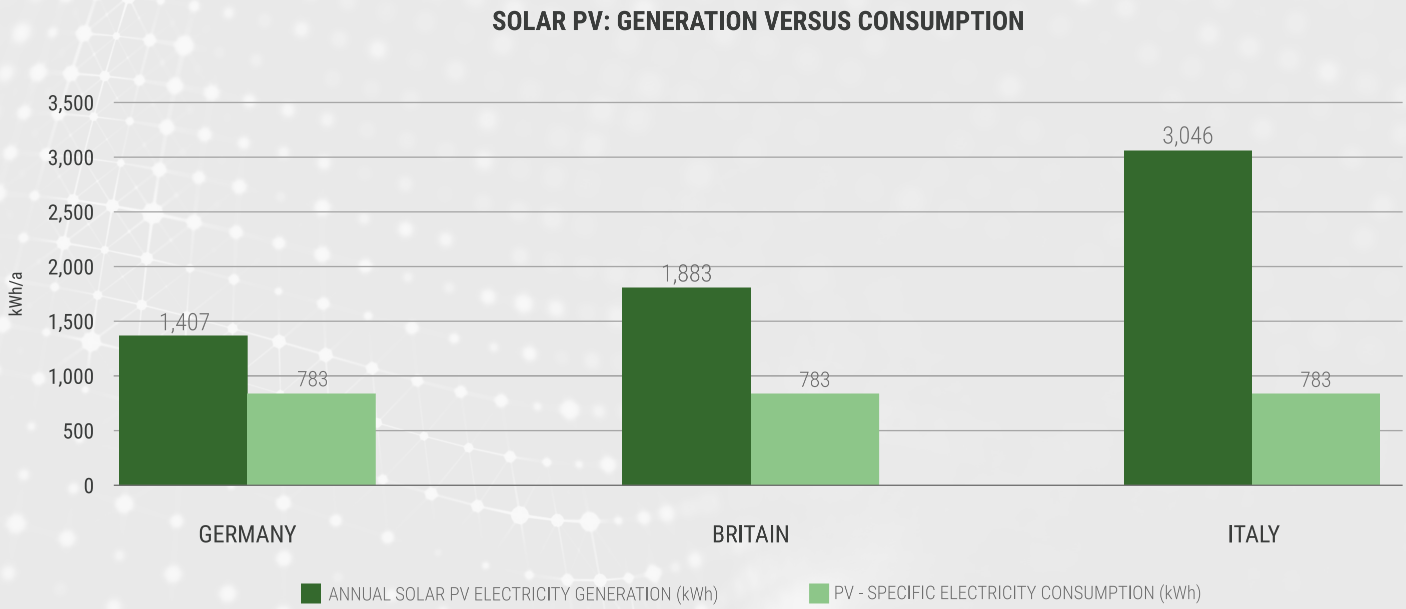
Figure 1: Dwellings per Country

We believe that, given our objectives, these archetypes provide a suitable basis to facilitate our analysis and presentation of results. Considering the overwhelming number of variables in housing stock typology, these allow us to cover the predominant trends suitably, without suffering an overload of archetypes and outcomes, as seen in other studies[14].

For the smart thermostat, we have focused on a single-zonal model to keep consistency between measurements, with primary data used[15]. This data was based on operational data of over 100,000 smart thermostat installations across Europe, provided by tado°. Location-specific energy-saving rates were applied between archetype locales to ensure a valid proxy for national differences in consumer behaviour. Our insulation upgrade packages were determined using the TABULA WebTool segmentation between renovation levels. Upgrades were considered as a package due to the compound effect of upgrades on the thermal transmission in each property. Put simply, the measures require one another to reach their full effectiveness, as discussed later.

The solar photovoltaic (PV) systems were modelled within the most installed sizes for households (0-4kWp). Storage has been excluded due to its usage limitations, added complexity for analysis, and limited use cases. The solar PV system, therefore, is assumed to sell excess electricity back to the grid at a market feed-in-tariff rate. In our modelling, energy saved is that which is directly consumed by the household, whilst carbon emissions saved is a function of the total energy generated by the panel. Given the differences in insolation rates across our archetypes, each installation will clearly generate different amounts of electricity. However, given the lack of storage, each household is modelled as consuming the same nominal amount of energy. This effect is illustrated more clearly in Figure 4, seen below:

Figure 4: Illustration of Solar PV Consumption Methodology



A communal PV system has been specified and modelled for the German archetype – however, due to the focus of this study on the individual property level and innate difficulties in ensuring collective purchasing for the system, we have excluded the result in our conclusions and recommendations. In each of the British and Italian archetypes, systems of 2kWp have been installed, the middle of the most installed size systems category

Heat pumps are widely regarded as a key solution to the decarbonisation of heating in domestic properties across Europe. For our analysis air-source (to water) heat pumps (ASHPs) were selected, due to their anticipated prevalence in the future compared to other heat pump technologies, and applicability to all three archetypes. It has been assumed that there is the external space for the heat pump unit to be placed for all archetypes as well as the internal space for heat emitter upgrades and a hot water cylinder where needed. Each heat pump is sized according to the heating demand of the properties and flow temperatures required to provide adequate heat, even on the coldest day of the year, through a Seasonal Coefficient of Performance.

None of the measures described in the technology overview below are necessarily optimal for installation on their own. Deep retrofit of properties comprising insulation package upgrades and decarbonisation measures provide a much greater reduction in energy use and carbon emissions. While this is optimal for energy use reduction and decarbonisation as an outcome, it adds complexity to the assessment of their individual benefits. Furthermore, keeping the measures separate allows for concise and clear conclusions to be drawn from our results – with the aim of informing consumers and policymakers on the most cost-effective route to net-zero. Finally, this analysis does not provide a full life-cycle assessment of each measure – heat pumps, for instance, use refrigerants that can have significant climate effects if not handled properly that are not included within this assessment.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TECHNOLOGY OVERVIEW

We will be comparing the cost-effectiveness and carbon reductions from an insulation package, heat pumps, solar PV and smart thermostats as individual measures installed on each archetype. In an abstract sense, the improvement measures for the decarbonisation of buildings can be split into 4 main categories:

1. Smart controls
2. Insulation Performance
3. Heating
4. Renewable electricity generation

We consider these different categories and outline the main technologies currently viewed as important options for the decarbonisation of homes across Europe for each that are analysed for this report. Some technologies have not been considered as part of the analysis, although could be deployed to aid decarbonisation, to keep our analysis within scope. These include ground source heat pumps, excluded based on a lack of consistently available space for installation. Solar thermal technology was excluded given the higher propensity for people to use their roof space for photovoltaic panels (although wall-mounted systems do exist). Even in the cases of these alternative installation mechanisms, our study already covers an adequate analysis of heating decarbonisation methods (heat pumps). Our study also does not look at the application of more energy-efficient household appliances – such as LED lighting.

SMART CONTROLS – SMART THERMOSTATS

Smart thermostats typically serve several functions and allow:

- Remote control of heating and cooling systems via an associated app or voice command.
- The setting of a smart schedule of heating for your home.
- Deviation from this schedule if additional elements are in play – for example, the presence of people, an open window, or outdoor weather.
- Weather compensation.
- An ability to "learn" your favourite temperature and lifestyle patterns and plan accordingly.
- Modular boiler control for more energy-efficient heating
- Oversight and visualisation of heating use patterns to help customers understand and control their heating use better

With this functionality comes far greater control and efficiency. This allows for the maintenance of more comfortable temperatures, avoiding temperature fluctuations, reducing energy usage and fuel bill expenditure. This is achieved via features such as Geofencing, which reduces the temperature when nobody is home, weather compensation, which adjusts the heating required according to the forecast or senses when there are open windows. As a result of these features, the smart thermostat reduces energy consumption from heating, cutting fuel bills and emissions. Whilst modern boilers possess some of these features as standard, they do not provide all the features mentioned and the same level of control and optimisation that a smart thermostat provides.

Table 2: Smart Thermostat Advantages and Disadvantages

ADVANTAGES	DISADVANTAGES
Very low upfront cost	Energy savings dependent on consumer behaviour before installation
Very easy installation	Carbon savings dependent on the heating system already in place
Negligible disruption caused	Does not "produce" any green energy
Suitable for all property types	
Ability to tap into smart grids	

Smart thermostats retail for around €200 for a single-zonal model, with manufacturers offering extensions that increase to the number of "zones" the thermostat controls, further increasing efficiency by reducing heating in unused areas. This study will focus on single-zone smart thermostats in each archetype, providing a straightforward comparison for the effects that this setup can have on energy performance and carbon savings..

INSULATION PERFORMANCE

The presence (or absence) of insulation is often one of the first elements considered when improving the energy efficiency of a property. Installing insulation measures reduces the heat loss from a building, lowering the energy required to reach the same temperature when heating, thereby reducing fuel bills and cutting emissions. Generally, installing only one type of insulation is considered inferior to ensuring that several aspects of the building are better insulated, due to the effects of thermal bridging[16]. The table below summarises some elements of the individual insulation measures:

Table 3: Insulation Measure Comparison

	CAVITY WALL INSULATION	SOLID WALL INSULATION	LOFT INSULATION	UNDERFLOOR INSULATION	DOUBLE GLAZING
ENERGY SAVINGS	High	High	High	Moderate	Moderate
DISRUPTION	Moderate	High	Moderate	High	High
UPFRONT COSTS	Moderate	High	Low	Moderate	High

The measures required vary on a case-by-case basis across the dwelling types, but all fall within the classification of an "insulation package", which aims to comprehensively enhance the thermal efficiency of the building. The analysis conducted for this report makes use of the TABULA database to apply a set of specific measures to the three housing archetypes selected (see below). A brief description of each of the measures considered follows:

CAVITY WALL INSULATION

The Energy Saving Trust (EST) estimates that around a third of all heat lost, from an uninsulated home, escapes through the walls. Houses that are built with the outer walls containing cavities between two layers of brick can benefit from filling this cavity with insulating measures, typically mineral wool, polystyrene beads, or an expanding foam, injected through the walls from the outside of the property. EST estimates that cavity wall insulation can be completed for between €450 and €800 and produce energy bill savings of up to €290/year[17].

SOLID WALL INSULATION

Solid wall insulation can be installed in properties without a cavity in the walls, often older properties, or those that have solid stone walls. The walls can be insulated externally or internally by adding on insulating layers – this takes up additional space, expanding the wall's original footprint by attaching additional insulating cladding. The EST estimates that solid wall insulation can cost between €9,000 and €12,000, depending on the building. The EST estimates fuel bill savings of up to €400/year, indicating a relatively long payback period[18].

LOFT INSULATION

The EST estimates that up to a quarter of all heat loss from an uninsulated home can be via the roof, thus insulating a roof or loft space can be an effective method of improving energy efficiency. Loft and roof insulation can be done with mineral wool, rigid insulation boards or sprayed foam insulation. EST estimates that loft insulation can cost between €300 and €460 and can save up to €360/year[19].

UNDER-FLOOR INSULATION

The type of insulation available for installation depends on the construction of the property. For properties that have solid concrete floors, the easiest way to insulate is to lay rigid insulation boards on top of the base structure. Another common floor type is suspended timber – where the floor is constructed from timber and raised off the foundations of the house. This type of flooring can be insulated either by raising the floorboards to place mineral wool underneath or by spraying insulating foam at the bottom of the floorboards from the crawlspace underneath them. EST estimates that installation can cost between €600 and €1,500 depending on the construction of the property and save up to €80/year[20].

DOUBLE GLAZING

The costs to install double glazing in a property vary depending on the energy ratings of the glazing being installed, window frame type and size of the property. EST estimates that for a typical semi-detached property, these costs can vary between €5,000 and €17,000, and save up to €110/year[21].

INSULATION PACKAGES

Our agreed scope of analysis features the modelling of insulation methods bundled into a package. The insulation packages used are based on those outlined in the TABULA database. This essentially models the house as being upgraded from its initial construction to one with several insulating additions, taking into account the complex interaction of thermo-dynamic behaviour that installing various insulation upgrades at the same time can have, such as thermal bridging. To reference Annex Table A.2.5.

HEATING SYSTEMS – HEAT PUMPS

Heat pumps are viewed as a key tool for decarbonising domestic heating. Typically, they extract the energy from the surrounding environment, using electricity to efficiently convert it to heat. As a result, heat pumps can replace the domestic fossil fuel use for heating, dramatically reducing a household's carbon emissions, but at the cost of increasing the household's electricity consumption. Due to high efficiency and the expectation that the production of electricity will become increasingly driven by renewable sources in the future, heat pumps are viewed as a crucial heating technology to meet the net-zero ambitions across Europe. They are seen as particularly viable for rural homes that are reliant on other carbon-intensive heating systems, especially oil-based heating.

Most European countries have a variety of facilitatory incentives, including loans, subsidies, and tax reductions, to encourage the uptake of heat pumps[22]. This is due to the considerably higher upfront costs than heat pumps have compared to fossil fuel alternatives. For example, the initial cost for the installation of an air-source heat pump (ASHP) in the German archetype is around €8,000, rising to ~€13,700 in the British archetype, reflecting both the change in climate, dwelling type, and need for radiator upgrades.

Heat pumps typically require additional space for installation compared to traditional heating systems. ASHPs require space to site the external unit as well as hot water cylinders. Existing heat distribution systems (radiators) within the property must also be suitable for installation for air-to-water systems to achieve a sufficiently low enough flow temperature to provide efficient heating whilst still heating the home enough. The cost of any radiator upgrades is included in the modelling, with the Seasonal Coefficients of Performance for heating a hot water provision ranging from 2.46 in the German Archetype, to 3.38 in the Italian archetype, with the British value sitting at 2.53. The typical lifespan of air source heat pumps is 18 years.

In some properties heat pumps also can require the upgrading of electrical infrastructure and additional capital cost for pipework, this can result in considerable expense and disruption to the consumer. These costs have not been included in the modelling for the archetypes analysed but should also be kept in mind when interpreting the results as they will apply to many consumers switching to heat pumps.

Table 4: ASHP Advantages and Disadvantages

ADVANTAGES	DISADVANTAGES
Widely supported by financial incentives and policy	High upfront cost
Remove reliance on multiple fuel types	Can increase fuel bills
Highly efficient heating process	Overall efficiency is sensitive to building fabric efficiency and heat distribution systems
Very high carbon savings when compared with fossil fuel heating	Performance can be affected by climate
Can tap into smart grids	Reliance on changes in electricity production for decarbonisation

RENEWABLE GENERATION – SOLAR PHOTOVOLTAICS (PV)

Solar PV has been the focus of several subsidy schemes across Europe, promoting a range of installations, from domestic systems to industrial solar PV farms. These schemes have been designed to subsidise the financial burden of installing solar PV, typically through guaranteeing repayments on electricity generated and fed back to the grid. Solar PV has also benefited from steep cost reductions and efficiency improvements in recent years. Furthermore, increased flexibility and user-friendliness has contributed to rapid growth across Europe. Germany is currently the biggest generator of electricity by solar PV in Europe[23], with an estimated 4.8GW of output.

As solar PV on a domestic scale requires little more than a suitable roof, it has been included in our analysis as one of the most widely available forms of domestic renewable energy generation. For our calculations, we have assumed that solar PV setups have a lifetime of 30 years and installation costs of between €1,700 and €2,000 per kWp capacity. However, solar PV is solely an electricity generation measure and is installed to reduce the dwelling's carbon emissions by increasing the ratio of renewable generation in its electricity consumption. As a result, homes that have carbon-intensive heating systems will still have the heat emissions associated with them. In the German archetype, it would require a communal system to be installed. Because of the difficulty in ensuring collective uptake of such a system in reality (all or most residents must agree) and the focus on decisions that can be taken at an individual level for this study, it has been excluded in our the results.

Table 5: Solar PV Advantages and Disadvantages

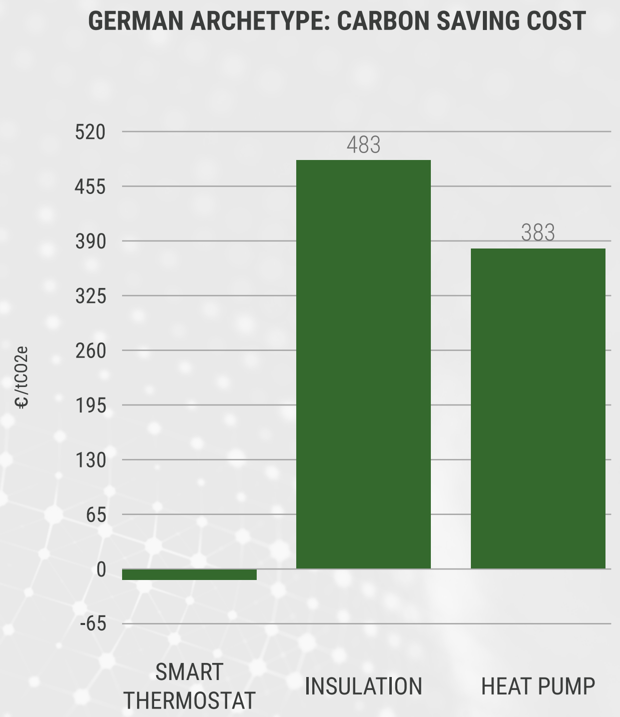
ADVANTAGES	DISADVANTAGES
◆ Initial costs of installation are decreasing ◆ Widely supported by financial incentives and policy ◆ No additional space requirements for roof installation (domestic level) ◆ Reduces reliance on centralised energy generation	◆ Output is dependent on climate and building aspect ◆ May require upgrades to property metering arrangements ◆ Not suitable for all property types ◆ Carbon savings are dependent on electricity grid intensity

RESULTS - GERMAN ARCHETYPE

Table 6: German Dwelling Summary

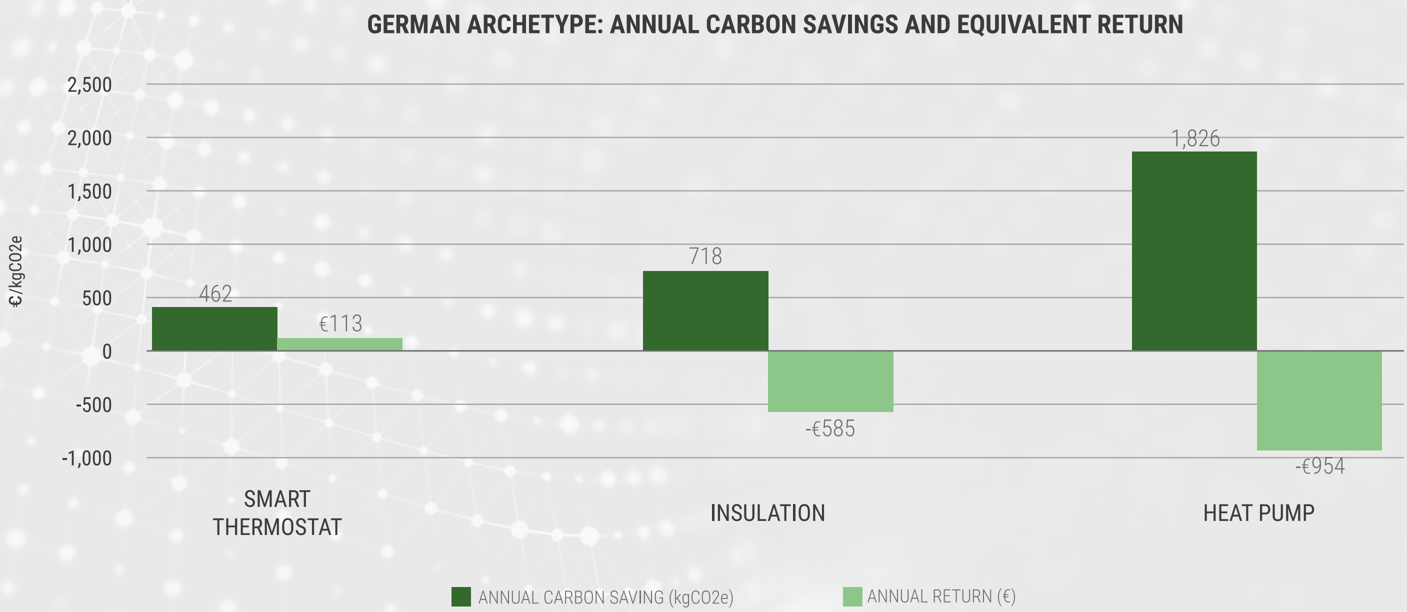
AVERAGE DWELLING SIZE	m^2	63
ANNUAL HEATING ENERGY REQUIREMENT	kWh	7,556
ANNUAL HEAT-DERIVED EMISSIONS	kgCO2e	2,024
ANNUAL ELECTRICTY ENERGY REQUIREMENT	kWh	4,573
CURRENT ANNUAL ELECTRICTY-DERIVED EMISSIONS	kgCO2e	1,408
REQUIRED HEAT PUMP SIZING	kW	4

Figure 5: Cost per Tonne of Carbon Saved - German Archetype



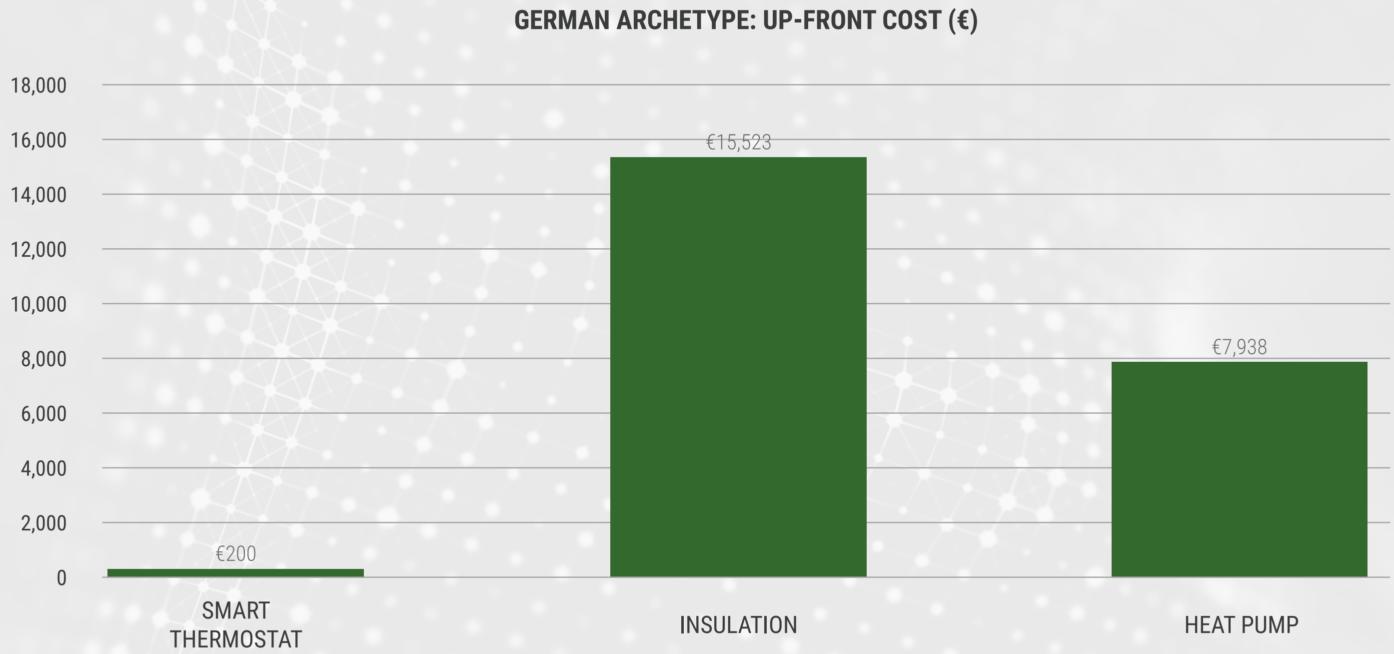
Starting with the carbon saving cost for each measure, the exclusion of the solar PV installation stands out and is justified for the reasons described earlier in the report. This example also highlights the quirk of the carbon saving cost (otherwise known as the marginal abatement cost) as a measurement for cost-effective decarbonisation. Because the smart thermostat presents a positive financial return, the results must be broken down further. Firstly, delving into the two main parts of the measure, the annual return, and carbon saving:

Figure 6: Annual Carbon Savings and Equivalent Return - German Archetype



As seen above, the smart thermostat creates an annual carbon saving of 462 kgCO2e, whilst providing an annual return of €113. Over the modelling period of thirty years, the equivalent annual return (also known as the equivalent annual annuity) provides net present valuation measurement of investments with different lifespans, allowing a comparison to be made between measures with different lifetimes. Whilst both other technologies provide higher annual carbon savings, they do so with negative financial returns. Put simply, the smart thermostat is the only profitable carbon-saving measure. Furthermore, it is important to consider the initial outlay required, as seen in Figure 7:

Figure 7: Comparison of upfront costs - German archetype



This comparison gives perspective to the differences in carbon savings – the alternatives to smart thermostats are orders of magnitude more expensive (with regards to up-front cost). This distinction can be seen more clearly below:

Figure 8: Annual carbon and fuel bill savings per €100 of up-front cost - German archetype

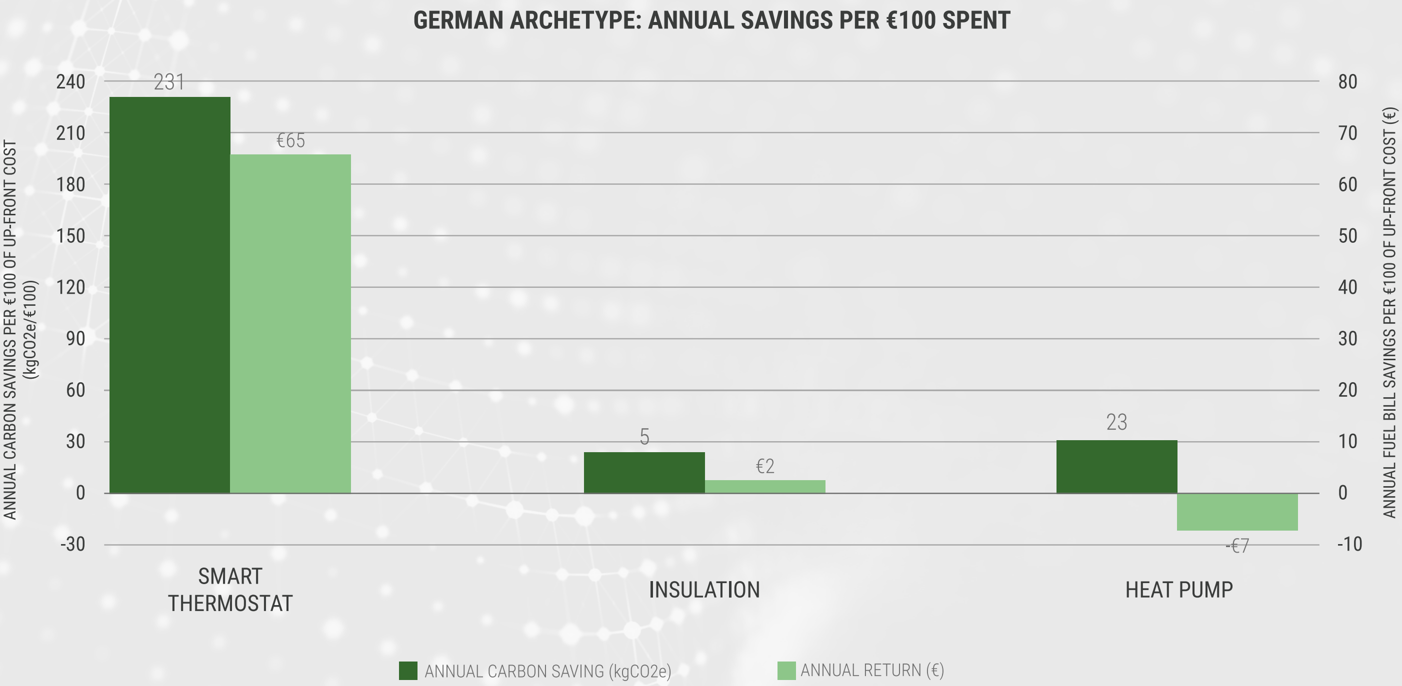


Figure 8 serves to illustrate the huge carbon-saving potential for smart thermostats with respect to the up-front cost. This viewpoint is particularly important for policy-makers, given budget constraints.

Table 7: Measures of performance - German archetype

	UNIT	SMART THERMOSTAT	INSULATION	HEAT PUMP
ANNUAL CARBON SAVING	kgCO2e	462	718	1,826
CARBON SAVING COST	€/tCO2e	-179	483	383
EQUIVALENT ANNUAL RETURN	€	113	-585	-954
UPFRONT COST	€	200	15,253	7,938
ANNUAL ENERGY SAVING	kWh	1,723	2,680	4,486
ANNUAL FUEL BILL SAVING	€	130	239	-522

†Negative values are mathematically incoherent and must be considered contextually.

Breaking the results down further, the smart thermostat performs well - the upfront cost of €200 is paid back over time with annual fuel bill savings of €113. The insulation package saves more carbon annually than the thermostat – around 718 kgCO2e - but incurs a higher installation cost of around €15,000 and a negative annual return of -€585. The heat pump performed as expected, delivering huge carbon savings of 1,826 kgCO2e – over two-and-a-half times that of the insulation package. Due to the fact the heat pump requires a fuel switch to electricity, the resulting annual fuel bill rises by €522, despite energy savings of 4,486 kWh per year.

Ranking the options, the smart thermostat is the only measure to offer a positive financial return on investment, marking it as clearly the most cost-effective upgrade. Whilst the other two incur financial losses over their lifetimes, the heat pump delivers the next best performance, with a carbon saving cost of €383/tCO2e, whilst the insulation package poses a cost of €483/tCO2e. This difference between the two is further compounded when considering the huge difference in up-front costs, with the heat pump costing around €7,000 less. Unfortunately, this may matter little to consumers with no interest in decarbonisation, as the heat pump performs worse in both financial metrics (fuel bill savings, and equivalent annual returns).


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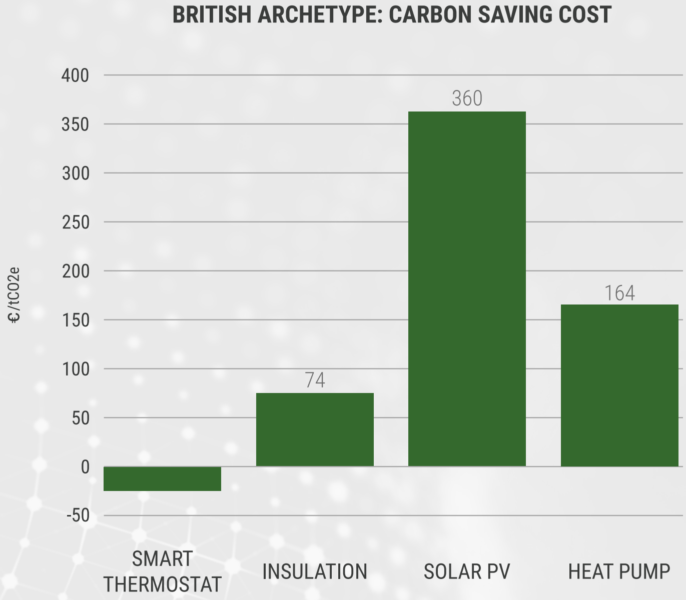
Table 8: British dwelling summary

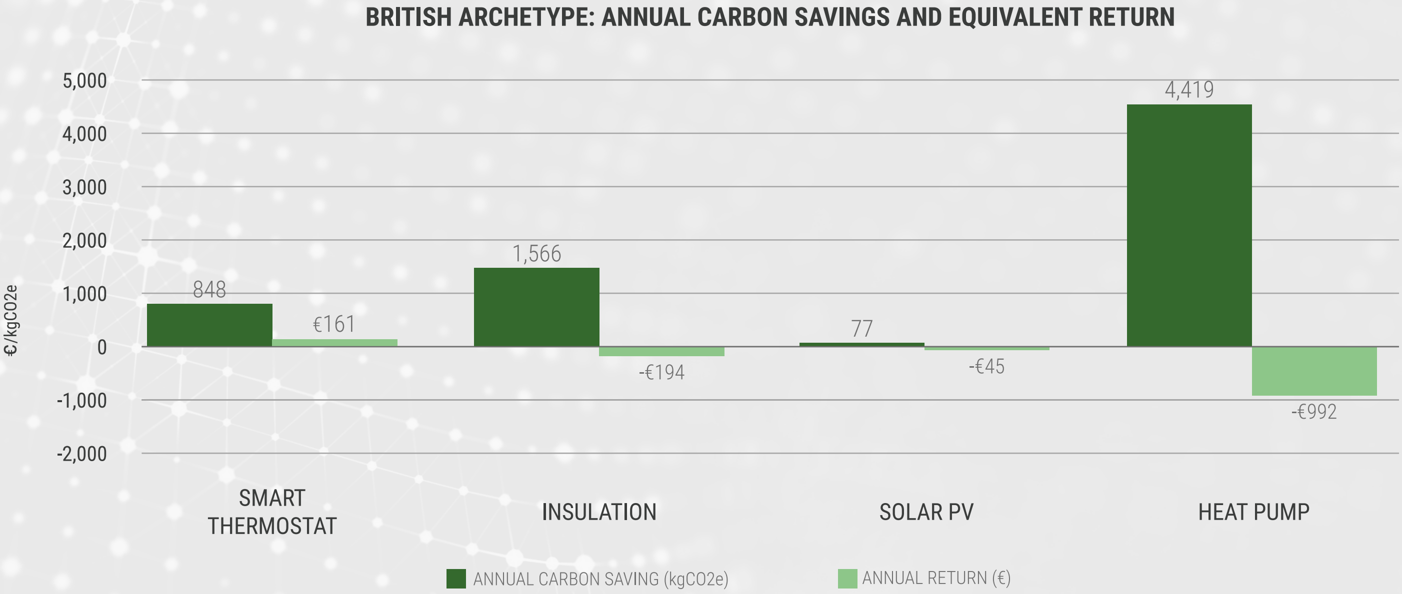
AVERAGE DWELLING SIZE	m^2	88
ANNUAL HEATING ENERGY REQUIREMENT	kWh	14,564
ANNUAL HEAT-DERIVED EMISSIONS	kgCO2e	4,790
ANNUAL ELECTRICTY ENERGY REQUIREMENT	kWh	6,231
CURRENT ANNUAL ELECTRICTY-DERIVED EMISSIONS	kgCO2e	944
REQUIRED HEAT PUMP SIZING	kW	11

Figure 9: Cost per tonne of carbon saved - British archetype



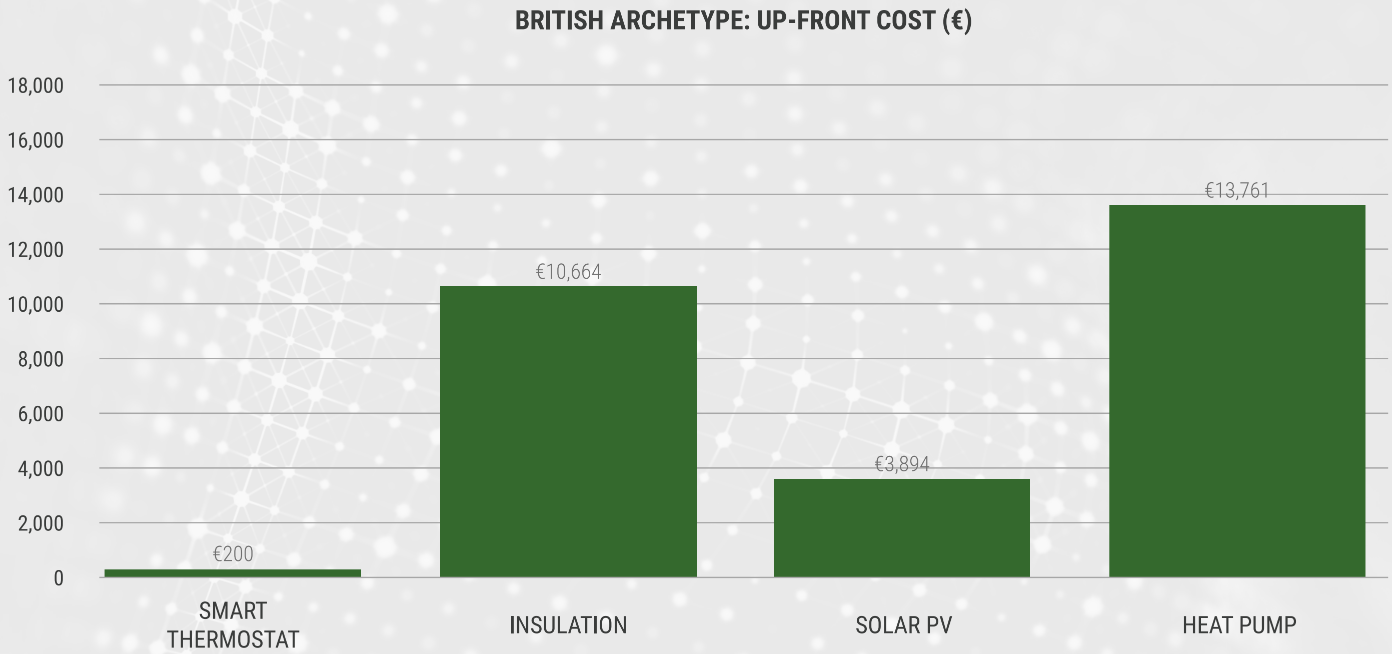
A notable difference from the German archetype is the inclusion of solar PV as part of the considered measures – it can be considered now because our archetype is a single-family home and does not require collective purchasing. In terms of the carbon saving cost (Figure 9), the smart thermostat presents a negative result. As discussed previously, this requires further examination. Solar panels perform poorly in this archetype – due to the relative low insolation rates in the UK, and the ambitious decarbonisation schedule for the national electricity grid. Insulation performs best after the smart thermostat, due to the poor thermal performance of the house before upgrade.

Figure 10: Annual carbon savings and equivalent return - British archetype



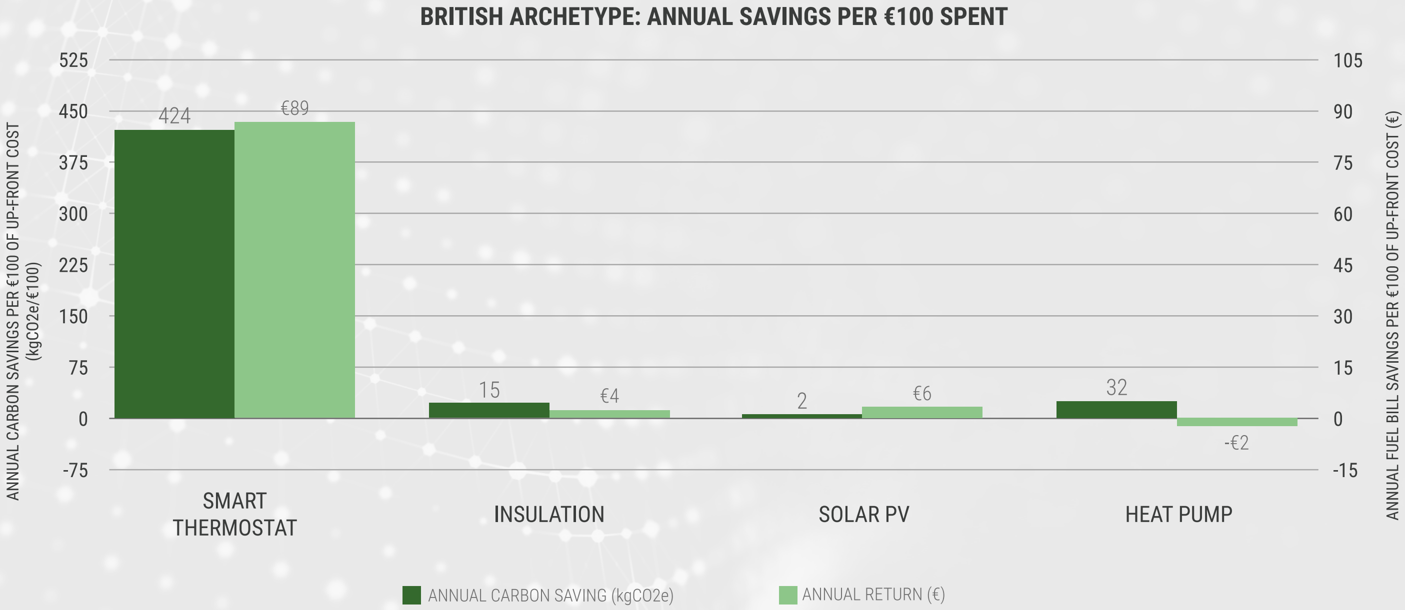
In this archetype, the smart thermostat creates an annual carbon saving of 848 kgCO2e, whilst providing an annual return of €161. The insulation package saves a considerable amount of carbon annually in this instance at 1,566 kgCO2e, but with a negative financial return of -€194. The solar PV installation performs poorly in this scenario, saving minuscule amounts of carbon with a negative (albeit small) financial return. The heat pump saves a significant 4,419 kgCO2e of carbon per year, but does so with the greatest financial cost, at an equivalent annual return of -€992.

Figure 11: Comparison of upfront costs - British archetype



To further differentiate, the up-front cost should be considered. Given that insulation presents the next-best cost of saving carbon, its lower up-front cost of around €10,500 makes it a more attractive choice than the heat pump, which costs around €13,800. Whilst the solar PV is cheaper than both, it must be considered alongside its paltry carbon saving potential, rendering it the most cost-ineffective measure for decarbonisation in this instance.

Figure 12: Annual carbon and fuel bill savings per €100 of up-front cost - British archetype



Evaluating the results in terms of those up-front costs, we can see that the smart thermostat again leads the way - and by a considerable amount. The heat pump offers the next best annual carbon saving (per €100 of up-front cost) but does so with a relative fuel bill rise. Solar PV offers the greatest fuel bill saving in this instance, but again with minuscule carbon savings. The insulation package strikes a balance between the two, offering fuel bill savings, and considerable carbon savings.

Table 9: Measures of performance - British archetype

	UNIT	SMART THERMOSTAT	INSULATION	SOLAR PV	HEAT PUMP
ANNUAL CARBON SAVING	kgCO2e	848	1,566	77	4,419
CARBON SAVING COST	€/tCO2e	-139	74	360	164
EQUIVALENT ANNUAL RETURN	€	161	-194	-45	-992
UPFRONT COST	€	200	10,664	3,894	13,761
ANNUAL ENERGY SAVING	kWh	2,578	4,761	783	8,815
ANNUAL FUEL BILL SAVING	€	179	392	248	-224

†Negative values are mathematically incoherent and must be considered contextually.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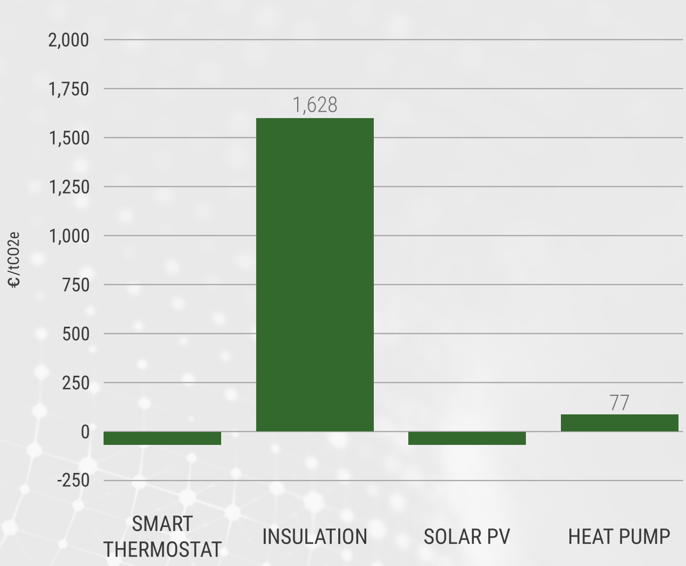
RESULTS - ITALIAN ARCHETYPE

Table 10: Italian dwelling summary

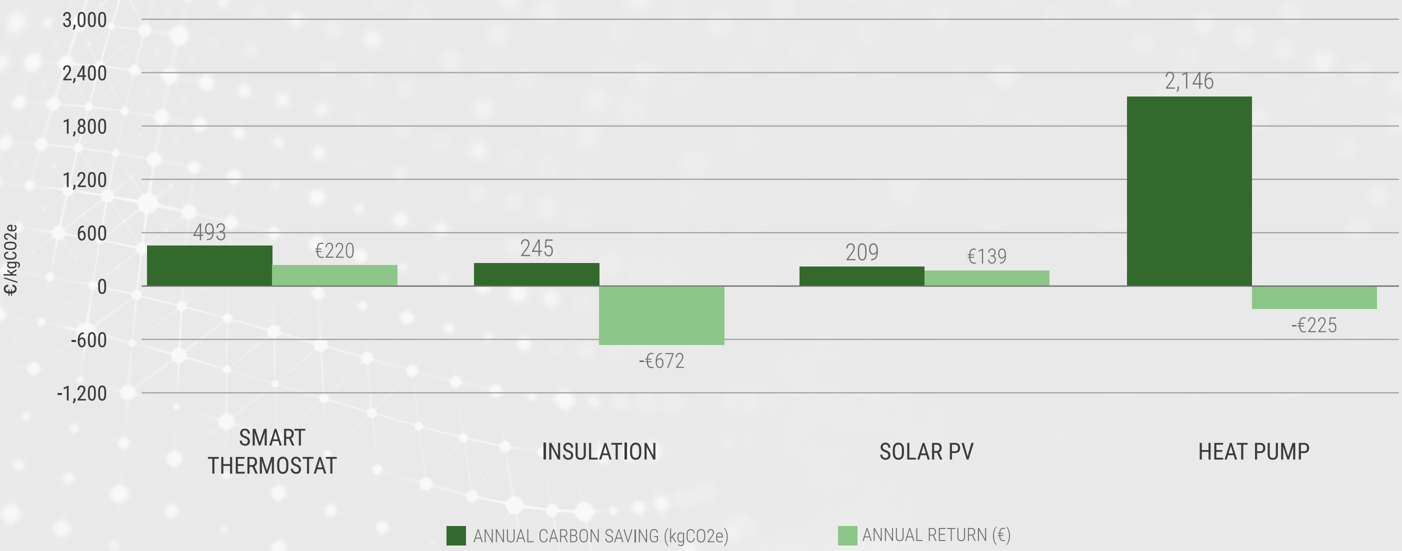
AVERAGE DWELLING SIZE	m^2	127
ANNUAL HEATING ENERGY REQUIREMENT	kWh	10,452
ANNUAL HEAT-DERIVED EMISSIONS	kgCO2e	2,345
ANNUAL ELECTRICTY ENERGY REQUIREMENT	kWh	4,346
CURRENT ANNUAL ELECTRICTY-DERIVED EMISSIONS	kgCO2e	891
REQUIRED HEAT PUMP SIZING	kW	4

Figure 13: Cost per tonne of carbon saved - Italian archetype



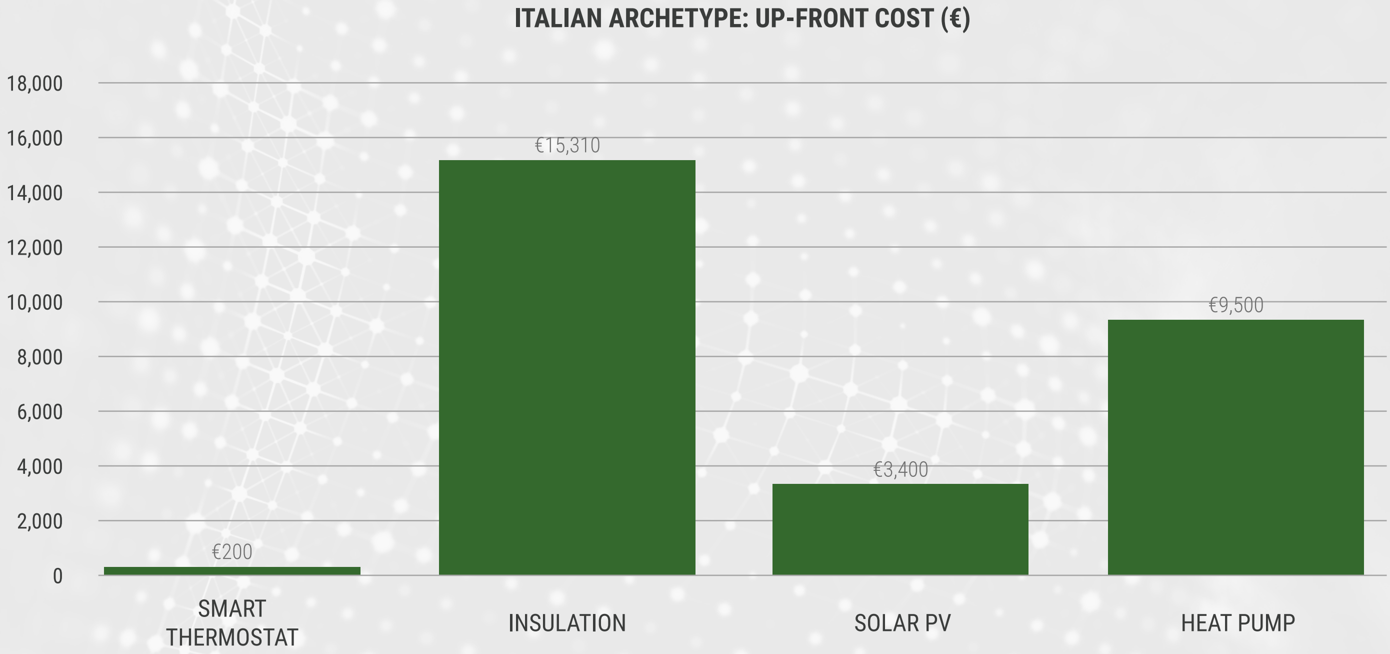
Onto the Italian archetype, where two measures present negative carbon saving costs – the smart thermostat and solar PV. The insulation package stands out here as orders of magnitude less cost-effective than all other measures – likely due to the warm climate in Rome, and the relatively newer build in our archetype. Whilst the warmer weather is detrimental to the performance of the insulation package, it proves beneficial for the heat pump. Given that there is more external energy to draw from, the heat pump runs more efficiently and decarbonises heating more cost-effectively as a result.

Figure 14: Annual carbon savings and equivalent return- Italian archetype



Examining the results further in Figure 14, the smart thermostat outperforms the solar PV installation across both metrics, creating annual carbon savings of 493 kgCO2e, with an equivalent annual return of €220. Despite utilising the highest level of insolation across all three archetypes, solar PV still falls behind the smart thermostat. Regardless, annual carbon savings of 209 kgCO2e and an equivalent annual return of €139 are admirable results. The heat pump again delivers huge carbon savings, at 2,146 kgCO2e per year, but with a negative financial return of -€225 per year.

Figure 15: Comparison of upfront costs - Italian archetype



To further highlight the difference between the solar PV setup and the smart thermostat, the up-front costs in combination with annual carbon saving both illustrate the better relative performance of the smart thermostat.

Figure 16: Annual carbon and fuel bill savings per €100 of up-front cost - Italian archetype

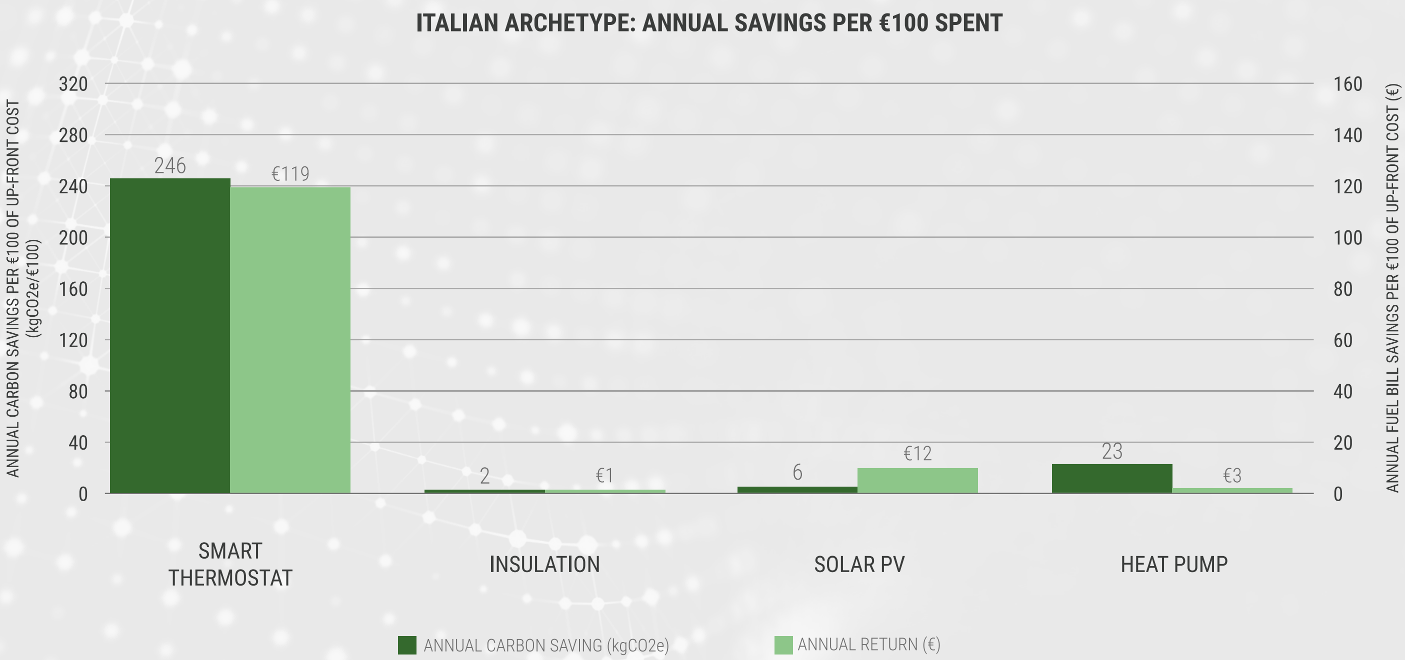


Table 11: Measures of performance - Italian archetype

	UNIT	SMART THERMOSTAT	INSULATION	SOLAR PV	HEAT PUMP
ANNUAL CARBON SAVING	kgCO2e	493	245	209	2,146
CARBON SAVING COST	€/tCO2e	-327	1,628	-408	77
EQUIVALENT ANNUAL RETURN	€	220	-627	139	-225
UPFRONT COST	€	200	15,310	3,400	9,500
ANNUAL ENERGY SAVING	kWh	2,195	1,092	783	7,364
ANNUAL FUEL BILL SAVING	€	239	141	398	261

†Negative values are mathematically incoherent and must be considered contextually.

The insulation upgrade in this archetype was the worst-performing, a reflection of the climate and more modern building design. The cost was the highest across the three archetypes at €15,310, but paltry fuel bill savings of €141, result in an equivalent annual return for this measure of -€627. The annual carbon savings for this archetype are similarly low at 245 kgCO2e. Heat pumps again provide save the most carbon annually, at 2,146 kgCO2e, but again with high installation costs at €9,50, with annual fuel bill saving for this archetype is €261.

When ranking the options in this archetype, it is again difficult to look past the smart thermostat as the most cost-effective option for decarbonisation. The high levels of insolation ensure that the solar PV presents an attractive option for clean energy generation, making it the next best option. The performance of heat pumps is notable here, particularly when compared with its results in the other archetypes. The poor cost-effectiveness of the insulation package here can be most likely explained by the fact that the building archetype was newer to begin with and sits within a warmer climate.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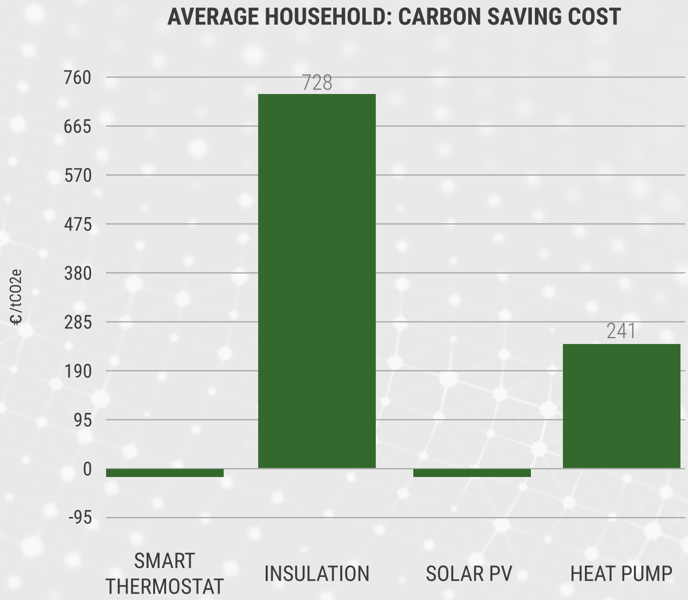
RESULTS - AVERAGE EUROPEAN HOUSEHOLD

As part of this report, the results of the prior three archetypes have been consolidated into a single set of results, for what is deemed to be most closely representative of the "average European household". The justification of this is to offer a streamlined set of results, which are easily and concisely digestible. The weighting valuations for the following results are presented in Annex Table A.2.8.

Figure 17: Cost per tonne of carbon saved - average European household



Focusing on the main result of interest, (the carbon saving cost), shows that both the smart thermostat and solar PV installation present negative results – indicating that they both offer positive financial returns, and warrant further investigation to separate the two.

Figure 18: Annual carbon savings and equivalent return - average European household

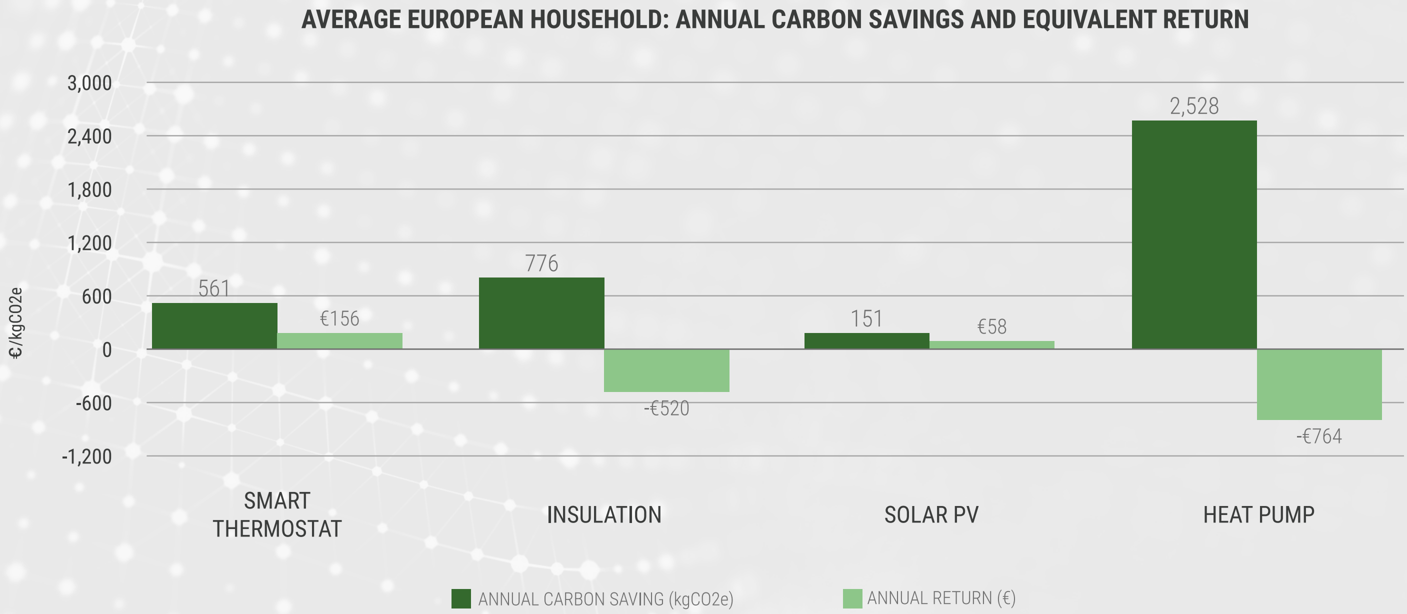
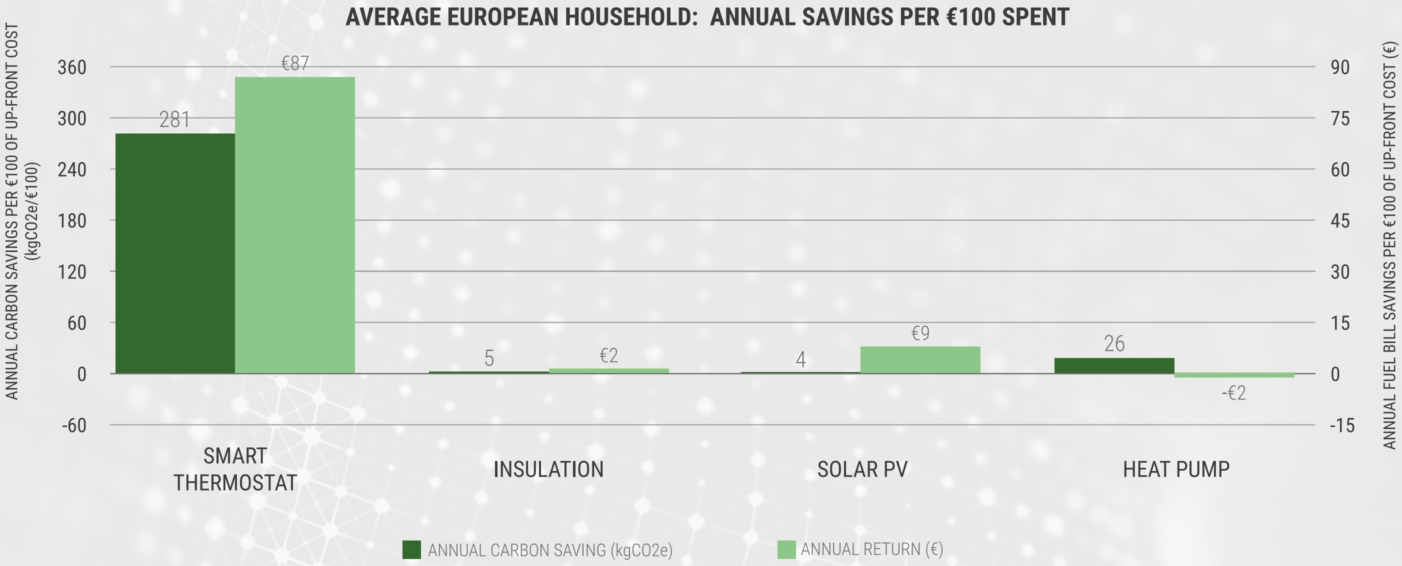


Figure 18 demonstrates a similar story to the rest of the archetypes – the smart thermostat offers the greatest financial return per year at €156, whilst delivering considerable annual carbon savings of 561 kgCO2e. Solar PV is the only other option to offer a positive financial return at €58 but does so with a fraction of the carbon savings at 151 kgCO2e. Heat pumps offer the greatest annual carbon saving, but with the greatest financial burden. The insulation package performance was heavily weighed down by its performance in the Italian archetype and performs poorly both in terms of carbon saving and financial return.

Figure 19: Annual carbon and fuel bill savings per €100 of up-front cost - average European household



Evaluating the carbon savings with respect to up-front cost, as seen above, demonstrates the same story as in all other archetypes, with the smart thermostat presenting the most cost-effective decarbonisation option. Table 12 presents the measures of performance in more detail.

Table 12: Measures of performance - average European household

	UNIT	SMART THERMOSTAT	INSULATION	SOLAR PV	HEAT PUMP
ANNUAL CARBON SAVING	kgCO2e	561	776	151	2,528
CARBON SAVING COST	€/tCO2e	-214	728	-70	241
EQUIVALENT ANNUAL RETURN	€	156	-520	58	-746
UPFRONT COST	€	200	14,916	3,617	9,765
ANNUAL ENERGY SAVING	kWh	2,063	2,694	783	6,355
ANNUAL FUEL BILL SAVING	€	174	246	332	-219

†Negative values are mathematically incoherent and must be considered contextually.

*German solar PV values are excluded from this average.

CONCLUSION

From the analysis carried out, the case for promoting the use of smart thermostats is compelling. The annual carbon, energy and fuel bill savings were significant, and they were the only measure with a positive equivalent annual return across all housing archetypes. Discounting solar PV in Germany for reasons previously mentioned, the only other measure that has a positive equivalent annual return was the solar PV in Italy (€139 compared to the thermostat's €220). Smart thermostats are the most cost-effective carbon saving measure that we have investigated as part of this report, reducing overall energy demand, and providing substantial annual carbon reductions.

However, the delineation must be made between full decarbonisation and incremental carbon reduction. Full decarbonisation ultimately focuses on eliminating carbon emissions from the economy, whilst incremental carbon reductions seek to lower the amount of carbon. In this context, the performance of heat pumps stands head-and-shoulders above the other measures, saving 2,500 kgCO2e annually in our average European household. The next best decarbonisation measure (the insulation package) saved under a third of this amount. Considering the simple fact that climate change is a race against time, heat pumps clearly will have a significant role to play. Unfortunately, heat pumps are simply not a cost-effective option right now, something which governments should seek to address, via measures such as appropriate carbon taxation. Whilst decarbonisation is ultimately the primary goal for long-term net-zero economies, it would be unwise to discount the importance of carbon reduction technology in the interim and the value of immediate carbon reductions.

Therefore, to pursue the joint goals of reducing final energy demand and reductions in emissions, optimal results will arguably be achieved by a combination of these measures. Heat pumps will become increasingly viable as the properties' thermal efficiency improves and electricity generation is increasingly produced through renewables. To complement the decarbonisation of heat, the deployment of smart thermostats will help to reduce fuel bills, no matter the heating technology. They would also help to provide better information and higher levels of control for heating systems, further reducing heating demand. Additionally, given their very low upfront cost, compared to envelope upgrades, heat pumps and solar PV, should be considered as an important technology option for the decarbonisation of Europe's building stock.

Further research in this important area should focus primarily on understanding the most cost-effective pathway to decarbonisation, specifically, in terms of which combinations of technology should be implemented. Ideally, this research could also elaborate on when, and where these combinations are best suited, including consideration of smart thermostats as part of this. Additionally, qualitative study should be conducted to better understand the benefits of the consumer interaction with smart thermostat products, and how decarbonisation can be maximised in turn, across a range of consumer behaviours. Further expansions could also include adjacent technologies, such as ground-source heat pumps, and solar thermal, amongst others.

POLICY RECOMMENDATIONS

The analysis conducted, and the conclusions derived from this report show a compelling case for the wider encouragement of smart thermostats as a decarbonisation measure. Based on the findings of this report, we would make the following recommendations to policymakers:

- Support smart thermostats in funding schemes, alongside other carbon saving measures, in subsidy/financial support schemes, where policymakers are looking to maximise carbon and energy savings.
- In cases where consumers are already choosing smart thermostats, there would appear to be little additionality adding them as a measure to subsidy support schemes.
- Recognise the value of smart thermostats in regulatory policy, such as Building Regulations.
- Consider promoting the use of smart thermostats as a cost-effective energy-saving measure as part of obligation schemes, such as the Energy Company Obligation in the UK.
- Public awareness campaigns to better educate consumers about the benefits of smart thermostats in saving both greenhouse gas emissions and lowering fuel bills.
- Seek to redress the financial obstacles around heat pumps, for example, improving the relative running cost via the use of carbon reflective taxation applied equally across all fuels.

ENDNOTES

1 https://publications.jrc.ec.europa.eu/repository/bitstream/JRC117739/cost_optimal_energy_renovations_online.pdf

2 Decarbonisation of Heat - Energy Systems Catapult

3 Filippidou, F. and Jimenez Navarro, J., Achieving the cost-effective energy transformation of Europe`s buildings, EUR 29906 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-12394-1 (online),978-92-76-12393-4 (print), doi:10.2760/278207 (online),10.2760/401441 (print), JRC117739.

4 Decarbonisation of Heat - Energy Systems Catapult

5 Filippidou, F. and Jimenez Navarro, J., Achieving the cost-effective energy transformation of Europe`s buildings, EUR 29906 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-12394-1 (online),978-92-76-12393-4 (print), doi:10.2760/278207 (online),10.2760/401441 (print), JRC117739.

6 Brussels, 14.10.2020 COM(2020) 662 final; Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of Regions; A Renovation Wave for Europe – greening our buildings, creating jobs, improving lives.

7 Filippidou, F. and Jimenez Navarro, J., Achieving the cost-effective energy transformation of Europe`s buildings, EUR 29906 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-12394-1 (online),978-92-76-12393-4 (print), doi:10.2760/278207 (online),10.2760/401441 (print), JRC117739.

8 Our sustainability story | ecobee

9 Marginal Abatement Cost Curves: A call for caution

10 TABULA WebTool (building-typology.eu)

11 Eurostat (2021) “Number of private households by household composition”. Available at: https://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do

12 Eurostat (2021) “Distribution of population by degree of urbanisation”. Available at: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=ilc_lvho01&lang=en

13 Eurostat (2021) “Number of private households by household composition”. Available at: https://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do

14 Mata, É. ; Sasic Kalagasidis, A. ; Johnsson, F. (2013) “Description of the European building stock through archetype buildings”. 8th Conference on Sustainable Development of Energy, Water and Environment Systems – SDEWES Conference, September 22-27, 2013, Dubrovnik, Croatia.

15 Data provided by tadoo

16 The importance of thermal bridging: BRE Group

17 How to install cavity wall insulation - Energy Saving Trust

18 Advice on insulating your solid walls - Energy Saving Trust

19 Roof and loft insulation guide - Energy Saving Trust

20 Floor insulation information and advice - Energy Saving Trust

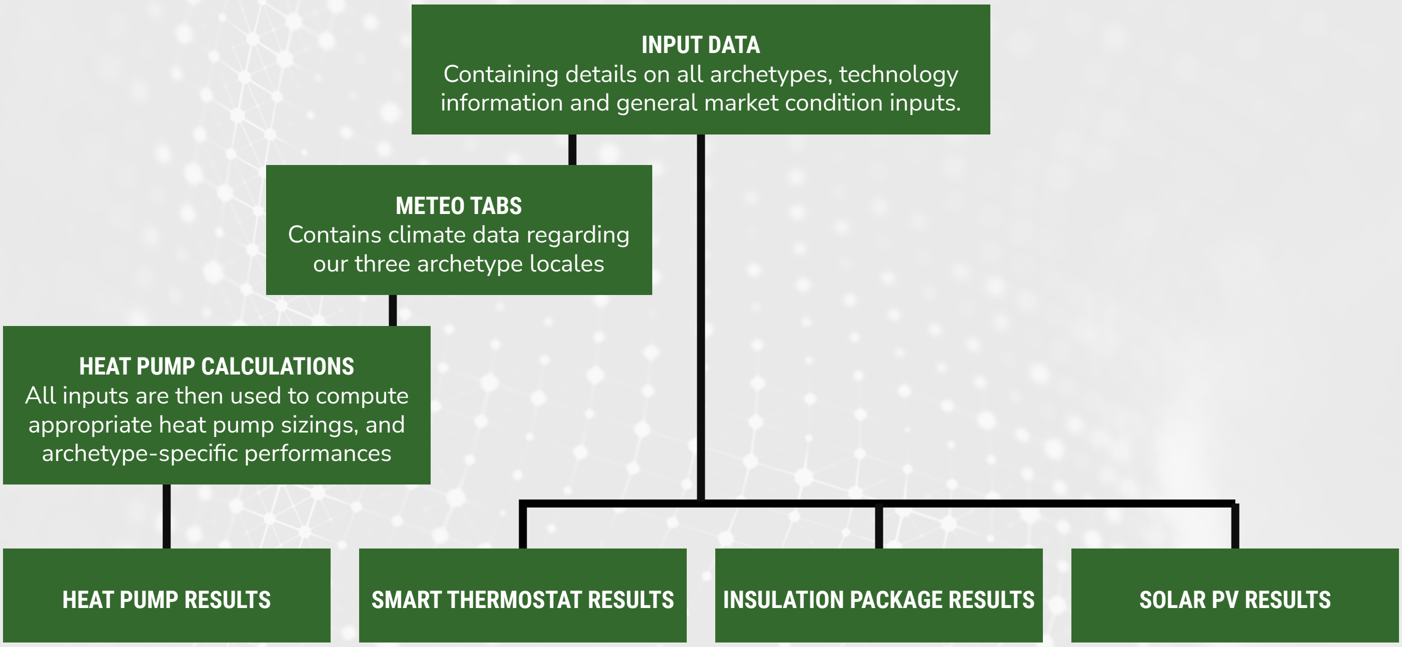
21 Energy efficient windows and doors - Energy Saving Trust

22 Tognetti, F. (2020) Analysis of existing incentives in Europe for heating powered by fossil fuels and renewable sources. European Environmental Bureau

23 SolarPower Europe (2020) EU Market Outlook for Solar Power 2020-2024

A.1 MODELLING STRUCTURE

Below contains a flow chart of the modelling process, showing in broad terms the method used from inputs to results:



A.2 INPUT TABLES

Table A.2.1: Housing Archetype Inputs

INPUT	GERMANY	BRITIAN	ITALY	UNIT	SOURCE
FLOOR AREA	63	88	127	m^2	TABULA
HEATING ENERGY REQUIREMENT	7,556	14,564	10,452	kWh/a	TABULA
HEAT TRANSMISSION	1.46	4.84	1.25	W/m^{2}K	TABULA
HEAT VENTILATION	0.51	0.51	0.42	W/m^{2}K	TABULA
NUMBER OF INHABITANTS	3	4	4	Persons	Estimate

Table A.2.2: Fuel Inputs - * Electricity values taken from current values, up to 2052. † Non-condensing gas boiler used.

INPUT	ELECTRICITY*	OIL	GAS	UNIT	SOURCE
BOILER EFFICIENCY	N/A	0.75	0.75 – 0.90†	COP	European Commission
GERMAN CARBON INTENSITY	0.3500 – 0.0111	N/A	0.2009	kgCO2e/kWh	Umwelt Bundesamt, EEA
BRITISH CARBON INTENSITY	0.1515 – 0.0070	0.2467	N/A	kgCO2e/kWh	BEIS
ITALIAN CARBON INTENSITY	0.2330 – 0.0074	N/A	0.2019	kgCO2e/kWh	IPCC, EEA
GERMAN FUEL PRICES	0.3006	N/A	0.0620	€/kWh	Eurostat
BRITISH FUEL PRICES	0.1905	0.0571	N/A	€/kWh	Eurostat, SAP 10
ITALIAN FUEL PRICES	0.2153	N/A	0.0897	€/kWh	Eurostat

† Non-condensing boiler used in the German archetype (0.75), condensing boiler used in the Italian archetype (0.90).

* Carbon intensities taken from current values, up to 2052.

Table A.2.3: Economic Inputs

INPUT	GERMANY	BRITAIN	ITALY	UNIT	SOURCE
GBP TO EUR CONVERSION RATE	N/A	1.1555	N/A	£/€	ECB
INFLATION RATE TARGETS	2.00	2.00	2.00	%	ECB, BoE
DISCOUNT RATES	3.50	3.50	3.50	%	Hermelink, and Jager (2015)

Table A.2.4: Smart Thermostat Specific Inputs

INPUT	GERMANY	BRITAIN	ITALY	UNIT	SOURCE
COST	200	200	200	€	tado°
LIFETIME	18	18	18	years	tado°
HEATING ENERGY SAVINGS	22.8	17.7	21.0	%	tado°

Table A.2.5: Insulation Package Costings, New Energy Requirements – N/A indicates non-inclusion in the package.

INPUT	GERMANY	BRITIAN	ITALY	UNIT	SOURCE
WALL INSULATION	7,857	611	1,098	€	BEIS
LOFT INSULATION	1,849	2,658	3,582	€	BEIS
FLOOR INSULATION	636	N/A	1,040	€	BEIS
DOUBLE GLAZING	4,506	7,395	9,591	€	BEIS
UPVC DOOR	404	N/A	N/A	€	BEIS
TOTAL COST	15,253	10,664	15,310	€	
NEW HEATING ENERGY REQUIREMENT	4,876	9,803	9,360	kWh/a	TABULA

Table A.2.6: Solar Photovoltaic Inputs

INPUT	GERMANY	BRITIAN	ITALY	UNIT	SOURCE
ANNUAL INSOLATION OUTPUT	1,067	942	1,523	kWh/kWp	GSA
SOLAR PV COST	1,200	1,947	1,700	€/kW	Dachgold, Solaranlagen, BEIS, Lucegas, Altroconsumo
O&M COSTS	1.50	1.50	1.50	%	Peters et. al. (2011)
PANEL LIFETIME	30	30	30	years	Branker et. al. (2011)
ANNUAL DEGRADATION RATE	0.50	0.50	0.50	%	Paper
PV SIZING PER HOUSEHOLD	1.32	2	2	kWp	BEIS
ELECTRICITY CONSUMPTION PER CAPITA	1,524	1,558	1,087	kWh	Eurostat
ARCHETYPE TOTAL ELECTRICITY CONSUMPTION	4,573	6,231	4,346	kWh/a	Combination with Table A.2.1
ESTIMATED FEED-IN-TARIFF	0.0747	0.0350	0.0747	€/kWh	Solaranlagen, Solar Guide

Table A.2.7: Heat Pump Data

INPUT	GERMANY	BRITAIN	ITALY	UNIT	SOURCE
ASHP INSTALLED SIZE	4	11	4	kW	
RADIATORS UPGRADED	No	Yes	Yes	-	
TOTAL ASHP COST (INCLUDING RADIATORS, AND UPGRADES)	7,938	13,761	9,500	€	BEIS, Stelrad

Table A.2.8: Average European Household Weighting Inputs; *European-wide values, each category is equally weighted

INPUT	GERMANY	BRITAIN	ITALY	UNIT	SOURCE
MULTI VERSUS SINGLE HOUSEHOLDS*	48.60	51.40	51.40	%	European Commission
LOCATION	41.50	27.80	26.20	Millions	Statistisches Bundesamt, ONS, Helgi Library
AGE OF CONSTRUCTION	34.12	10.83	25.48	%	European Comission
RESULTANT WEIGHTINGS	46.83	23.40	29.77	%	

* European-wide values, each category is equally weighted.

† Weightings used for exclusion of solar PV results.

A.3 RESULTS TABLES

Table A.3.1: German Archetype Results, Split by Technology

RESULT	SMART THERMOSTAT	INSULATION PACKAGE	SOLAR PV*	HEAT PUMP	UNIT
NET PRESENT VALUE	1,485	-10,763	1,460	-12,585	€
ANNUAL CARBON SAVING	462	718	132	1,826	kgCO2e
TOTAL CARBON SAVED	8,308	22,260	3,973	32,873	kgCO2e
MARGINAL ABATEMENT COST†	-179	483	-367	383	€/tCO2e
EQUIVALENT ANNUAL ANNUITY	113	-585	155	-954	€
UP-FRONT COST	200	15,253	1,582	7,938	€
ANNUAL ENERGY SAVING	1,723	2,680	783	4,486	kWh
TOTAL ENERGY SAVING	31,011	80,408	24,273	80,740	kWh
ANNUAL FUEL BILL SAVING	130	239	376	-522	€
TOTAL FUEL BILL SAVING	2,333	7,183	11,290	-9,399	€
ANNUAL CARBON SAVING PER €100 UP-FRONT COST	230.79	4.71	8.37	23.01	kgCO2e/€
ANNUAL FUEL BILL SAVING PER €100 UP-FRONT COST	64.80	1.57	23.79	-6.58	€
TOTAL ENERGY SAVED PER €100 OF UP-FRONT COST	15,506	527	1,534	1,017	kWh/€

* Solar PV not included in combined results or presented in the above report.

† Referred to as the carbon saving cost in the report

Table A.3.2: British Archetype Results, Split by Technology

RESULT	SMART THERMOSTAT	INSULATION PACKAGE	SOLAR PV*	HEAT PUMP	UNIT
NET PRESENT VALUE	2,119	-3,577	-829	-13,080	€
ANNUAL CARBON SAVING	848	1,566	77	4,419	kgCO2e
TOTAL CARBON SAVED	15,260	48,536	2,306	79,535	kgCO2e
MARGINAL ABATEMENT COST†	-139	74	360	164	€/tCO2e
EQUIVALENT ANNUAL ANNUITY	161	-194	-45	-992	€
UP-FRONT COST	200	10,664	3,894	13,761	€
ANNUAL ENERGY SAVING	2,578	4,761	783	8,815	kWh
TOTAL ENERGY SAVING	46,401	142,824	24,273	158,677	kWh
ANNUAL FUEL BILL SAVING	179	392	248	-224	€
TOTAL FUEL BILL SAVING	3,214	11,747	7,437	-4,037	€
* ANNUAL CARBON SAVING PER €100 UP-FRONT COST	423.88	14.68	1.97	32.11	kgCO2e/€
ANNUAL FUEL BILL SAVING PER €100 UP-FRONT COST	89.27	3.67	6.37	-1.63	€
TOTAL ENERGY SAVED PER €100 OF UP-FRONT COST	23,200	1,339	623	1,153	kWh/€

† Referred to as the carbon saving cost in the report

Table A.3.3: Italian Archetype Results, Split by Technology

RESULT	SMART THERMOSTAT	INSULATION PACKAGE	SOLAR PV*	HEAT PUMP	UNIT
NET PRESENT VALUE	2,901	-12,368	2,556	-2,972	€
ANNUAL CARBON SAVING	493	245	209	2,146	kgCO2e
TOTAL CARBON SAVED	8,865	7,597	6,260	38,627	kgCO2e
MARGINAL ABATEMENT COST†	-327	1,628	-408	77	€/tCO2e
EQUIVALENT ANNUAL ANNUITY	220	-672	139	-225	€
UP-FRONT COST	200	15,310	3,400	9,500	€
ANNUAL ENERGY SAVING	2,195	1,092	783	7,364	kWh
TOTAL ENERGY SAVING	39,509	32,766	24,273	132,548	kWh
ANNUAL FUEL BILL SAVING	239	141	398	261	€
TOTAL FUEL BILL SAVING	4,300	4,235	11,934	4,698	€
ANNUAL CARBON SAVING PER €100 UP-FRONT COST	246.35	1.60	6.14	22.59	kgCO2e/€
ANNUAL FUEL BILL SAVING PER €100 UP-FRONT COST	119.45	0.92	11.70	2.75	€
TOTAL ENERGY SAVED PER €100 OF UP-FRONT COST	19,754	214	714	1,395	kWh/€

† Referred to as the carbon saving cost in the report

Table A.3.4: Weighted Average Results, Split by Technology

RESULT	SMART THERMOSTAT	INSULATION PACKAGE	SOLAR PV*	HEAT PUMP	UNIT
NET PRESENT VALUE	2,055	-9,559	1,066	-9,839	€
ANNUAL CARBON SAVING	561	776	151	2,528	kgCO2e
TOTAL CARBON SAVED	10,100	24,042	4,520	45,503	kgCO2e
MARGINAL ABATEMENT COST†	-214	728	-70	241	€/tCO2e
EQUIVALENT ANNUAL ANNUITY	156	-520	58	-746	€
UP-FRONT COST	200	14,196	3,617	9,765	€
ANNUAL ENERGY SAVING	2,063	2,694	783	6,355	kWh
TOTAL ENERGY SAVING	37,141	80,827	24,273	114,398	kWh
ANNUAL FUEL BILL SAVING	174	246	332	-219	€
TOTAL FUEL BILL SAVING	3,125	7,373	9,955	-3,948	€
ANNUAL CARBON SAVING PER €100 UP-FRONT COST	280.57	5.46	4.16	25.89	kgCO2e/€
ANNUAL FUEL BILL SAVING PER €100 UP-FRONT COST	86.80	1.73	9.17	-2.25	€
TOTAL ENERGY SAVED PER €100 OF UP-FRONT COST	18,571	569	671	1,171	kWh/€

† Referred to as the carbon saving cost in the report

A.4 PEER REVIEW

A.4.1 Review: Decarbonisation of The European Housing Stock, Report and Model

Prepared for: Gemserv Ltd. on behalf of Tado GmbH

Prepared by: Dr Tim Forman, University of Cambridge

Submitted 30 August, 2021

This review includes a 1.5-page written summary of findings and is accompanied by a comments register, which describes specific points and critiques in further detail.

We have been engaged by Gemserv Consultants to undertake a technical peer review of the 'Cost-effective decarbonisation of the European housing stock' report and model, commissioned by tado°. By way of response, we include a summary of our findings and append a Comments Register for further information.

The study contributes to the complex yet critical task of decarbonising the existing European building stock, via assessing the carbon and energy-saving potential of a range of technological and practical retrofit upgrade measures, for three archetype domestic dwellings located in Germany, United Kingdom and Italy. The upgrade options considered are smart thermostats, air source heat pumps (ASHPs), fabric insulation upgrades and solar photovoltaics (PV).

The study investigates the viability of each option in isolation, without stipulating combinations of options for each respective dwelling. The method utilises a modelling approach to forecast 'current' energy consumption for each archetype. The return on investment, energy and subsequent carbon savings are then presented, from a marginal abatement cost perspective (e.g. cost/carbon saved [€/tCO2e]).

The report initially describes policy context and wider drivers for the project; these are recognised as reasonably and usefully comprehensive. The Technology Overview section then details technical information for each proposed upgrade measure. A sub-section outlines general information relating to the specification of wall, loft, underfloor and glazing retrofit measures, and notes that installing a single option is considered a redundant measure. There is some limitation to the analysis due to single energy performance/energy efficiency measures being considered in isolation, rather than in concert (frequently in existing buildings, multiple efficiency measures are introduced together). This perhaps limits the potential interpretation of findings; as for instance, insulation measures are consequently presented as a combination of all feasible options, inflating capital costs and thus reducing appeal. Similarly, double glazing is considered a default option of the 'insulation' category, despite relatively high rates of installation across western Europe. Moreover, although the practical constraints of retrofitting ASHPs to existing dwellings are alluded to in the report, corresponding capital cost penalties associated with these constraints are not assigned in the model. Common enabling works include upgrading electrical infrastructure and heating distribution pipework, due to flow temperatures <50°C. Domestic hot water operation can also result in lower coefficients of performance (COP's).

The report describes research that follows a repeatable and defensible approach, drawing on reasonable assumptions and inputs; however, it is important to note that the benefits of smart heating controls depend on i) the subjective nature of user input, which could be misrepresented in a quantitative model such as the one reviewed here, ii) the interaction of smart heating controls with existing heating plant and related technologies and the absence or presence of other energy-related interventions in a building; and iii) a full and representative comparison and costing of alternatives. Correspondingly, the reader would benefit from understanding the full detail of how forecast savings have been calculated and the boundaries of this assessment. In one example, some of the described control functions including weather compensation and modular boiler control are available on some modern boiler plant, but perhaps this could be described in detail. In a second example, it may be helpful to present the three-archetype building energy consumption as a function of the total floor area, as it appears that the German archetype is <47% smaller than the UK dwelling, which may skew the results.

To conclude, the study specifically recommends retrofitting smart thermostats to assist in the decarbonisation of European buildings. This energy efficiency improvement measure is reported to provide substantial savings from a marginal abatement cost perspective due to the comparatively low upfront cost. Indeed, a device which enhances the efficiency of a system at comparatively low cost is welcome. It is important to recognise that decarbonisation of the built environment requires multiple demand-side measures and changes in occupant behaviour (as well as supply-side measures) -- including a wide range of retrofit measures -- and such interventions have compound and complex interactions. This report presents analysis showing the compelling potential of smart thermostats to contribute to building energy demand reduction, thereby enabling significant potential for decarbonisation, within the study and reporting limitations described here.

A.4.2 Review: Comments Register

Gemserv / Tado

Cost-effective decarbonisation of the European housing stock: Technical Peer Review Comments Tracker

	ITEM	COMMENT	REFRENCE	AUTHOR	RESPONSE	AUTHOR
1.1	Exec summary / formatting	Perhaps additional numerical data / infographic / chart may allow the reader to glance over the numbers. May enable reader to absorb key message. Section headings could also be numbered / page numbers for ease of reference Explain report has been commissioned by Tado controls, for clarity.	All	JW	Changes made in final version of report and infographic.	CL
1.2	Decision to assess upgrade options in isolation	Expand on justification for nominating individual upgrade options during the analysis elements of the report. Why have combinations not been considered, especially since smart thermostats will likely form part of a combination to drastically reduce carbon emissions moving forwards	Exec Summary	JW	Scope limitations expanded upon appropriately.	CL
1.3	Germany communal PV system omission	It is unclear why a PV system has been nominated for the German archetype. The report notes this is due to complexity of modelling communal PV, although an ASHP system would likely be in a district / energy centre arrangement for residential tower. Why was a stand alone building not nominated for Germany?		JW	Additional clarification included in the methodology section.	CL
1.4	Smart controls - difference between existing heating controls	Could expand on differentiators from existing heating system controls. Modern boilers have many of the functions listed already included	Technology overview	JW	Included in the final report.	CL
1.5	Modelling methodology smart controls	Perhaps the reader may benefit from learning more as to how the model quantifies the energy savings potential from smart controls. Is the data taken from case studies etc?	Methodology	JW	Additional information added in the final version.	CL
1.6	Underfloor insulation disruption	Typically older properties have sufficient floor voids for operatives to access to retrofit underfloor insulation. Although, most modern buildings do not have sufficient space. Recommend upgrading disruption input from 'moderate' to 'high'	Technology overview (Table 3)	JW	Change included in the final report.	CL

1.7	Double glazing energy savings potential	Listed as 'moderate', although substantial improvements to air tightness alone can result in ample energy savings. Could upgrade to 'high'	Technology overview (Table 3)	JW	We believe moderate is a fair reflection of the average.	CL
1.8	Heat pumps COP	Confirm COP of heat pumps and clarify if the model assessing energy usage based on system operating at peak or intermittent COPs. We assume HP has been modelled to serve space heating and domestic hot water load. Typically DHW operation reduces COP <2	Technology overview	JW	Heat Pump methodology expanded upon in the methodology section.	CL
1.9	Heat pumps disruption	Model does not appear to allow for capital cost of pipework and electrical infrastructure upgrades. May also result in substantial disruption	Model 'HP' tab	JW	Expanded upon in the methodology section.	CL
1.10	Heat pump ODP/GWP	From a 'net zero' carbon perspective. It may be worth adding text outlining refrigerants still pose an issue during lifecycle	Technology overview	JW	Comment on refrigerants in heat pumps added alongside recognition of the need to consider lifecycle costs.	CL
1.11	Heat pump UK / Germany cost difference	Report notes 5K Euro cost difference between UK and Ger heat pumps. Although the dwelling sizes are much different. Does this cost difference represent economies of scale due to higher uptake in Germany or smaller unit?	Technology overview	JW	Heat pump sizing clarified in the report.	CL
1.12	Solar PV system energy saving results	The PV energy savings noted for UK/Italy appear low at <1000kWh per annum	Results	JW	Made clearer in the methodology and results tables added.	CL
1.13	Heating / Electrical energy usage per archetype	The reader may benefit from viewing modelled energy usage per application type. For example, heating energy could be split between space heating and hot water. This would show how much energy savings are 'on the table'	Results	JW	Excluded in order to keep our results and conclusions clear and concise.	CL

1.14	Fabric insulation upgrade options	It would be useful to split the results from the different fabric upgrade options, particularly for the double glazing and wall/roof/floor options. The capital costs appear to be high and more clarity would inform the reader of the specific benefits of each	Results	JW	Justification included in multiple sections of the report.	CL
1.15	LED Lighting	The report does not appear to mention LED / low energy lighting as a viable upgrade option. Is it assumed the dwellings already have LED throughout. A sentence in the report would help confirm this	General	JW	Comment included in the technology overview.	CL
1.16	Additional low/zero carbon energy generation plant	May be useful to confirm why other technological solutions are not included in the study, including; ground source heat pumps or solar thermal	General	JW	Further expanded upon in the final report.	CL

DISCLAIMER

This report has been commissioned by tado° and seeks to investigate the cost-effectiveness of using smart thermostats and the potential for their use as an energy efficiency measure. The relative cost-effectiveness of individual measures, packages of measures and smart thermostats have been evaluated based on their energy savings and carbon reduction statistics.

While Gemserv consider the data and analysis included in this report to be reasonable based on current information, Gemserv offer no warranty or assurance as to accuracy and completeness. Details of the principal sources used are set out within the document.

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