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System analysis of the significance of energy poverty on household energy use and emissions in Germany

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Audrey Dobbins

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System analysis of the significance of energy poverty on household energy use and emissions in Germany

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"A journey of a thousand miles begins with a single step."

Lao Tzu (5th Century BC)

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Abbreviations, acronyms and initialisms

€	Euro
2HM	Second-hand market
2M	Energy expenditure is below half the national median
a	Year
AGG	Aggregated
AHC	After Housing Costs
AHT	Ambient heat
APEE	Heating and Ventilation package of the Energy Efficiency Incentive programme / Heizungs- und Lüftungspaket des Anreizprogramms Energieeffizienz
AROPE	At risk of poverty or social exclusion
Avg.	Average
bbl	Barrel
BEHG	Emissions trading law / Brenstoffemissionshandelsgesetz
BHC	Before Housing Costs
BIO	Biomass
BMWi	German Federal Ministry of Economy and Energy / Bundesministerium für Wirtschaft und Energie
bn	Billion
CB	Climate bonus (scenario)
CBLI	Climate bonus low income (scenario)
CDR	Clothes drying
Ch.	Chapter
CO2	Carbon dioxide
CO2TO	Carbon tax distribution 50:50 Tenants:Owners (scenario)
CO_2-eq	Carbon dioxide equivalent
COA	Coal
COK	Cooking
COL	Cooling
COVID-19	Corona virus disease 2019
CWA	Clothes washing
DWA	Dishwashing
EBS-Programm	Carbon refurbishment programme / CO_2-Gebäudesanierungsprogramm
EEG	Renewable energy surcharge / Erneuerbareenergiengesetz
EKF	Energy and climate funds / Energie- und Klimafonds
ELC	electricity
EP	Energy poverty (scenario)

EsanMV	Energy refurbishment measures regulation / Energetischen Sanierungsmaßnahmen-Verordnung
ESCo	Energy service company
ETS	Emissions trading system
EU	European Union
EU-I	Energy use intensity
EU-SILC	Eurostat Survey on Income and Living Conditions
EXP	Expenditure
EXT	Extended technical lifetime
FREEZ	Freezer
GAS	Natural gas
GDP	Gross Domestic Product
GEG	Building energy law / Gebäudeenergiegesetz
GEO	Geothermal energy
GHG	Greenhouse Gases
GHG-I	Greenhouse gas intensity
GJ	Gigajoule
GVV	Basic services regulation / Grundversorgungsverordnung
H	Heating
HBS	Household Budget Survey
HCLI EI	High cost, Low income equivalised income
HH	Household
HZO	Heating Optimisation Programme / Heizungsoptimierungsprogramm
ICT	information and communication technology
IEA	International Energy Agency
INV	Investment
KfW	Credit for reconstruction / Kreditanstalt für Wiederaufbau
kW	Kilowatt
kWh	Kilowatt-hour
LIG	Lighting
LIHC	Low Income High Cost
LPG	Liquid Petroleum Gas
LTH	District heating
m	Million
m^2	Square meters
M/2	Low absolute energy expenditure
MAP	Market incentive programme / Marktanreizprogramm
MFH	Multi-family homes

MW	Megawatt
MWh	Megawatt-hour
NECP	National Energy and Climate Plan
OECD	Organisation for Economic Co-operation and Development
OEL	Other electric appliances
OIL	Oil
Own.	Owner
p.a.	Per annum
PJ	Petajoule
pop	population
ppl	People
PV	Photovoltaics
R1	Income group <900€ per household and month
R2	Income group 900-1500€ per household and month
R3	Income group 1500-2000€ per household and month
R4	Income group 2000-2600€ per household and month
R5	Income group 2600-3600€ per household and month
R6	Income group 3600-5000€ per household and month
R7	Income group 5000+ per household and month
RE	Renewable energy
REF	Reference (scenario)
REFRI	Refrigeration
REFRZ	Refrigeration/freezer
RWI	Rhineland Westphalien Institute
SFH	Single-family homes
SGB	Social law / Sozialgesetzbuch
SOL	Solar thermal
TAM	TIMES Actors Model
TAM-HH	TIMES Actors Model-Households
Ten.	Tenant
TFH	Two-family homes
TIMES	The Integrated MARKAL-EFOM System
UK	United Kingdom
US	United States
VC	Vulnerable consumers (scenario)
WH	Water heating

"All things are possible until they are proved impossible – and even the impossible may only be so, as of now."

Pearl S. Buck (1892-1973)

Abstract

Germany's ambitious energy transition aims to significantly increase the use of renewable energy and decrease energy consumption and emissions. Households represent a third of the final energy consumption and have a crucial role to play towards achieving sector-specific targets including increasing renewable energy and energy efficiency. Households are responsible for investing in privately-owned infrastructure (building insulation, heating systems, and appliances) that comply with these objectives. However, limited income influences how some households are able to engage with and benefit from the transforming energy system given that the majority of households lack either the sufficient disposable income to afford the high upfront costs of investments, or the decision-making power to undertake meaningful investments. At the same time, it is estimated that 11-21% of the German population already experiences energy poverty, and is on the rise. Yet the phenomenon is not recognised by the government as an issue requiring a tailored response. Current energy policy is based on modelling assessments which assume a homogenous population, which can underestimate the impact on lower income households and overestimate the possible contributions from this sector towards achieving the overall objectives of the energy transition.

This research provides an empirical basis for recognising the significance of energy poverty outside of the current "vulnerable consumers" lens and within the energy transition process, thereby presenting the momentum to actively address inequalities within the energy system. Based on the TIMES-Germany model, the TAM-Households model was further developed to account for the heterogeneity of the population and the limitations in investment arising from socio-economic constraints. The suitability and capabilities of the method developed are demonstrated through several scenarios to explore issues relevant to energy vulnerable households, such as access and affordability. The results showed that disaggregation is a useful methodology to assess the differentiated energy needs of households based on socio-economic parameters, but highlighted that disaggregation alone is not enough to represent the lack of financial capacity of households. The incorporation of budget constraints is a critical methodological inclusion to assess the significance of energy poverty in the energy system. A case study evaluated the impact of coping mechanisms, such as buying second-hand appliances, which underscored the disadvantages of unaffordability of the high upfront costs which come at the cost of higher fuel consumption into the future. The methodology enabled an analysis of the impacts of policies designed to support lower income households, such as investment or consumption subsidies or the effects of carbon taxes, or schemes to redistribute funding. Overall, due to the household disaggregation the results could be analysed from the perspective of different households: by income group, tenure, location and building type. The addition of the budget constraint provided insights into the limitations of households to comply with overarching climate targets while meeting maximising their energy welfare. This facilitated the estimation of the supressed demand experienced by different socio-economic groups.

The value of this methodology provides a platform to support the analysis of a differentiated policy response – effectively strengthening opportunity to achieve the desired active participation in the energy transition and the energy welfare of households.

Kurzfassung

Deutschlands ambitionierte Energiewende zielt darauf ab, den Einsatz erneuerbarer Energien deutlich zu steigern und den Energieverbrauch und die Emissionen zu senken. Haushalte machen ein Drittel des Endenergieverbrauchs aus und spielen eine entscheidende Rolle bei der Erreichung Sektor spezifischer Ziele, einschließlich der Steigerung der erneuerbaren Energien und der Energieeffizienz. Die Haushalte sind dafür verantwortlich, in eine private Infrastruktur (Gebäudedämmung, Heizungsanlagen, Geräte) zu investieren, die diesen Zielen entspricht. Ein begrenztes Einkommen beeinflusst jedoch, wie einige Haushalte in der Lage sind, mit dem sich wandelnden Energiesystem zu interagieren und davon zu profitieren, da der Mehrheit der Haushalte entweder im ausreichenden Maße das verfügbare Einkommen fehlt, um die hohen Investitionskosten zu tragen, oder die Entscheidungsmacht, um sinnvolle Maßnahmen zu ergreifen. Gleichzeitig sind Schätzungen zufolge bereits 11 bis 21 % der deutschen Bevölkerung von Energiearmut betroffen, Tendenz steigend. Das Phänomen wird jedoch von der Bundesregierung nicht als Problem erkannt, das eine maßgeschneiderte Reaktion erfordert. Die aktuelle Energiepolitik basiert zudem auf Modellrechnungen, die von einer homogenen Bevölkerung ausgehen, die die Auswirkungen auf einkommensschwächere Haushalte unterschätzen und die möglichen Beiträge dieses Sektors zur Erreichung der Gesamtziele der Energiewende überschätzen könnten.

Die vorliegende Arbeit liefert eine empirische Grundlage für die Anerkennung der Bedeutung von Energiearmut außerhalb des aktuellen Blickwinkels der "schutzbedürftigen Verbraucher" und innerhalb des Energiewendeprozesses, wodurch der Impuls gegeben wird, Ungleichheiten innerhalb des Energiesystems aktiv anzugehen. Basierend auf dem TIMES-Deutschland-Modell, dem Modell TAM-Households wurde entwickelt, um der Heterogenität der Bevölkerung und den aus sozioökonomischen Zwängen resultierenden Investitionsbeschränkungen Rechnung zu tragen. Die Eignung und die Möglichkeiten der entwickelten Methode werden anhand mehrerer Szenarien demonstriert, um Fragen zu untersuchen, die für energiegefährdete Haushalte relevant sind, wie etwa Zugang und Erschwinglichkeit. Die Ergebnisse zeigen, dass die Disaggregation eine nützliche Methode ist, um den differenzierten Energiebedarf der Haushalte auf der Grundlage sozioökonomischer Parameter zu bewerten, aber sie machen auch deutlich, dass die Disaggregation allein nicht ausreicht, um die mangelnde finanzielle Leistungsfähigkeit der Haushalte darzustellen. Die Einbeziehung von Budgetbeschränkungen ist ein entscheidendes methodisches Instrument, um die Bedeutung von Energiearmut im Energiesystem zu bewerten. In einer Fallstudie wurden die Auswirkungen von Bewältigungsmechanismen wie dem Kauf gebrauchter Geräte bewertet, was die Nachteile der Unbezahlbarkeit der hohen Vorlaufkosten unterstrich, die mit einem höheren Brennstoffverbrauch in der Zukunft einhergehen. Die Methodik ermöglichte eine Analyse der Auswirkungen politischer Maßnahmen zur Unterstützung einkommensschwächerer Haushalte, wie z. B. Investitions- oder Verbrauchssubventionen oder die Auswirkungen von Kohlenstoffsteuern oder Regelungen zur Umverteilung von Finanzmitteln. Insgesamt konnten die Ergebnisse aufgrund der Aufschlüsselung nach Haushalten aus der Perspektive verschiedener Verbraucher analysiert werden: nach Einkommensgruppe, Besitz, Standort und Gebäudetyp. Die Ergänzung um die Budgetbeschränkung ermöglichte Einblicke in die Grenzen der Haushalte, die übergeordneten Klimaziele einzuhalten und gleichzeitig ihren Energiewohlstand zu maximieren. Dies erleichterte die Abschätzung der unterdrückten Nachfrage verschiedener sozioökonomischer Gruppen.

Diese Methodik liefert eine Plattform zur Unterstützung der Analyse differenzierter politischer Reaktionen, um auf wirkungsvoller Art und Weise die Möglichkeit zu schaffen, dass Haushalte an der Energiewende und dem Energiewohlstand wie beabsichtigt aktiv teilhaben können.

"No sensible decision can be made any longer without taking into account not only the world as it is, but the world as it will be..."
Isaac Asimov (1920 – 1992)

1 Introduction and scope

Consumers at the heart of the energy transition are key to unlocking the potential to achieve energy and climate change targets in Germany. Embedded in the European energy policy direction, it is becoming increasingly evident that without the active participation of consumers (households), the ambitious renewable energy and energy efficiency targets of the energy transition will remain unattainable. Households in Germany are directly responsible for almost a third of the total final energy demand and therefore have a significant role to play in the energy transition. However, the majority of households in Germany are not in the financial or decision-making position to undertake the required investments in renewable and energy efficiency technologies. Current national energy planning is limited in providing a realistic assessment since the household sector is considered homogenously, which may cause some targets to overestimate the contributions from this sector. Discounting and not addressing these gaps in energy planning will likely result in falling short of the energy and climate change targets, a lack of active participation and a reduction in the energy welfare in the vulnerable population. With energy poverty on the rise across Europe, recognition for energy poverty in the legislation is crucial to ensuring all households have the opportunity to participate in the energy transition and are not disproportionately disadvantaged. This requires consideration for energy poverty within the planning process, and therefore the development of methods to assess the impact of measures introduced for the household sector to incentivise a shift to a more sustainable energy system.

This thesis sheds light on the significance of taking energy poverty into account for energy planning as well as develops a methodology to assess the energy welfare of households towards within the context of achieving the overall energy and climate change targets in Germany. This chapter proposes that energy poverty as a significant barrier to the energy welfare of households requires recognition (Chapter 1.1). This study argues for the disaggregation of the household sector to better account for varying investment and consumption patterns (Chapter 1.2). The challenges and future of the energy system are explored in Chapter 1.3. Chapter 1.4 outlines the overall research objectives. The structure of this thesis is introduced in Chapter 1.5.

1.1 Energy poverty: a significant barrier to energy welfare

The term "fuel poverty" was first coined in 1991 in the United Kingdom and since then, together with the progression of the liberalisation of the energy markets in the EU, has become an increasingly prevalent topic within the energy transition debate (Boardman 1991). Energy poverty typically affects households made vulnerable by a single or combination of effects resulting from low income, higher energy bills and inefficient buildings and appliances (Pye et al. 2015a). Energy poverty is a multi-dimensional concept commonly understood as:

> *"a situation where households are not able to adequately meet their energy needs at affordable cost, and is caused by a combination of overlapping factors including low income, high energy prices, poorly insulated buildings and inefficient technologies and sometimes limited access to clean and affordable energy sources" (Dobbins et al. 2019).*

Energy poverty is also linked to wider health issues, including excess winter death and poor mental health (Liddell and Guiney 2015; Liddell et al. 2015). Energy poor households may also face disproportionately higher energy costs due to lower levels of access to competitive tariffs and other energy market benefits (European Commission 2016c). Households experiencing energy poverty often enter into a cycle of debt and energy disconnections which becomes difficult to escape thereby reinforcing a status of energy vulnerability, unable to meet basic energy needs (Jones 2016; Bouzarovski et al. 2021). Energy poverty impacts not only the energy welfare (and other aspects) of life and economy, but also the amount of energy consumed exhibiting so-called suppressed demand – or hidden energy poverty, which represents abnormally low energy consumption (Csiba 2016; Rademaekers et al. 2016). Energy poverty is a phenomenon found across all member states in Europe, including Germany. While some member states are proactive in addressing the issues facing households experiencing energy poverty, other member states are less inclined to recognise and tackle energy poverty directly, preferring to indirectly address it through the social welfare system. This depends on the legislative approach (Pye et al. 2015a; Dobbins et al. 2016). Energy poverty first appears in EU legislation in 2009, where member states are required to define vulnerable consumers, which "could refer to, inter alia, energy poverty" (European Parliament 2009a, 2009b). With this wording, there is confusion about the differences between vulnerable consumers and energy poverty and how this then relates to the obligations of each member state to energy consumers. Without guidance from the EU, member states individually define vulnerable consumers along a range of characteristics, encompassing a broader or narrower set of the population. The concept of energy poverty is intertwined with but distinct from that of vulnerable consumers (Pye et al. 2017). The definition of each concept is critical to identifying the target group and specifying the required policies and measures required to address the issue. Some member states, like Germany, decline to recognise energy poverty as a phenomenon requiring targeted policies and measures (Bundestag 2014, 2017; Kanschik 2015).

Recognising the role the legislative approach has in ensuring the energy welfare of households is crucial in view of achieving the objectives of the energy transition (EESC 2010). There is an upward trend towards meaningful recognition by the European policy community particularly since the inclusion in further pieces of European legislation (European Parliament 2009a, 2009b, 2018a, 2019, 2018c) and within the energy transition discourse (Middlemiss et al. 2020a; Sovacool et al. 2019). Although a formal definition of energy poverty does not exist in the German context, there has been a noticeable increase in the number of households who struggle to afford adequate energy services such that approximately 11-21% of German households are estimated to live in energy poverty (Pye et al. 2015a; Bleckmann et al. 2016; Heindl 2014). In 2018, more than 296,000 households were unable to pay their electricity bills and over 43,000 unable to pay their gas bills and were consequently cut off from services (BNetzA 2019). Due to the COVID-19 pandemic, evidence shows that these aspects are exacerbated and will negatively affect households further, but these circumstances also give rise to a unique opportunity to take action to resolve the multiple inequalities exposed by the pandemic (European Commission 2020a, 2020c).

Energy poverty is increasingly prevalent in the energy transition discourse. It is no longer a question of if the energy transition will benefit lower income households, but how to enable this (Ugarte et al. 2016; European Commission 2016c; Sunderland et al. 2020). The lack of a common understanding on what energy poverty is results in fragmented approaches or discounting its significance entirely (Pye et al. 2015a). This is a problem because there are indications of an increasing trend and current strategies risk leaving lower income households behind (Dobbins et al. 2019). There is a need to assess energy poverty by classifying the main arguments towards the recognition of and taking action on tackling energy poverty and not only for vulnerable consumers.

1.2 The household sector: key to achieving the energy transition

In 2018, households consumed 27.5% of the total final energy domestic consumption (excluding mobility) and emitted 10.1% of the total greenhouse gases (BMU 2019b, 2018; BMWi 2021; AGEB 2019). As such, households in Germany are responsible for a significant share of the final energy consumption and are expected to increase shares of renewable energy use in heating and self-generated electricity while also decreasing energy consumption (or increasing energy efficiency) in line with energy transition targets (BMWi 2019c). The major relevant end-uses and fuel types targeted in the household sector include space heating, oil and gas.

The average household in Germany consumes 65 GJ annually, spending 1,872 € on consumption (direct household energy expenditure) and 252 € on investments (linked to indirect energy expenditure) in 2013 (BMWi 2021; Destatis 2013b). As expected, expenditure is closely coupled to income and the analysis conducted in this thesis will show that there is a mismatch between the expected financial capacity of the majority of households according to their income levels and that of the average household. Table 1-1 presents a comparative overview between the lowest two and upper two income groups indicating the unequal distribution of share of households and population, average monthly income per household, and available savings within each income group (indicative wealth).

Table 1-1: Inequality across the two lowest and highest income groups, 2013
Source: (Destatis 2013b; BMWi 2021)

	Unit	<1500€/HH and month	>3600€/HH and month	Total/ Average
Average energy consumption	*GJ/HH*a*	49	90	65
Average direct energy expenditure	*€/HH*a*	1,116	2,574	1,872
Average indirect energy expenditure	*€/HH*a*	52	396	252
Share of total households	*%; m*	23.2%	31.6%	39.3
Share of total population	*%; m*	28.7%	44.3%	78.9
Share of total tenants	*%; m*	35.8%	16.7%	21.9
Share of total disposable income	*%; bn. €*	8.0%	56.9%	125
Average disposable income	*€/HH*mth*	1,104	5,734	3,130
Average savings	*€/HH*mth*	-85	969	319

The lower two income groups are disadvantaged on two fronts: lack of capital and lack of decision-making power. These lower income groups have less capital available with an 8% share of the total disposable income available, increase their debt with an average of 85 € per month and constitute 35.8% of all rental properties in Germany. In contrast, while the upper two income groups have a higher share of the total population and households and dominate with 56.9% of the total theoretical disposable income, they also have more decision-making power encompassing only 16.7% of all rental properties. The exclusion of the consideration of this inequality is further compacted by the fact that current policies determining strategies for the household sector are based on modelling assessments which assume a homogenous population and monitoring benchmarks for policies are gauged according to average households (BMWi 2018). This oversimplifies the assumptions for the household sector and leads to one technology (and therefore policies, measures and targets) identified as the most cost-effective solution to meet a particular demand. An average household does not adequately capture the observed technological diversity and the differences in investment decisions and consumption behaviour across different types of households and does not account for barriers to actual investment behaviour on the part of this sector. Therefore, there is a need to differentiate between the financial and decision-making ability of different households to be able to better determine how to meet the required investment demands leading to the achievement of sector-specific renewable energy and energy efficiency targets, especially when aiming to stimulate an increase in the numbers of prosumers, which is contingent on the mobilisation of capital from the private sector.

1.3 Challenges and future demands of the energy system

The German '*Energiewende'*, or energy transition, aims to transform the energy system from fossil and nuclear-based energy sources to include more renewable energy sources and energy efficiency (Bundesregierung 2010). Efforts from the household sector will contribute towards achieving the targets in 2050 of an overall reduction in GHGs of -80 to -95% (compared to 1990 levels), 60% share of renewable energy in the final energy consumption, 80% share of renewables in gross electricity consumption, 50% less energy and 25% less electricity compared to 2008 levels, and 80% less primary energy demand in buildings compared to 2008 (BMWi 2018). This ambitious move towards a more renewable and energy efficient energy system is well-founded and even required in order to avert the most detrimental effects of climate change, which are already felt around the world. Underpinned by the Paris Agreement, action on climate includes the transition to a low carbon economy, which entails alternative, clean technologies resulting in the reduction of emissions.

The next 10 years is critical for climate action, recognised by the fact that on the EU level climate milestone targets have been increased to a reduction by 55% by 2030. Given this urgency to act, Germany – within the European energy policy framework – has defined targets to achieve carbon neutrality by 2050 with milestones in 2030 of 30% renewables in the total energy consumption and a reduction of energy consumption of 30% (BMU 2019b; BMWi 2020b). The strategies relevant to the household sector developed from these aspirations require the renovation of the building envelope, replacement of inefficient, fossil-fuel driven heaters with efficient, renewable-based heating systems, increasing energy efficiency of appliances, the installation of decentralised energy generation technologies, and discouraging fossil fuel consumption through the introduction of a carbon tax (BMU 2019b). However, achieving this roll-out poses a challenge since it depends on the co-investment by the private sector where a trend of decreasing willingness-to-pay is evident despite the overall consensus that environmental goals should be reached (Andor et al. 2017).

It is estimated that the energy transition in Germany will require an annual investment of between 15-40 billion € annually for the next 30 years – although it should be noted that the full costs of the energy transition are unknown and estimates need to take into account the damage costs of not taking action as well as incorporate the savings (Agora Energiewende 2018). This highlights concerns about the economic impact of the energy transition in the debate and gives rise to the need to define what is meant by growth and include assurances for well-being (social and economic) within the limits of the environment.

Energy efficiency is outlined as a fundamental step towards not only achieving the energy transition targets but also alleviating energy poverty in European legislation as this addresses some of the underlying causes of energy poverty (European Parliament 2018b). Investments in energy efficiency increase with income, which underscores that the greatest energy efficiency potential often resides in the appliances used and buildings occupied by lower income households, who by default, often do not have the financial capital for the high-upfront costs of investments nor the decision-making power as tenants. The challenge will be to mobilise investment in the lower income and rental sector and this begins with the acknowledgement and inclusion of the variation in investment capabilities of households in energy system modelling leading to sector targets and policy measures.

1.4 Research objectives

While all three of these research areas – energy poverty, household energy, and the energy transition – are stand-alone fields with a depth of research into various aspects of these, there is a lack of a systematic analysis creating a direct interlinkage between two crucial areas of debate: energy poverty and the energy transition. The holistic view of these areas is critical in understanding why households continue to experience energy poverty, why energy and climate policy targets may not be achieved and why participation in the energy transition from the private sector is insufficient. In particular, in order for Germany to comply with the requirements on developing long-term renovation strategies as outlined in the Renovation Wave for the National Energy and Climate Plans (BMWi 2020a), it is imperative for modelling to explore pathways to target the lower income household sector, which has to date been neglected in the energy planning process. Given the arguments laid out, this research will look specifically at energy poverty in Germany and the effects of the energy transition on the ability of lower income households to continue to afford basic energy needs and participate in the energy transition by:

- Providing a pathway towards recognising and addressing energy poverty in Germany,
- Developing a basis for the disaggregated assessment of households within the context of energy poverty and the energy transition, and
- Developing a method to support policy assessment through an energy system analysis for households to meet energy transition targets without compromising their energy welfare.

Parts of this research were undertaken within the framework of the "INSIGHT_E" project funded under the FP7 Research programme of the European Commission (INSIGHT_E 2017) and the "Decentral" project funded by the German Federal Ministry for Economic Affairs and Energy (Ahanchian et al. 2020). Some of the research conducted in this thesis resulted from contributions to the INSIGHT_E project, which led to a new framework on energy poverty at the highest levels of European governance culminating in legislative changes within the revised Electricity Directives in 2019 (Dobbins et al. 2016; European Commission 2016c; European Parliament 2019; Pye et al. 2015a).

1.5 Thesis structure

The thesis begins with a review of energy poverty in the European and the German context in Chapter 2. The typical drivers of energy consumption are underpinned from the perspective of the socio-economic constraints of the household sector relating to energy consumption based on a literature review and available statistics to characterise the household sector in Chapter 3. Chapter 4 describes the methodology for assessing the significance of energy poverty on household energy demand and emissions from an energy system perspective. Distinct scenarios are applied to explore the impact of the consideration for energy poverty and other aspects of limited financial and decision-making capacities through a newly developed energy system model in Chapter 5. Chapter 6 concludes with a summary of the research and provides an outlook for future research.

Table 1-2: Overview of thesis structure

Ch.	Title	Contents
1	Introduction and motivation	Overview of motivation, introduction to the status of existing research, objectives and research questions
2	Vulnerable consumers and energy poverty in Europe and Germany	Overview of energy poverty in general and specifically in the case of Germany relating to definition, monitoring and action
3	Characterisation of household energy consumption	Description of household energy consumption, fuels, technologies, policies within an energy system and characterisation of household profiles to be analysed
4	Assessing the significance of energy poverty on the German energy system	Energy system analysis, adaptation and application of the TIMES model for the household sector in Germany towards achieving the objectives of the energy transition
5	Integrated assessment of energy poverty	Scenario results and discussion
6	Conclusion and way forward	Conclusion and outlook

"There is no solution, because there is no problem."

Marcel Duchamp (1887-1968)

2 Energy poverty and vulnerable consumers in Europe and Germany

The overall objective of this chapter is to provide a pathway towards recognising and addressing energy poverty in Germany. The following chapter sections will outline why and how energy poverty should be understood and relate its significance to the energy transition. This chapter begins with an exploration of the concept of energy poverty as well as the associated causes and consequences on not only individuals but also the wider economy and energy system in Chapter 2.1. Leading on from this, Chapter 2.2 unravels the legislative basis for addressing energy poverty and tackles the misunderstanding associated with the linked but distinct concept of vulnerable consumers, where it is made clear that the terminology is crucial to determining the extent and impact of energy poverty and vulnerable consumers in the energy sector and the ability to measure the number of households affected. This is followed by an overview in Chapter 2.3 of the current policy response, including the measures, in place to address energy poverty across Europe, which will form the basis for the analysis related to exploring options to improve the energy welfare of low income households in Chapter 4. Chapter 2.4 follows with an assessment of the specific situation in Germany, which includes an overview of the policies and measures that influence and address energy poverty and vulnerable consumers. This chapter concludes in Chapter 2.5 to summarise the understanding energy poverty not only as a barrier but also an opportunity to achieving the energy transition targets.

2.1 Energy poverty: a concept in need of recognition

Energy poverty is a concept most often associated with developing countries and refers to households without “access to modern energy services includes household, access to a minimum level of electricity; household access to safer and more sustainable cooking and heating fuels and stoves than traditional biomass stoves; access that enables productive economic activity; and access for public services” (United Nations 2015). This sub-chapter challenges this common association of the term energy poverty and introduces reasoning behind the need to recognise the concept as well as the causes and consequences in industrialised countries like Europe.

Poverty remains one of humanity’s greatest challenges with more than 700 million people living on extremely low wages across the globe (Banerjee et al. 2019). Since the disruption caused by the COVID-19 pandemic and the ongoing climate crisis, it is estimated that up to 150 million additional people will move into poverty by the end of 2021 (World Bank 2021). Inequality, and its related impacts on development, is a growing concern globally. In OECD countries before the pandemic, it is estimated that about nine times as much income already goes to the richest 10% of the population as to the poorest 10% (OECD 2021). Through their work on development economics, the 2019 Nobel Prize winners in Economics Sciences, detailed an approach to reduce global poverty by moving away from the common approach focussing on broader objectives such as increasing incomes in general to tackling the micro-issues and causal pathways leading to poverty, such as education and health (Banerjee et al. 2019). By breaking the issue down into smaller pieces, the issue becomes not only more manageable, but also more tangible for policy intervention. Tackling energy poverty directly as a sub-set of overarching poverty-reducing initiatives could, therefore, be more effective in improving the quality of life through increased living standards.

On the global scale, energy poverty is estimated to affect 18% of the global population (1.1 billion people) (United Nations 2015). The aim of a large majority of energy poverty eradication programmes in developing countries is therefore to increase access to modern energy. Access to modern energy alone does not mean households will necessarily be able to afford the use of these services, because the underlying levels of poverty mean households do not always have sufficient financial means to sustain the ongoing costs of investments into new technologies or energy consumption thus rendering them unable to meet their basic energy needs (IEA, 2017). Energy is at the heart of living and economic activity to meet basic human needs, so it is the essential part of poverty which needs to be alleviated. Access to affordable energy is deemed crucial for sustainable and economic development and eradicating poverty (United Nations 2015).

Yet, energy poverty is not a phenomenon relegated only to developing countries. Households in Europe have been 100% electrified since at least 1990 (World Bank 2017) and as such the common global definition for energy poverty would not apply in the European context. The term "fuel poverty"[1] often refers to "the inability to afford adequate warmth because of the inefficiency of the home" (Koh et al. 2012) and was first coined in 1991 in the UK and since then, together with the progression of the liberalisation of the energy markets in the EU (Boardman 1991). Since then, there is increasing evidence that households in Europe have difficulty affording modern energy services, and accumulating debts lead to reduced consumption (suppressed demand) (Pye et al. 2015a; European Commission 2016b), which implies that households would lose access to modern energy services. This cycle of affordability and access is the basis of energy poverty as depicted in Figure 2-1.

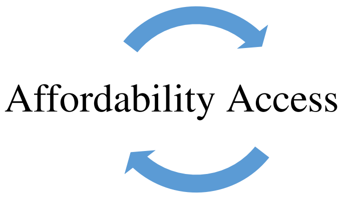

Figure 2-1: Affordability and access as the basic concept of energy poverty

Comparable to energy access statistics, estimates suggest around 34 million Europeans suffer from energy poverty (EUROSTAT 2018b). Under the European Pillar of Social Rights, access to energy as an essential service should be guaranteed (EPSR 2017). Given the expected socio-demographic development and increases in income inequality in Europe and the associated costs of the energy transition, the share of households experiencing energy poverty are also likely to increase (European Commission, 2013). While recognition for energy poverty is being firmly entrenched at the highest European level through legislative revisions (European Parliament 2018a, 2019) and guidance on how to address energy poverty (European Commission 2020a, 2020c), some Member States, including Germany, do not officially recognise energy poverty as a separate concept affecting households in industrialised countries and in need of specific recognition and targeted policy interventions.

Energy poverty has far-reaching consequences not only for households in terms of health and costs but also for the government in terms of economic output potential and required budget allocations to ensure the welfare of society. A variety of factors contribute to the phenomenon of energy poverty resulting in households in energy poverty or vulnerable to energy poverty. Energy poverty is a dynamic situation meaning that households can move into and out of energy poverty due to, for example, losing a job, facing an unexpectedly large payment, sudden health issues or

[1] The term "fuel poverty" is interchangeable with "energy poverty" and most commonly used in the UK context

needing to care for an ill relative, or even earning more than the threshold for social welfare – which leads to households no longer qualifying for benefits, but not earning enough to be able to sustain a minimum standard of living (Heindl 2014). Unhealthy homes (e.g. as a result of disconnection or insufficient heating – both of which lead to cold indoor climate as well as damp, mouldy homes) are linked to subsequently leading to ill health, such as increased respiratory illnesses, circulatory diseases, mental health and allergies, which left unchecked result in absence from work and a loss of productivity estimated to total 9.8 billion € annually in Europe (Wegener and Fedkenheuer 2016; MARMOT Review 2011; Liddell and Morris 2010; Liddell et al. 2015).

Beyond the socio-economic and health consequences posed by energy poverty, it also has a bearing on the overall energy transition. In this context, energy poverty impacts the *"energy welfare"* of households, which can be compressed to mean the state where households within a just transition are able to meet their household service demands (often driven through direct energy consumption or improved or minimised through indirect energy-related investments, such as energy efficiency upgrades or renewable technologies) at affordable cost. A just transition relates to the equity and fair distribution of costs and benefits in environmental policies (Sovacool et al. 2019; Pye et al. 2019; TUC 2008) and can be assessed through indicators of energy cost burden and levels of investment needed (Pye et al. 2019; Montenegro et al. 2020). While technological improvements have proven to bring multiple benefits in terms of energy improvements and increasing quality of life (IEA 2015), the associated costs of achieving the energy transition objectives can reveal injustices in the legal, financial and procedural channels resulting in negative impacts on vulnerable households and economic sectors affected by a shift away from coal towards renewable energy (Sovacool et al. 2021; Pye et al. 2019; Feenstra et al. 2021). The implications are that while the energy transition requires the active participation from households (and should ensure the ability of households to participate), financial (and other) barriers can prevent the required investments from occurring whereas the climate cannot afford further delays in the upscaling of renewable and energy efficiency measures.

The underlying drivers of energy poverty are multidimensional to include household income, the socio-political system, policy framework, climate, market system, state of the economy as well as social relations (Rademaekers et al. 2016; Middlemiss et al. 2019). Without minimising the recognition for the complexity of the issue and acknowledging that recent discourse calls to broaden the understanding of energy poverty to allow a more comprehensive space to address the multifaceted aspects through qualitative means (Hesselmann and Tirado Herrero 2020; Grossmann and Kahlheber 2017), this thesis will remain with a pragmatic depicted in to simplify the complexity of energy poverty into three main drivers, as illustrated in Figure 2-2 (Pye et al. 2015a).

These main drivers are a combination of high energy bills, low income and poor energy efficiency of the building envelope (Pye et al. 2015a) and corroborated in several studies (Thomson and Snell 2013; EPEE 2009; Schweizer-Ries 2009; Bouzarovski 2011; ACHIEVE 2014; BPIE; Grevisse and Brynart 2011). The overlapping regions highlight areas where indicators for measuring these aspects of energy poverty reside. For example, the type of heating system and share of central heating and the energy efficiency of the building will influence the amount of the energy bill, while a high level of energy consumption will result in higher energy bills, which will negatively affect households with lower income levels. The degree of energy poverty experienced by households will depend on the number and severity of factors affecting the household.

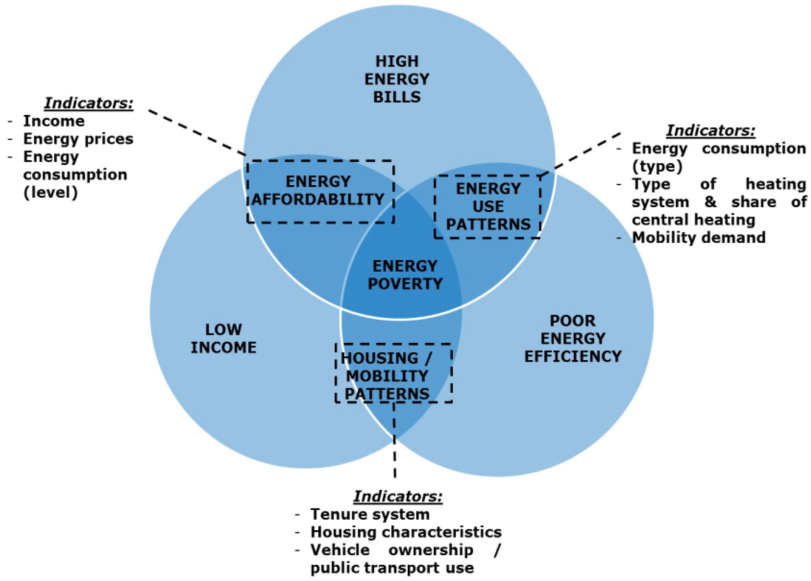

Figure 2-2: Drivers of energy poverty and key indicators
Source: (Pye et al. 2015a)

However, despite the extensive impacts energy poverty presents, there remains a certain resistance to recognising energy poverty as an issue worth addressing in itself (Dobbins et al. 2019; Council of the European Union 2018; EPEE 2009; Thomson 2014). Given these complexities around energy poverty, consensus on a common definition and indicators to measure the impact becomes difficult, without which recognition in the national legislation remains inoperative. The reasons behind the different levels of recognition for energy poverty are manifold. The problem with not addressing energy poverty head-on is that the underlying causes of energy poverty are not specifically tackled through targeted policies and measures thus allowing the consequences to persevere. To date, the dominant practice is to view energy poverty as a subset of poverty and to oblige the social services departments to govern over an area where they do not hold full jurisdiction not adequate budget to cover the often insufficient costs of providing services in the energy sector to vulnerable consumers through welfare benefits (European Parliament 2009a; Pye et al. 2015a). Since energy and climate matters are assumed in other departments, vice versa there is little to no crossover to address energy challenges in lower income households directly. This lack of recognition for the cross-cutting nature of energy poverty means that the mandates and jurisdiction of different departments are performed in silos rather than tackling the same issue across domains (Dobbins et al. 2016; Martiskainen et al. 2021; Feenstra et al. 2021). The ramifications of this also prevails in Germany and represents a challenge to meeting energy and climate objectives.

2.2 The legislative road to recognising, defining and measuring energy poverty

To better understand energy poverty and why it is not recognised in Germany, it is imperative to understand how it has been commonly approached in the EU and other member states. This sub-chapter outlines the legislative challenges around solidifying the concept of energy poverty as separate to that of vulnerable consumers, and highlights the impact on measuring the status and progress on energy poverty in the European and national context.

While addressing overall poverty is deeply entrenched in the objectives and strategies towards the European vision for social inclusion and protection, energy poverty as a distinct concept has only emerged in recent years particularly in light of the transition towards the European internal energy market and the objectives of the Energy Union to ensure adequate protection for vulnerable consumers in the energy sector. The main European legislative driver for addressing energy poverty began under the Third Energy Package on the common rules for the internal electricity and gas markets (European Parliament 2009a, 2009b). This provides the foundation for mandating action on consumer vulnerabilities within the energy markets by focussing on protection and safeguards for vulnerable consumers, but owing to the principle of subsidiarity, freedom is given in terms of how such groups are defined (Pye et al. 2017). As such, the approaches toward addressing energy poverty vary across Member States. Distinctly, very few Member States (UK, Ireland, France, Cyprus, Slovakia) provide explicit recognition for the concept of energy poverty while the definitions for vulnerable consumers in the energy sector vary widely ranging greatly from narrow definitions including, in some instances, only households dependent on a continuous supply of electricity for life support, to broad definitions including all social welfare beneficiaries (Pye et al. 2015a). This lack of recognition for energy poverty on the national policy level has even been shown to risk perpetuating energy poverty because policies fail to address the causes nor integrate the energy poor into the energy transition process (Feenstra et al. 2021).

While these provisions to define the concept of a vulnerable consumer has led to more awareness, the legislation failed to incorporate the cross-sectoral nature of the issue resulting in the tenacious view that the welfare – and therefore also the energy welfare – of consumers should be addressed within the social policy arena (European Commission 2016a). Recent European legislative revisions have rectified the basis for this misconception, yet the lag in widening the responsible policy domains tasked with addressing energy poverty also means a delay in specifically channelling legislation and targets towards addressing energy poverty above overall poverty, with the Dutch government leading the way on developing a White Paper on addressing both energy poverty and the energy transition, thereby recognising and directly addressing two issues which are not in competition with each other (Straver et al. 2020). Figure 2-3 presents the evolution and silos of European-level legislation related to energy poverty. The centre represents the energy poverty-related milestones and dedicated observatory, which is flanked by overlapping legislation with each of the policy areas reserved for vulnerable consumers towards the left and legislation on energy efficiency and buildings towards the right. In this representation, it is clear that addressing energy poverty requires the overlapping of policy domains for effective action.

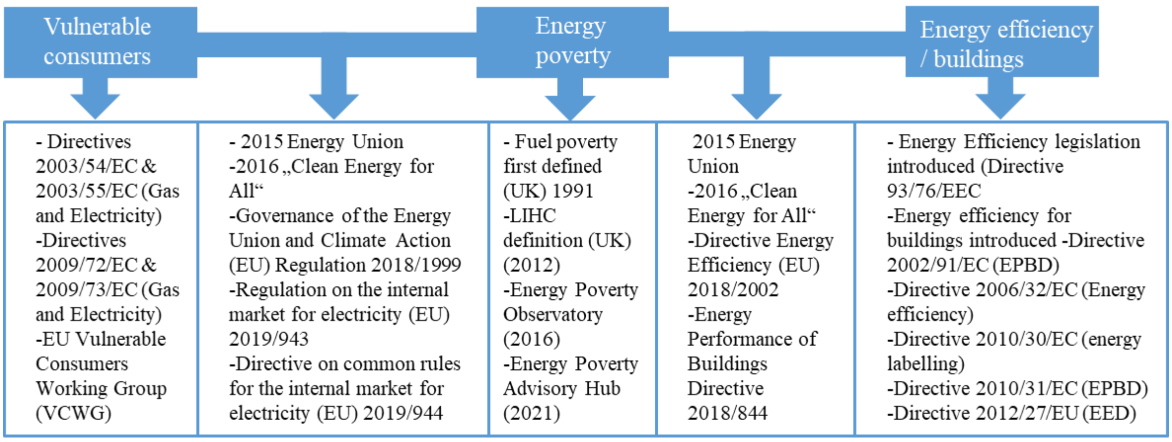

Figure 2-3: Evolution and silos of European legislation related to energy poverty

A further challenge in cementing the concept of energy poverty also arises from the internal energy market directives due to the focus on vulnerable consumers. Energy poverty is interconnected with but distinct from that of vulnerable consumers. The legislation governing the protection of vulnerable consumers in the energy sector also reduces the impacts of energy poverty, but is limited to protection of those defined as vulnerable consumers and only relates to electricity and gas customers. This distinction rules not only the types of consumers that are afforded protection, but also what type of action is taken by whom, as summarised in Table 2-1 (Dobbins et al. 2019).

Table 2-1: Distinction between vulnerable consumers and energy poverty
Source: (Dobbins et al. 2019)

	Vulnerable consumers	**Energy poverty**
Concept	Includes individuals in energy poverty and those at risk, but also a broader group of specific consumers such as recipients of social welfare or those with disability and/or health issues who may be at a disadvantage in the purchasing and use of energy	Commonly understood to describe a situation where individuals or households are not able to adequately heat or purchase other energy services at an affordable price
Energy sources	Focus on electricity and gas, based on legislative requirements (for example, internal energy market directives)	All household energy sources, possibly including for mobility
Timeframe	Shorter-term curative focus on consumer protection and continued access to gas and electricity	Longer-term focus on prevention and addressing the underlying causes, such as poor building efficiency, low incomes and high energy costs
Target group(s)	Specific disadvantaged groups, such as those that receive social welfare or have health and/or disability issues	Lower income households facing energy affordability issues
Implementing agent	Typically the regulator or consumer protection agencies, utilities and government	A broader range of stakeholders such as government, consumer groups and non-governmental organisations, not just regulators and utilities

Vulnerable consumers are defined within the energy markets as requiring additional protection and support as individuals or a group of specific consumers (such as social welfare beneficiaries based on socio-economic criteria such as income, disability, age), and who may be at a disadvantage in the purchasing and use of electricity and/or gas. As such the protective measures centre around ensuring maintaining access to electricity and gas connections, usually through short-term financial support and disconnection prevention. With this focus on the regulated markets, the types of key actors to take this protective action include regulators, consumer protection agencies, utilities and governments. Energy poverty on the other hand goes beyond the energy markets to include all household energy sources and could include mobility. Here the focus is on affordability of energy, but the measures aim at addressing the underlying cause of unaffordability with longer-term support, for example, on improving energy efficiency in buildings and appliances. These measures address the structural issues and therefore involve the competencies from stakeholders in government, consumer groups and the energy industry. There is no common definition for what constitutes a vulnerable consumer, nor is there a common definition for energy poverty, before the issuance of guidelines on how to develop a definition for the European context (European Commission 2020c). Due to these different definitions, a comparison across countries of the situation is not possible, because in the one case a vulnerable consumer is defined as anyone drawing social welfare (comparable to AROPE statistics, e.g. 18.7% of the total population in 2018 in

Germany, representing 15.5 million people (EUROSTAT 2021c)), whereas in another case a vulnerable consumer could be, for example, limited specifically to the elderly at risk of poverty (19% of the elderly population in 2018 in Germany, representing 3.4 million people (EUROSTAT 2021b)).

Similarly, different definitions for energy poverty exist and there is no single agreed definition at the EU level. Grevisse and Brynart (2011) argue that a precise definition and specific indicators allow for quantifying and monitoring of the problem and that without this, progress towards addressing energy poverty will remain stalled as it is not possible to reduce the numbers of people suffering from energy poverty. The continual redefining of the term is problematic as it makes it difficult to compare research, statistics and monitoring of the situation if each Member State or research project defines energy poverty anew. This means that at times the definition will encompass a broader set of fuel types and energy services or be narrow so as to only address specific end-uses such as heating requirements. This fragmented approach and the lack of a common definition has ramifications on selecting indicators and the measurement since an estimation of the extent of energy poverty depends on the definition given. Furthermore, the content of the definitions is often also mixed up by including an indicator thereby causing confusion and resistance to acceptance of the concept (Pye et al. 2015a). This further complicates the comparability because the definition now becomes specific to that particular context. The definition should not include a metric due to the differences in the structure of different systems. For example, taking a comparison of the overall energy system and socio-economic characteristics in Germany and Bulgaria – where in both cases energy poverty is not recognised in policy – we compare the climate, characteristics of energy supply and use, housing condition, type and tenure, state of market liberalisation, energy prices, household income and overall share of households at risk of poverty, in Table 2-2.

Table 2-2: Comparison of structural differences in Germany and Bulgaria
Source: (EUROSTAT 2021a, 2021c; Pye et al. 2015a)

	Germany	Bulgaria
Climate	Moderate	Temperate continental
Energy supply and use	Gas dominant; central heating	Solid fuels, biomass, central heating
Housing condition, type and tenure	Low ownership level, moderate building efficiency	High ownership level, poor building stock condition
State of market liberalisation	Market liberalised	Partial liberalisation
Residential energy prices	High electricity prices, moderate gas prices	Low electricity prices, high gas prices
Avg. household income; % households at risk of poverty	28,534€, 16.1%	10,875€, 23.4%

The national circumstances vary greatly with different starting points (e.g. home ownership, building stock condition, levels of poverty (EUROSTAT 2021c) and unique opportunities for the types of action required and possible (e.g. due to the state of the market liberalisation, energy prices, energy supply and use, household income in 2017 (EUROSTAT 2021a)). As such, the quantifications of “affordable” and “adequate” energy will have distinctive significance in each context. A common definition is, therefore, important as it will delineate the target group and provide a framework for action as well as harmonise a concept across different contexts. Key is to understand the origins and applications of the various terminology, as well as the crucial distinctions between them. Figure 2-4 maps the evolution of the concept of energy poverty as well as highlights the differences to the interrelated terms. Central to the energy transition is the holistic approach to address the targets through sector coupling, and energy poverty is the term that most flexibly allows various policy domains to integrate into their existing activities as it encompasses diverse fuels and wider target group, rather than only electricity or gas, or a pre-defined target group.

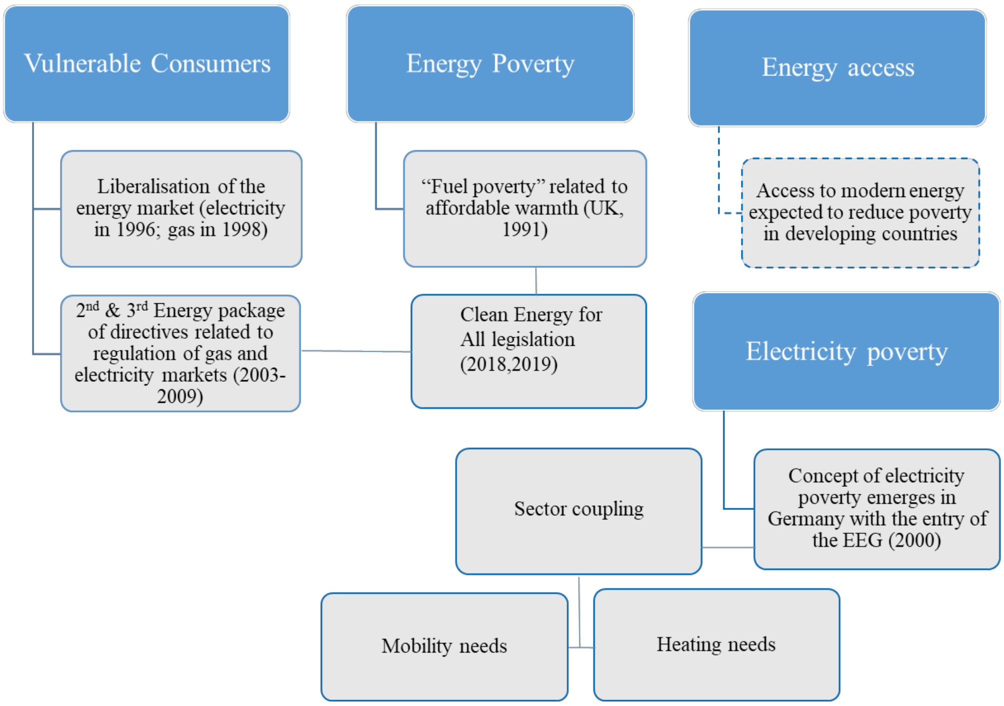

Figure 2-4: Evolution of the concept of energy poverty

Yet, in the absence of a specific definition and since a single indicator cannot capture the complexity of energy poverty, several general indicators are applied to provide some understanding of the status of energy poverty. Without a single metric for energy poverty, several so-called energy poverty proxy indicators are used across research initiatives to assess the situation and draw conclusions about the status of energy poverty (Tirado Herrero 2017; Simcock et al. 2016). These indicators are categorised into primary and secondary indicators, and further categorised as consensual or expenditure based (Thomson and Snell 2013; Thomson et al. 2017; Rademaekers et al. 2016; Thema and Vondung 2020).

The consensual method assesses whether a household is in energy poverty via a survey based approach regarding living conditions and are based on the qualitative statistics such as those collected through the Eurostat Survey on Income and Living Conditions (EU-SILC), e.g. ability to keep warm, arrears on utility bills (EUROSTAT 2018b; Thomson and Bouzarovski 2018; Thema and Vondung 2020). While the consensual method offers a standardised pan European basis, the expenditure method is usually more relevant for the national context although it cannot be compared directly across Member States. Expenditure-based indicators are also included in the primary energy poverty indicators and measure 1) the low absolute energy expenditure (households spending less than half the median energy expenditure (M/2), which reveals a hidden energy poverty with households likely suppressing demand), and 2) the share of households spending twice the median expenditure on energy (2M). Limitations of expenditure-based indicators means simplifying the measurement to only issues of affordability, but on the other hand enable the operationalisation of an indicator. The value of expenditure also does not capture the condition of the building stock and the potential of suppressed demand, thereby repressing the actual number of households potentially affected (Thema and Vondung 2021). While none of these metrics stand alone to measure energy poverty since they result from various drivers, taken together a picture of energy poverty begins to form (Rademaekers et al. 2016; Pye et al. 2015a). While these types of indicators can more easily be operationalised, they cannot contextualise the lived experience, and such qualitative evidence should be coupled to quantitative evidence to provide deeper insights into the experience of energy poverty and the respective capabilities of different people (Middlemiss et al. 2020b; Middlemiss et al. 2019).

These definitions and indicators have a decided impact on assessing the vulnerabilities in the energy system. Within the energy transition, households experiencing or at risk of poverty face disproportionately high costs to keep comfortably warm and have limited financial scope for addressing the issue (e.g. through energy efficiency upgrades to buildings or appliances). The objectives of the energy transition are to ensure a secure, affordable, consumer-friendly, efficient and environmentally-friendly energy system. Monitoring of the energy transition in relation to energy poverty typically unfolds around the affordability of energy consumption, which is limited in capturing the wider social drivers of the energy welfare of households and the impact of changes in the underlying energy structures. Policies to address household energy vulnerabilities can be shaped around the drivers of income, energy costs and energy requirements to monitor and illicit changes in energy prices, investment requirements and other socio-economic trends (Pye et al. 2019). However, current monitoring efforts on the energy transition, e.g. in Germany (BNetzA 2019) or in Europe (EUROSTAT 2010), typically only cover the end-user expenditures on energy and discount the investments made for indirect energy consumption, i.e. energy efficiency. An economic modelling of the impact of energy efficiency concluded that fuel subsidies (which are generally provided as the main means to counter energy poverty) are less cost-effective than investments into home energy efficiency (NICE 2015). This indicates that short-term solutions such as bill support are only one part of ensuring households can pay their bills and should be complemented with additional longer-term solutions. Therefore, expanding monitoring for the energy transition and energy poverty in quantitative terms should include expenditure on energy *and* investments to better measure the changes in the energy welfare of households within the context of the energy transition.

2.3 Policies and measures to address energy poverty

The approach taken to design policies and measures is directly related to the definitions and identification of the target groups. This sub-chapter reviews the role of policies and the types of measures applied to address energy poverty.

European legislation directs member states to develop National Climate and Energy Plans (NECPs) and, within them, to specify action plans to reduce the households affected by energy poverty *if* a significant share is affected (European Parliament 2019, 2018c). While these obligates member states to define and address energy poverty within energy transition objectives, opposition to integrating two policy domains remains. The common policy approach to addressing energy poverty is through the social welfare system, which is driven from the national level. Yet with vulnerabilities in the energy sector typically defined as a social issue related to general poverty on the national level (Bouzarovski et al. 2021), the policies are designed in silos under the associated mandate with limitations in jurisdiction (e.g. social departments cannot influence the energy policy and interconnected measures) (Dobbins et al. 2019; Feenstra et al. 2021). This approach, led by social policy, views vulnerability as an issue of low income (i.e. poverty) and not interconnected with energy issues and therefore not as an issue in itself is prevalent in Scandinavian and northern European countries (including the Netherlands, Germany and Poland) as well as a few eastern European countries (such as Bulgaria, Czech Republic and Croatia). These countries exhibit relatively low rates of overall poverty and therefore remain warranted in their approach to not explicitly identify strategies to address energy poverty within their NECPs as is required by the European legislation (European Parliament 2018c; Bouzarovski et al. 2021). Countries such as Portugal, France or Spain view the issue through energy policy but identifying the social roots, with Spain transposing the European legislation with a national policy framework to explicitly quantify, monitor and develop action to reduce the situation (Feenstra et al. 2021).

The integration of both the social and energy policy silos is the most comprehensive approach, and crucial in addressing energy poverty is that the policy approach taken will define the types of measures implemented (Pye et al. 2017). Policies under social welfare are focused on short-term, curative action that facilitates bill payment and disconnection protection either through 1) increasing the financial ability of households or reducing energy prices (social tariffs), or 2) reducing energy consumption, as depicted in Figure 2-5 (Pye et al. 2015a; Kerr et al. 2019). The policies and measures in the first category are typically those developed under the auspices of addressing the needs of those defined as vulnerable consumers within the energy sector and include financial support and consumer protection, while the measures in the second category are largely those aiming to address energy poverty and include information and awareness, and energy efficiency (Pye et al. 2015a). A summary of these four measures is provided in the following sections, while a broader elaboration of these measures in the German context can be found in Appendix A.2.

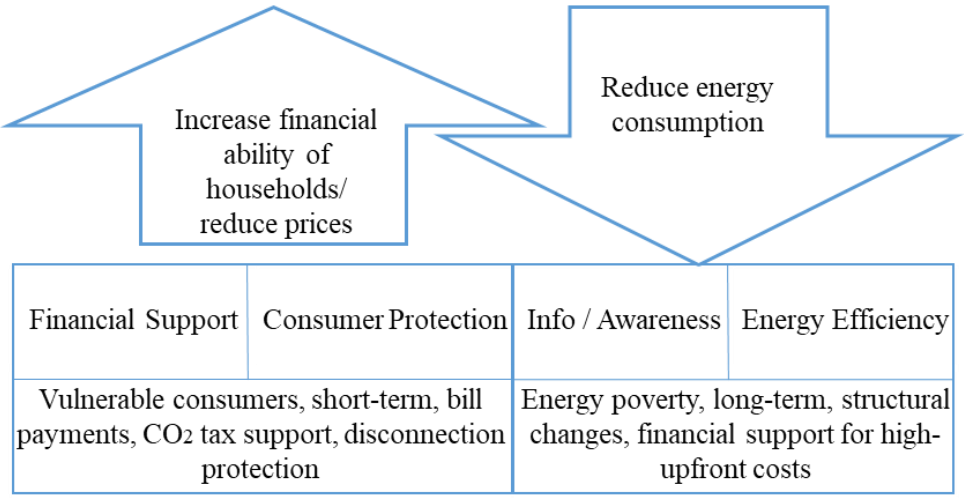

Figure 2-5: Summary of types of measures to tackle energy vulnerabilities
Source: own graph based on (Pye et al. 2015a)

2.3.1 Financial support

Financial interventions centre on direct support for bill payments. This type of financial support is critical for short-term support and usually dispensed through the social welfare system. This measure is relatively easy to distribute to beneficiaries defined in the social welfare system and is one of the main support mechanism to vulnerable consumers in around 75% of member states. Other examples include: direct social support, energy subsidies and payments, targeted energy subsidies and payments (e.g. elderly), social tariffs, or a negotiated tariff with the utility. Direct financial support alone is insufficient to address the underlying causes of vulnerabilities in the energy sector, but coupled with measures such as energy efficiency, can be particularly effective (Dobbins et al. 2016; Dobbins et al. 2019; Pye et al. 2015a; Feenstra et al. 2021; Pye et al. 2017).

2.3.2 Consumer protection

Ensuring that the regulated markets operate smoothly and without disadvantaging vulnerable consumers has required provisions of measures to guarantee vulnerable consumers can maintain access. While regulated prices in the form of social tariffs had been a part of the European market, the liberalised markets should phase these out to avoid market distortion and reflect the true costs of energy provision and drive competition in the supply sector (European Commission 2016c). At the same time, infrastructure charges are distributed to consumers and these can sometimes negatively affect some consumers (Sunderland et al. 2020). The types of measures aimed at consumer protection focus on vulnerable consumer protection, and are dominated by disconnection protection. This category also has the most diverse set of measures including such a code of conduct for suppliers, billing information, debt protection and consumer advice and are primarily coordinated by regulators and energy supply companies (Pye et al. 2015a; Dobbins et al. 2016; Pye et al. 2017).

2.3.3 Information and awareness

Information provision and raising awareness are the foundations for improving the understanding of consumer rights and information on market tariffs and include measures related to national advice organisations, price comparison, transparent billing, and advice campaigns. Civil society organisations play a key role in creating awareness for vulnerable households on options, but also on driving issues up the political agenda, both of which are important to underpin recognition and understanding of energy poverty issues (Pye et al. 2017).

2.3.4 Energy efficiency

Energy efficiency measures, particularly those focusing on building retrofit, are a key part of a strategy to address energy poverty. The majority of these types of measures reviewed relate to building retrofit measures, but only a third of these are targeted on low income households. There is considerable scope for increased targeting of such measures, although this requires an understanding of which are the energy-poor households, so a need for improved data (Pye et al. 2015a).

The majority of energy efficiency efforts directed towards energy-poor households are therefore typically aimed at appliance upgrades, since inefficient appliances directly contribute to increased incidence of energy poverty and circumvent the complexity of integrating measures into rental properties (Feenstra et al. 2021; Pye et al. 2015a). One example of this type of effort is the “Energy Savings Check” (Stromsparcheck) in Germany. By 2015, this initiative trained 4,200 long-term unemployed people to become energy consultants who provide other lower income households with a free energy consultation and advice about energy saving behaviour and some simple energy efficiency interventions, such as energy efficient light bulbs and low-flow showerheads to a value of 70€ per household. Each household was able to save on average 149€ annually on electricity and water costs. Where a refrigerator was included, the average savings increased to 245€ per household annually. Over the lifetime of the installations, total savings of 1,070€ per household can be achieved, while for all households this figure is around 136 million Euros. National governments are able to save about 18 million Euros and regional governments save about 22 million Euros. Per “Energy Savings Check”, the regional government saves about 135€ and the federal government saves 113€, and overall the public sector saves 248€ per household as shown in Figure 2-6 (Caritas 2015).

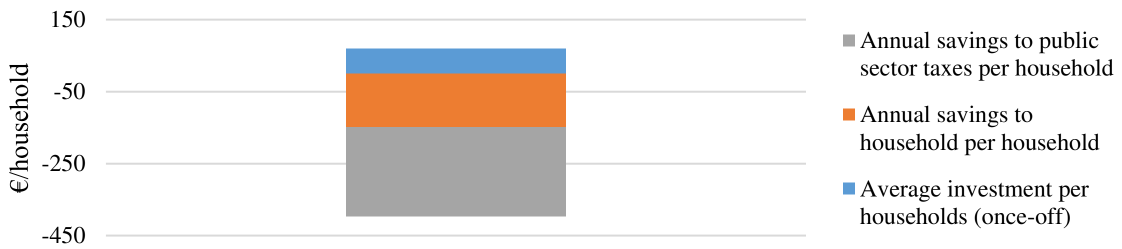

Figure 2-6: Annual savings per household through an "Energy Savings Check"
Source: own graph based on (Caritas 2015)

These are substantial savings given that a qualifying household at the time only received 28.12€ per month to cover electricity needs – an amount that had not been increased due to inflation and which was subsequently shown to be almost 14€ too little to cover the electricity needs of a household – and is the basis for the increase in financial support (Spiegel 2013; Aigeltinger et al. 2015). A similar project was undertaken through the sister project where similar results were attained in other European countries, attesting to the universal transferability of this best practice measure (ACHIEVE 2014). Additional detail on the "Energy Savings Check" is given in Appendix A.2.1.

While these kinds of initiatives have positive impacts to households and savings to the public budget, the greatest impact on increasing energy efficiency is in buildings. However, reaching the lower income household segment outside of the social housing sector is difficult because it requires a deeper understanding of the building stock and specifically which are the energy-poor households and several studies aim to improve the targeting of retrofit initiatives (Walker et al. 2014; Preston et al. 2014). Energy efficiency policies can also have unintended consequences, especially in the rental sector where conflicts arise from gentrification and increased housing costs which are passed onto the tenants in full (Grossmann and Kahlheber 2017; Grossmann 2019). By not addressing energy efficiency and energy poverty holistically, there is a lack of integration across policy domains which can lead to negative consequences and an unjust energy transition.

2.3.5 National policy to local action

As previously described, the definition for energy poverty provides the basis for identifying, measuring and monitoring the numbers of affected households. Equally, the share of households impacted by an issue will also give rise to the types of measures required and the financial resource volume necessary. If the definition at the national level is too broad, the funds may be diluted, whereas if the definition is too narrow it risks missing the opportunity to take meaningful action across several policy domains to address energy poverty and the energy transition holistically. The allocation of the responsibility to address energy poverty and the required budget can be complex if a common understanding is not achieved. A national policy dedicated to integrating energy poverty into the energy transition is proposed in the case of the Netherlands, which builds on consensus gained through a stakeholder engagement process (Feenstra et al. 2021). In Spain, a Royal Decree directed the development of an energy poverty strategy in 2018, which was developed through a public consultation process (Barella 2020).

It is the responsibility of the local or regional governments to disburse support to qualifying households, which can limit the effectiveness due to a lack of sufficient funding to support activities (Feenstra et al. 2021). While a national level framework is key to ensuring recognition for the issue and sufficient resources can be dedicated to the implementation of meaningful measures, the functions at the lower levels of government will ultimately decide the success of initiatives due to their enhanced capabilities to identify and target the appropriate beneficiaries (Straver et al. 2020).

The advantage of consolidating a national framework is that the fragmented approaches from the bottom-up can be unified, with support given to promising initiatives. Similar to the principle of subsidiarity for EU policy to member states, so should energy poverty policies devolve to support local government in their integration and involvement of various departments as well as the implementation of effective measures. In addition to the vertical integration of energy poverty from national to local government, equally essential is the horizontal integration across different departments to coordinate efforts and to counter the common siloed approach to achieving goals and fulfilling responsibilities (Feenstra et al. 2021). Further examples of horizontal governmental collaboration are given at the end of Chapter 2.4 to support the argument in the German context.

2.4 Energy poverty and vulnerable consumers in Germany

It has been estimated that approximately 11-21% of the German population is vulnerable to or experiences energy poverty, which signifies a considerable share of the population (Pye et al. 2015a; Bleckmann et al. 2016; Heindl 2014; Pye et al. 2015b). However, despite these estimates, energy poverty remains a contentious issue in German politics where the resolute position remains to not recognise energy poverty as requiring attention separate from efforts to address overall poverty and is therefore neither defined nor measured (Schultz 2018; Heindl 2014; Bundestag 2017). This sub-chapter explores the status of and response to energy poverty in Germany.

The Netherlands have recently developed a dedicated White Paper on energy poverty opening an opportunity for Germany to learn from their experiences (Straver et al. 2020). Similar to Germany, there is a lack of recognition for energy poverty with the national government approach to focus efforts on alleviating overall poverty rather than energy poverty, and that this should be addressed through social policy rather than energy policy, and that the social welfare system is sufficient in addressing the needs of the population (Feenstra et al. 2021). Each country neglected to provide a dedicated assessment on energy poverty in their NECPs, with the Netherlands incorporating an update on local studies undertaken in their final plans (Feenstra et al. 2021), but with Germany reiterating only their stance to support hardships through the social welfare system deemed as adequate in providing affordable energy (BMWi 2020a). Both the Netherlands and Germany have relatively low incidence on the consensual indicators, i.e. 2.2% and 2.7% of the national population have an inability to keep comfortably warm in 2018, respectively (EPOV 2021). Both governments have also faced pressure from other political parties to address energy poverty concerns with motions filed for the implementation of energy poverty alleviation measures in the Netherlands (Straver et al. 2020) and with requests for a definition, data and status on the situation in Germany (Bundestag 2014, 2012, 2017) – with both efforts rejected. The Netherlands, however, is poised to harness the momentum from the White Paper to address the non-conflicting objectives to integrate energy poverty into the movement for a just energy transition strategy, recognising that planning for the future is in the interest of achieving the overarching objectives for social and energy policy (Feenstra et al. 2021).

The discourse on energy poverty in Germany has chiefly arisen as a result of the energy transition and the corresponding increasing electricity prices. Generally, Germany's approach to address energy poverty alleviation and prevention strategies through their social policies is considered as substantial as the objective is to address poverty as a whole (BMWi 2012). However, this approach has been criticised as insufficient with the lack of an official definition for energy poverty is deemed the missing starting point to assessing the impact and taking action against a growing problem (Schuldzinski et al. 2014; Tews 2013; Tews 2014). Regardless of the broad-based social system, households are not able to maintain affordability and therefore access to a supply of energy to meet their basic needs. Although disconnections are tightly controlled through legislation, more than 296,000 households (representing 0.6% of household electricity customers) were unable to pay their electricity bills and over 43,000 unable to pay their gas bills and were consequently cut off from services in 2018 (BNetzA 2019) despite the support options available to customers in arrears (BMWi 2020b). However, it should be noted that any measures provided to protect against disconnections through the state are aimed only at those households within the social welfare system and no socio-economic data is collected to characterise households affected by disconnections (e.g. by income group, household composition (e.g. children, elderly)), nor the length of the disconnection (e.g. days, weeks), but it is reported that 18% of disconnections recur in the same customer (BNetzA 2019). The share of electricity customers affected by disconnections decreased from 0.8% in 2014 to 0.6% in 2018, and to put this into perspective a comparison of disconnection rates across other selected European countries in 2014 is undertaken in Figure 2-7 (Dobbins et al. 2016; ACER 2015). With the exception of several member states with lower household incomes and higher incidence of overall poverty (e.g. Portugal, Italy, Spain, Poland, etc.), the remainder of the countries average 0.6% of the share of electricity customers disconnected indicating that the share of affected households is on par with equivalent countries, and not particularly low as is implied in the national reporting on energy poverty and why it is sufficiently addressed (BMWi 2020b).

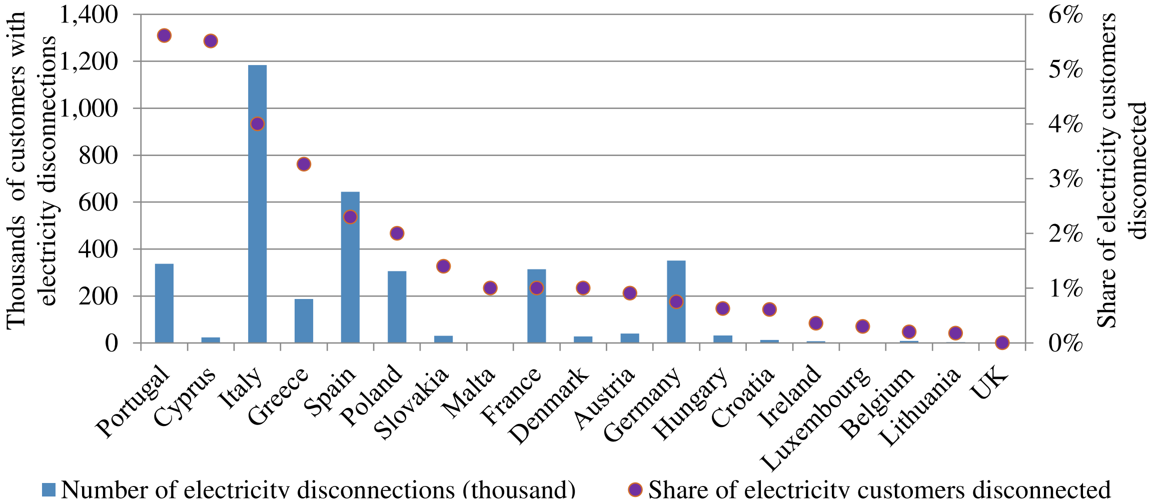

Figure 2-7: Numbers and shares of disconnected electricity customers in selected European countries, 2014

Source: own graph based on (ACER 2015; Dobbins et al. 2016)

Despite the resolute national governmental position refuting the need to address energy poverty explicitly in Germany as it is not accommodated under constitutional provisions (BMWi 2020b), there is evidence that energy poverty does indeed affect households in Germany with the existence of programmes driven by provincial and local government and other agencies. Looking at the causes and consequences of energy poverty and how these may affect households in Germany, the triad reveals that Germany has one of the highest energy prices in Europe, income levels have not increased as quickly as energy prices and energy efficiency implementation in the household sector remain low.

As energy poverty is not officially recognised in Germany, there are no official statistics to describe the state of energy poverty and those reported on the European level are deemed to be statistical without reference to the individual needs (BMWi 2020b). Taking the European primary energy poverty indicators and reviewing the possible severity and extent of energy poverty in Germany reflects that while the severity may be low in comparison to the EU average for arrears on utility bills and inability to keep comfortably warm, the two indicators on share of national population with expenditure on energy more than twice the median and those with expenditure less than half the median are higher than the EU average and ranks 7th in the EU overall, as shown in the upper graph in Figure 2-8. However, taking the national population of Germany affected as the total share of the European population affected reveals that the extent of energy poverty is experienced in Germany with Germany ranking third for the consensual indicators and first for the expenditure indicators.

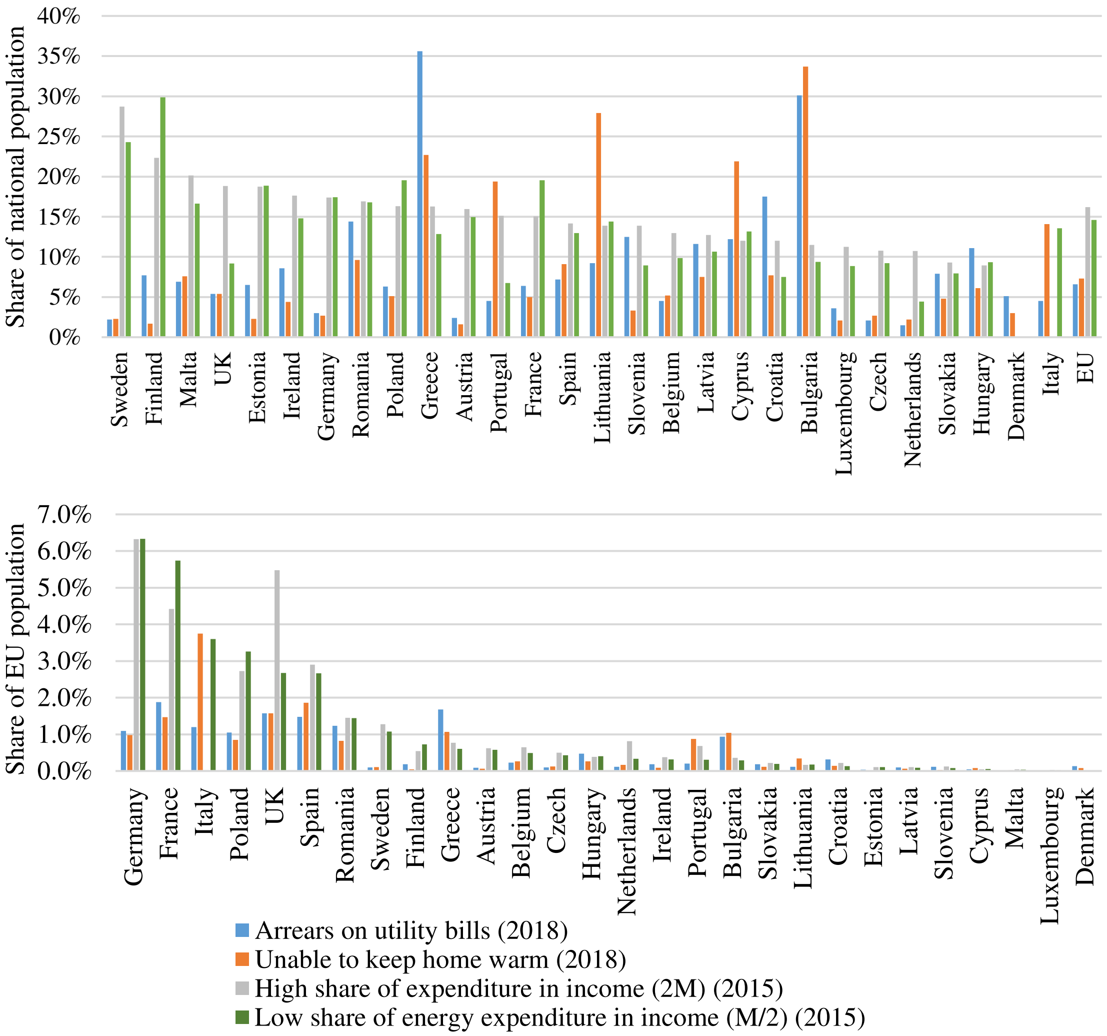

Figure 2-8: Severity (share of national population, upper graph) and extent (share of EU population affected, lower graph) of energy poverty in Germany in an EU comparison, sorted by share of expenditure (M/2)

Source: (EUROSTAT 2018b, 2018a; EPOV 2021)

Heindl (2014) provided a review of common energy poverty measurements and applied them to the German context, which showed great differences depending on which indicator was taken and emphasised that any indicator taken could be deemed as arbitrary since the line must be drawn somewhere, but that the chosen measurement is decisive in the resulting energy poverty assessments (cf. Table A-2 in Appendix A). However, this assessment showed a range between 2.4 – 29.8% of the population experiencing energy poverty, pointing to the necessity to arrive at a definition and identify the appropriate indicators so that the actual status and progress of energy poverty can be monitored, as prescribed by European legislation.

Since energy poverty is such a multifaceted issue, the jurisdiction for the various components contributing to households' vulnerability to energy poverty falls under several different government departments and thus would require a collaboration to holistically address energy poverty, as depicted in Figure 2-9 and elaborated in Table A-4 in Appendix A. For example, energy-related issues around energy use and emissions, the building stock, access, transport, and affordability (of energy) are distributed across five different ministries, while other aspects around health issues as a result of harmful housing spans two ministries and the legal responsibility for addressing poverty in Germany resides with the Ministry of Labour and Social Affairs. Consultation processes, such as "round tables" offer a chance to bring different stakeholders together to reflect on a specific issue and work through barriers and opportunities to acknowledge and incorporate aspects of energy poverty into their ongoing policy agendas and, crucially, collaborating with other departments where goals and activities overlap.

Figure 2-9: Jurisdictional relationship to energy poverty by government department

For example, financed by the Ministry for the Environment, Nature Conservation and Nuclear Safety and the German Environment Agency, a high-level exchange between experts in Germany and Poland discussed measures to reduce both energy poverty and air pollution (adelphi 2017). The very positive lessons from the experiences derived through this interministerial working group could translate to establishing a platform for the different, relevant ministries to coordinate and agree a definition on energy poverty and the applicable data to determine and monitor affected households, as well as strategies to tackle the negative impacts of energy poverty. Established in 2012, a regional working group on energy poverty based in the regional government in North-Rhine Westphalia brings together stakeholders from regional government, city, energy utilities, social organisations and research to discuss and develop strategies to support energy utilities on preventing disconnections and mitigating the negative effects of energy poverty (MWIDE-NRW 2012). International initiatives, such as the Energy Poverty Observatory as a platform to exchange on information and showcase projects around energy poverty, have progressed beyond the European body to replications in Italy, Spain and Finland. Organisations, such as the Covenant of Mayors, also work together with local governments to develop strategies and implement measures on energy poverty from the bottom-up (Covenant of Mayors 2021). Both of these initiatives offer replicability in the German context and allow the possibility to build on existing frameworks. The energy transition and climate-related initiatives are already integrated into the mandates for the majority of ministries in Germany irrespective of their main function, and similar to the process unfolding in the Netherlands, energy poverty should be included in these initiatives as part and parcel of the just energy transition process.

Failing to understand the consequences of addressing vulnerabilities in the energy sector through the vulnerable consumer lens means that Germany is undermining efforts towards achieving their energy transition objectives. The reasoning is threefold: by continuing to provide only bill support to households struggling financially, the problem is not resolved but perpetuated, 1) an opportunity to diversify the types of measures implemented and harness the energy efficiency potential inherent in the lower income building sector is relinquished, and 2) subsidising fossil fuel consumption directly excludes lower income households from participating in the shift towards a decarbonised future as is required, and 3) subsidising fossil fuel consumption is in contradiction to the objectives of the energy transition to shift away from fossil fuels.

2.5 Conclusion: Energy poverty as a key barrier (and opportunity) to achieving the objectives of the energy transition

Energy poverty presents itself as both a challenge and an opportunity within the energy transition process. Access to energy is a right enshrined in the European Pillar of Social Rights and affordability is a pillar in the energy transition. The objectives of the energy transition aim to reduce the impacts of climate change by decarbonising the way we produce and consume energy. While this transformation is expected to result in more affordable energy to consumers in the long-run, in the short-term this will require the mobilisation of capital to fund the investment costs towards increasing energy efficiency and renewable energy. Lower income households are not able to cope with demand for the high upfront costs of these investments and risk being left behind. The principles behind a just transition include a fair distribution of the costs and benefits.

Energy poverty results not only in a lack of access to energy due to affordability issues (and resulting disconnections) but also has far-reaching consequences impacting the wider economy and health and livelihood of individuals, households and communities. Despite an increased momentum to recognise and address energy poverty on the EU level, energy poverty is not recognised nor tackled directly through policies or initiatives across the majority of member states in the EU, including Germany. By addressing energy poverty directly, the adverse impacts on health associated with an inadequate supply of energy, can be targeted. There remains a political position to not address energy poverty outside of the social welfare framework of addressing overall poverty. While there is a discourse on whether a common definition is needed to ensure action is taken with one side arguing that a lack of definition makes it more difficult to mobilise policy and action, and the other side (mostly on the local level) declaring that activities will occur regardless of what happens on the national policy level. While both perspectives can both drive and hinder progress, a clear definition provides a common ground and on the national level will support the integration of energy poverty into the diverse pillars of government where the issue is not readily recognised and, crucially, will enable the distribution of mandates and funding to address the issue comprehensively.

The evolution of the concept of energy poverty in the European context is crucial to understand going forward towards a just energy transition. Energy poverty and vulnerable consumers are distinct but linked issues. Linked to the internal energy market, vulnerable consumers are those disadvantaged in the regulated electricity and gas markets and are commonly defined along socio-economic circumstances associated to social welfare beneficiaries. The energy transition is, however, not only an electricity transition – it encompasses all fuels and relates a complex integration of measures and activities across all sectors and actors. Similarly, energy poverty encompasses a broad range of fuels and relates the affordability and dependencies of households on specific fuels. Policies and measures to address energy poverty can support both the energy transition and improve the energy welfare of households. Currently, the main measure to support households struggling financially is through bill support, however, the drawback with the dependence on financial support as the main measure to counter energy vulnerabilities in households is that it does not address the underlying cause (lack of energy efficiency) and continues to fund the status quo for the consumption of fossil fuels, which goes against the energy transition targets. The more sensible approach would be to share the available funding to support acute needs in addition to financing energy efficiency because this supports not only households' immediate needs but also the objectives of the energy transition – goals which are not in competition to each other.

However, policies designed within the energy transition process without regard for the impact on the energy welfare of households can have adverse consequences for the most vulnerable. For example, while the carbon tax aims to incentivise a shift towards energy efficiency and renewable energy, lower income households do not have the financial means nor the decision-making capacity (as tenants) to make the high-cost investments required in order to achieve the decarbonisation targets; and, if the cost burden to households outside of the social welfare sphere is not acknowledged, the costs of investments in the rental sector could be passed onto directly to the tenant. If the role income plays is not explicitly considered in the planning process of the energy transition, then different recommendations will be made about the best way to achieve the targets and energy poverty could be exacerbated as households are left behind. The energy transition shifts the problem of energy consumption costs towards energy investment costs, and bill support is an antiquated response to a dynamic shift in the energy system, which demands flexible solutions. The COVID-19 pandemic has magnified existing inequalities and revealed the need to take action now to reverse and not entrench the damages. As the energy transition takes off, the time to act is now, by including participation from all government departments. New policies and strategies are being developed and we should not overlook the opportunity to take action now to formulate just policies that will not only meet the objectives of the energy transition but also ensure that no one is left behind. There are discussions on the EU level about setting a 2030 target of zero energy poverty and in view of the expected increasing energy consumption and the accompanying emissions as governments pour funding towards economic recovery from the COVID-19 pandemic means that we should ensure that any action taken does not further lock-in households or the energy system towards maintaining the status quo or even going backwards. There are opportunities to guide the path taken in the energy transition and if we base planning on averaged households this opportunity will be missed to improve the energy welfare of households while achieving the energy transition targets at the same time. This thesis contributes to the current policy direction in Germany by acknowledging the perceived cross-roads to addressing energy poverty or the energy transition. The differentiated situation of households must be considered in order to understand the impact of energy poverty on the energy transition and vice versa. If the differentiated situation is not considered, then the types of solutions explored may be inadequate. Therefore it will be necessary to develop an appropriate method to undertake this assessment and this thesis maps out a methodology towards recognising and integrating consideration for both holistically to account for the differentiated situation of households within the context of the energy transition.

"All animals are equal, but some animals are more equal than others."

George Orwell, Animal Farm, 1945 (1903-1950)

3 Characterisation of household energy consumption

This chapter reviews and characterises household energy consumption as it relates to the overall German energy system where the main objective is to develop a basis for the disaggregated assessment of households within the context of energy poverty and the energy transition. An overview of the energy transition in Germany and the role of households is given in Chapter 3.1 including a summary of the energy policies and measures influencing household energy consumption and a synopsis of the drivers of investment decision-making and consumption behaviour in households as the key parameter driving (and encumbering) the energy transition. As the main objective of this thesis is to show the impact of energy poverty on the investment and consumption patterns of various households and highlight the need to incorporate consideration for these variations to ensure all households have the opportunity to participate in the achievement of the objectives of the energy transition, the population is disaggregated into profiles to represent these different behaviours within an energy system analysis according to various demand drivers, as described in Chapter 3.2. Chapter 3.3 details the final baseline of the energy consumption by these disaggregated profiles. The chapter concludes in Chapter 3.4 with a summary and way forward for the further analysis to be undertaken in the modelling assessment (Chapter 4).

3.1 The energy transition in Germany and the role of households

Embedded in the European energy policy direction, it is becoming increasingly evident that without the active participation of households, the ambitious renewable energy and energy efficiency targets of the energy transition will remain unattainable. The energy transition is driven by the need to address climate change with the objective of reducing greenhouse gas emissions and guided by the Energy Union under five overarching dimensions: i) decarbonisation, ii) energy efficiency, iii) energy security, iv) internal energy market, and v) research, innovation and competitiveness. The Paris Agreement aims to keep global warming well below 2°C, resulting in political long-term decarbonisation targets agreed on the EU level to reduce greenhouse gas emissions by 55% by 2030 in order to achieve carbon neutrality by the half century (European Commission 2020d).

On the German level, this is underpinned by the political aim to restructure the energy supply sector and the goal to decommission the use of nuclear energy and phase out coal. Strategically this leads to the objectives to increase the shares of renewables and energy efficiency while ensuring affordability, reliability of supply and environmental soundness within the energy transition (Bundesregierung 2010). Overarching steering goals to achieve the energy transition are then divided into different sectors: heating (*Wärmewende*), transport (*Verkehrswende*), electricity (*Stromwende*) (BMWi 2020a). Heating demands from the household sector lead to shifts in the electricity sector through appliance use and self-generation, as well as to the transport sector through mobility needs. Expected participation is reinforced through specific targets, as described in Chapter 1.3, and specific measures further described in Chapter 3.1.1. The demands of the energy system and the integration of various components aimed at achieving the energy transition objectives is transforming rapidly as different sectors and actors seek to find their footing, including defining strategies for sector-specific solutions, cross-sectoral sector coupling, digitalisation, national and local stakeholders, and financing mechanisms. While there is a general consensus that efforts need to be stepped up, with the higher climate targets set for 2030 it means that action will need to be taken more rapidly (BMU 2019b).

Consumers at the heart of the energy transition are key to unlocking the potential to achieve energy and climate change targets in Germany. Households in Germany have a significant role to play in ensuring the success of the energy transition since, in 2018, this sector is directly responsible for 27.5% of the total final energy consumption (8,416.9 PJ), corresponding to about 10% of the overall, direct greenhouse gas emissions (905 Mt CO_2-eq) as shown in Figure 3-1 (BMU 2019b; AGEB 2019; BMWi 2021; BMU 2018). The emissions attributed to households include the direct consumption without the emissions produced to supply the consumed electricity and district heating, which are typically allocated to the producer in emission balances (BMU 2021). Including these indirect emissions would double the share of emissions attributed to the household sector thereby amplifying the significance of this sector's role in the energy transition (BMU 2021).

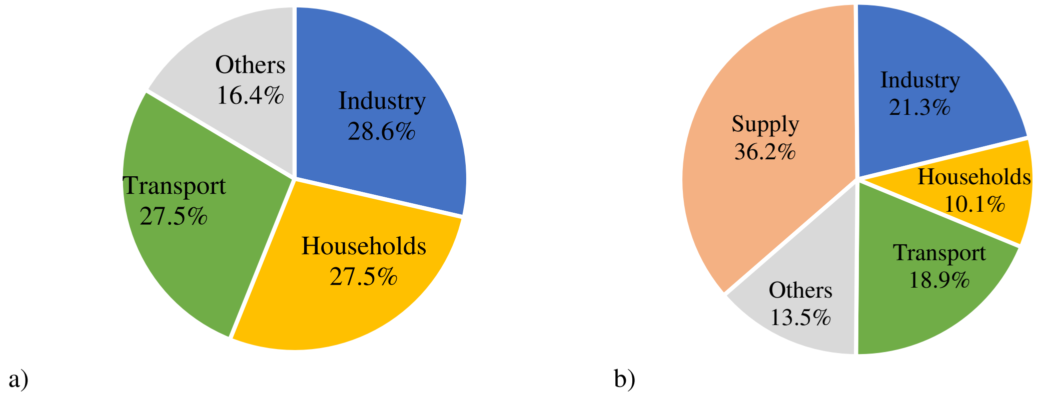

Figure 3-1: Final energy consumption (a) and emissions (b) by sector in Germany, 2018
Source: (BMU 2018, 2019b; BMWi 2021; AGEB 2019)

Household energy demands are categorised by the energy services they provide, lending credence to the fact that it is the services (outcome of energy) that are important to people and not the energy itself (Day et al. 2016), while the energy is more important to the greater system. The majority of household energy demand goes towards space heating (67.7%) and water heating (16%) and is met largely with fossil fuels, such as gas (39.7%) and oil (18.2%), plus electricity (19.7%), as reflected in Figure 3-2.

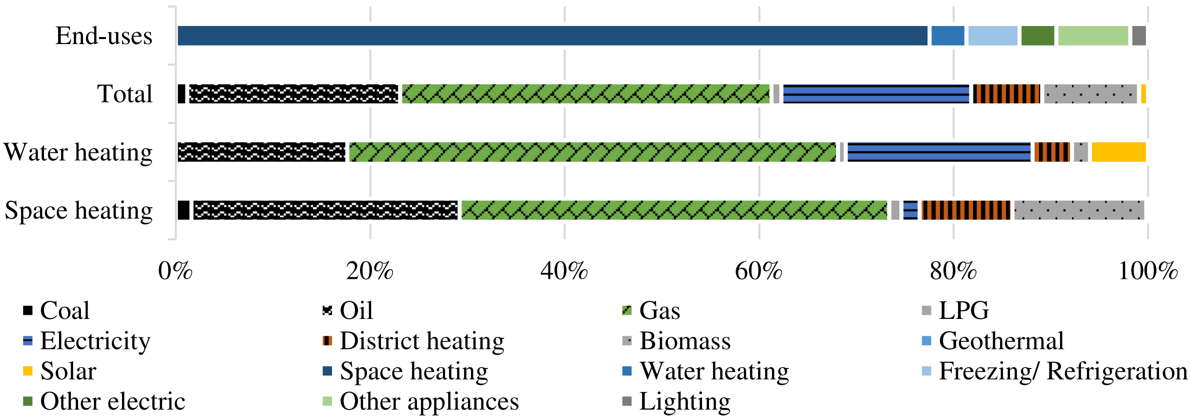

Figure 3-2: Shares of final energy consumption for the household sector by end-use, and end-use by fuel type in Germany, 2018
Source: based on (BMWi 2021)

This energy consumption structure highlights the significant shifts (and investments) that will be required in order to bring about the transformation in the types of fuels consumed by the household sector. Thus, the energy transition must overcome certain hurdles around the mobilisation of capital in the private sector, as was introduced in Chapter 1.3, and the inclusion of differentiated opportunities for the range of actors within the household sector. Current methods to explore meeting the targets and inform policies and the definition of measures are often based on modelling assessments which do not represent the socio-economic heterogeneity in the household sector (BMU 2019b). Monitoring benchmarks are calculated for average households which discounts the impact of the diversity within this sector regarding acceptance, preferences, access, affordability, opportunities (BNetzA 2019). This type of simplification of analyses based on averaged actor groups could lead to erroneous conclusions about the cost-optimal perspective of the types of technologies required to achieve specific targets and does not account for the affordability of specific actor groups.

The purpose of this thesis is to develop a methodology that is equipped to understand the role of energy poverty from the household perspective within the energy system perspective and so there is a need to obtain an overview of the variated energy consumption patterns of households, including those experiencing, or vulnerable to, energy poverty, as well as of how policies enable or pose barriers to the capabilities of all households to participate in the energy transition.

3.1.1 Overview of policies and measures influencing household energy demand

In order to achieve the objectives of the energy transition and incentivise behaviour change regarding consumption and mobilise capital towards investments, strategies are developed with the purpose of stimulating transformation in the three key areas of electricity, heating and transport, within the overall strategic direction introduced in Chapter 3.1 as depicted in Figure 3-3.

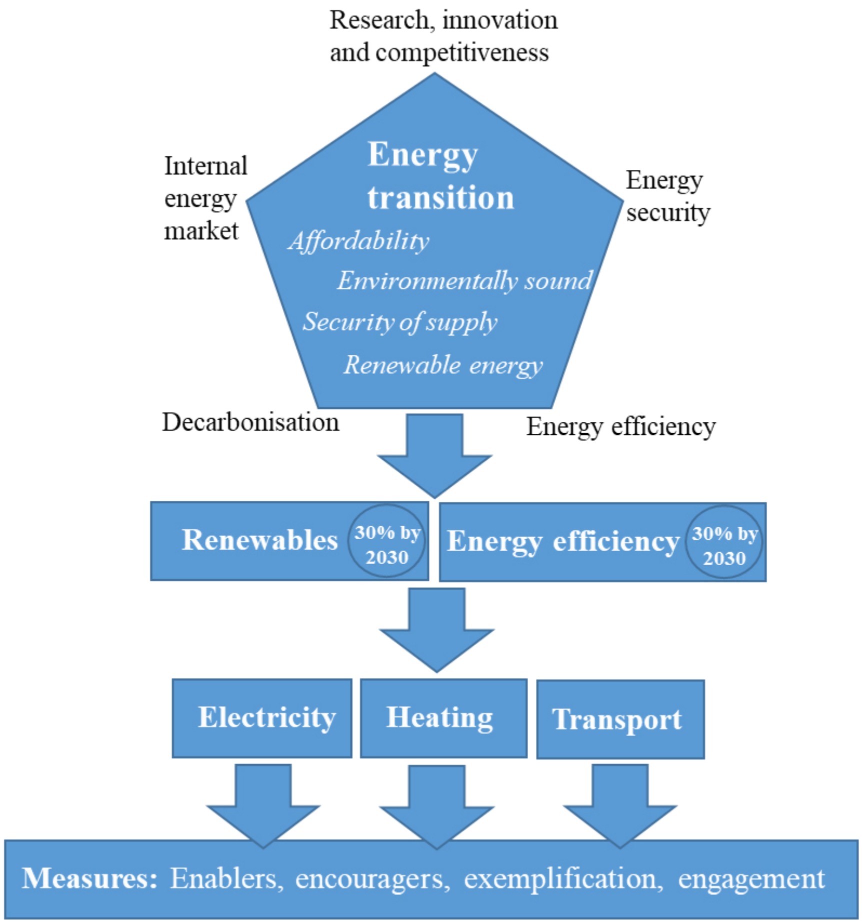

Figure 3-3 Energy and climate policy architecture in Germany

From these, a wide range of policies and instruments generally aim to increase investment in renewable energy and energy efficiency measures and encourage energy conservation behaviour in households, as summarised in the Integrated National Energy and Climate Plan (NECP) (BMWi

2020a). The main policies aimed at decarbonisation for the household sector are included under the Climate Action Plan 2050 and also service meeting European directed strategies, such as the NECPs, Renovation Wave, Long-term Renovation Strategies, Energy Performance of Buildings, and other policies (BMU 2019b) while the decarbonisation of the grid fuels consumed by households (and other sectors) are guided by the EU emissions trading system (ETS) and the Fuels Emissions Trade Law (*Brenstoffemissionshandelsgesetz (BEHG)*), which limits the allowable greenhouse gas emissions from power stations, industry and aviation (European Commission 2003; BMU 2019a).

Therefore, policies relevant to the household sector comprise an assortment of measures to increase renewable energy and decrease consumption in line with the energy and climate architecture of the energy transition in Germany. In terms of influencing households, these policies and measures provide conditions to foster investment and alter consumption behaviours and can be broadly categorised as enablers (e.g. removal of barriers, information, provision of facilities, viable alternatives, education and skills), encouragers (e.g. taxes, grants, reward schemes, recognition programmes, penalties), engagement (e.g. community action, co-production, media campaigns, networks) and exemplification (e.g. leading by example, consistent policy achievements) (Defra 2005; Chatterton 2011). In the German context, some of these measures are designed to facilitate the renovation of buildings (including residential buildings) mainly through *encouragement* and include tax incentives, subsidies and loan schemes, serial refurbishment, city-wide retrofitting, energy standards for appliances, energy certificates for buildings and innovation programmes like "Future building" (*Zukunft Bau*). Further *encouragement* measures foster a shift away from fossil fuels towards renewable energy and include the prohibition and phase-out of oil-fired boilers, a renewable energy subsidy scheme, tenant PV electricity as well as financial disincentives such as carbon taxing. The renovation of public buildings as a leadership initiative is an *exemplification* measure. Energy consultations are an important means to *enable* consumers with offers of information and support for building owners to develop a renovation plan as well as for lower income households to save electricity. Campaign-related measures, such as the "Germany does it efficiently" campaign, help to *engage* consumers to take action but is the hardest to measure progress on. Additionally, there are also a range of mobility-related policies and measures, which are not evaluated in this thesis but would also influence how households make holistic decisions regarding investments (e.g. electric vehicles as mobile battery storage) (BMU 2019c; Harthan et al. 2020). An overview of the policies categorised under the strategic objectives of *renewable energy* or *energy efficiency* as pertaining to the household sector is summarised in Table 3-1.

The main measures currently employed to push households towards increasing renewable energy and energy efficiency (and are featured in modelling exercises to forecast the policy impact on greenhouse gas emission reductions) centre around financial support for renovations, banning oil-fired boilers and the carbon tax. The financial support includes tax incentives aimed at owner-occupied buildings under the Energy Renovation Measures Ordinance (*Energetische Sanierungsmaßnahmen-Verordnung (EsanMV)*), which is limited to one action such as heater exchange or insulation of one aspect of the building and cannot be combined with other financial support. The Buildings Energy Act (*Gebäudeenergiegesetz (GEG)*) aims to unite the various financial support programmes such as the CO_2-building renovation programme (*CO_2-Gebäudesanierungsprogramm (EBS-Programm)*), market incentive programme (*Marktanreizprogramm (MAP)*), Heating and Ventilation package of the Energy Efficiency Incentive programme (*Heizungs- und Lüftungspaket des Anreizprogramms Energieeffizienz (APEE)*) and parts of the Heating Optimisation Programme (*Heizungsoptimierungsprogramms (HZO)*), and includes a ban of oil-fired boilers.

Table 3-1: Overview of energy policies and measures relevant to the household sector

Policy area	Policies	Objective/Strategy/Evaluation	Measures	Target group
Renewable energy	Renewables surcharge (EEG)	Tax on electricity consumption to fund renewable energy; Through the introduction of the Fuel Emissions Act, the EEG levy on electricity should be funded through revenues derived from the CO_2 tax	KfW Renewable Energies Programme; Regulatory framework for the expansion of self-sufficiency with renewable electricity; Regulatory framework for the development of renewable energy communities;	All consumers of electricity pay the tax
	Renewable Energies Heat Act (EEWärmeG)	Increase renewable energy for heating	Contracting models, Incentive programme; heat pump optimisation, loans and grants	Homeowners
	Mieterstrom	Not shown to be financially feasible as is		Tenants
	Carbon pricing in the heating and transport sectors	Financial instrument to influence consumers to switch to non-fossil fuels. Revenues will be used to reduce the renewables surcharge for power consumers	Starting at 25€/tonne of CO_2 equivalents from 2021, increasing to 30€ in 2022, 35€ in 2023, 24€ in 2024 and 55€ in 2025; auctions in 2026 and market prices from 2027	Transport and heating fuels (petrol, diesel, coal, oil, natural gas)
	Climate Action 2030, 2050		Information campaign	
Energy efficiency	Energy efficiency obligation schemes and alternative policy measures under Articles 7a, 7b and 20(6) of Directive 2012/27/EU (EU Energy Efficiency Directive (EED)) Long-term renovation strategy (LTRS) under EPBD, Directive (EU) 2018/844	Energy Efficiency Strategy 2050: target setting for 2050 and 2030; development of the Energy Efficiency Roadmap 2050; National Energy Efficiency Action Plan (NEEAP 2.0); to promote energy efficiency in the buildings sector; Roadmap for the renovation of the national building stock; National Energy and Climate Plan (NECP)	Measures as defined under Efficiency First, Renewable Energies Act, Energy consultations, Financial grants and loans, e.g. KfW programme; Measures under NEEAP 2.0 still to be defined	Owners, builders and contractors
	Energy Conservation Act (EnEG) Energetischen Sanierungsmaßnahmen-Verordnung (ESanMV) Buildings Energy Act (GEG) Climate Action Plan 2030 Climate Action Plan 2050	"Efficiency First" principle drives the implementation of energy saving measures; Overarching rules for the energy requirements for new buildings, for existing buildings and for the use of renewable energies for provision of heating and cooling in buildings	Measures and funding programmes (e.g. CO_2 Building Modernisation Programme, Market Incentive programme (MAP), Energy Efficiency Incentive Programme (APEE), Heating Optimisation Programme; public relations; consultations; Federal funding scheme; Energy Performance Certificates; State funding scheme	Largely for owner-occupied buildings
	EU Eco-design Directive	Information and awareness	Appliance labelling; efficiency labels for heating	All households
	Carbon pricing	(see above)		
Other	Bill support	Social welfare system	Heating and electricity bill payments	Social welfare recipients

These measures apply to residential and non-residential buildings, whereas the oil-fired ban applies to buildings with sufficient access to alternatives such as a gas or district heating network. Furthermore, the establishment of the Energy and Climate Fund (*Energie- und Klimafonds (EKF)*) should finance the Climate Action Plan 2030's household measures for building renovations, environmentally-friendly heaters and heat pumps. Revenues derived from the CO_2 tax should fund a levy relief resulting from the EEG levy on electricity as a means to dampen the distributional impacts (Harthan et al. 2020; BMF 2019).

Nonetheless, the carbon tax will disproportionately impact lower income households and tenants who lack the financial capacity or decision-making power to alter the structure designating the types of fuels and amount of energy necessary to meet household energy service demands. Carbon taxes have long been implemented as a means to reflect the environmental damage incurred through the combustion of fossil fuels. These can be applied to the supply sector to encourage electricity generation towards alternative-based energy sources, e.g. renewables. Similarly, the tax can be applied to the demand side where the consumer pays a tax per consumption of carbon-emitting fuels thereby leveraging a financial incentive for consumers to invest into more efficient technologies based on renewable fuels. While the theory is straightforward, the tax can have unintended distributional impacts (Bach et al. 2020). This relates particularly to the lower income and rental sector without the capital or decision-making abilities to make these required investments. This problematic is debated in the German parliament, where a proposal to shift the burden of a carbon tax from tenants by splitting the costs between landlords and tenants equally in recognition of the fact that the hard-to-reach building sector has missed the emission targets for 2020 (Schultz 2021). Figure 3-4 emphasises the potential additional burden of expenditure on energy if a CO_2 tax (25€/tonne CO_2-eq.) was added to the existing (2018) expenditure.

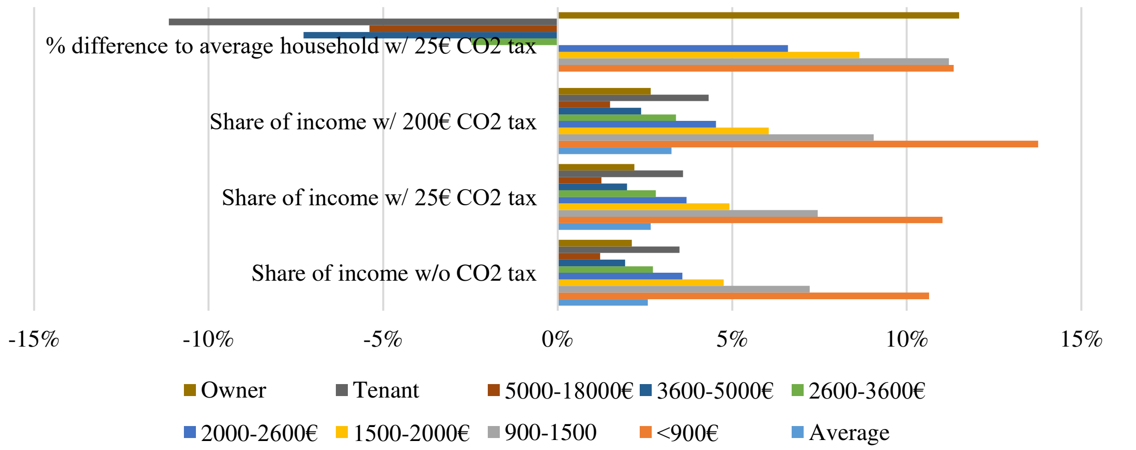

Figure 3-4: Impact of a carbon tax on the share of income spent on energy by income group and tenure

Source: own graph and calculations based on (Destatis 2013b)

While the average household will spend 2.63€ additionally per month to compensate for the carbon tax, the lower four income groups pay between 6-11% more than and the three higher income groups between 2 and 8% less than the average household. Tenants would pay about 12% less than, and owners 12% more than the average household to compensate for the carbon tax, because owners consume more on average than tenants. The carbon tax will increase to 200€/tonne CO_2-eq by 2035, giving households less than 15 years to become less fossil fuel dependent. However, where tenants and lower income households have less capacity to take action, the share of income spent on energy increases to 13.8% for the lowest income group and to 4.3% for tenants, given current consumption fuels and levels. Higher income households will only increase their share of income spent from 1.2% to 1.5%, indicating they are also in a stronger financial position to make investments.

As shown in Figure 3-5, lower income households rely to a greater extent on fossil-based fuels than higher income households and since lower income household sizes are smaller, the cost burden is condensed. However, while a wide array of measures is available, there is limited meaningful support for tenants and lower income households. The government plans to increase the heating cost quota for social welfare beneficiaries in order to compensate for the addition of the carbon tax, and at the same time to evaluate the best way to implement the carbon tax for the rental sector such that tenants are encouraged to conserve energy while landlords are incentivised to invest in energy efficient or renewable heating systems as well as building renovations (Harthan et al. 2020). Measures aimed specifically at lower income households are restricted to bill support and consultations on saving electricity. Yet, electricity averages only 11-17% of the total energy consumed, whereas the majority of consumption is with gas and oil for space heating such that measures targeting these fuels and heating as an end-use would result in more meaningful support. The relief through the reduction of the EEG levy will, therefore, have minimal impact for the lower income households. Support specifically for lower income households is complicated through the top-down legislation which regulates financial support to pay for energy consumption and investments through the social welfare system, as described in Chapter 2.4.

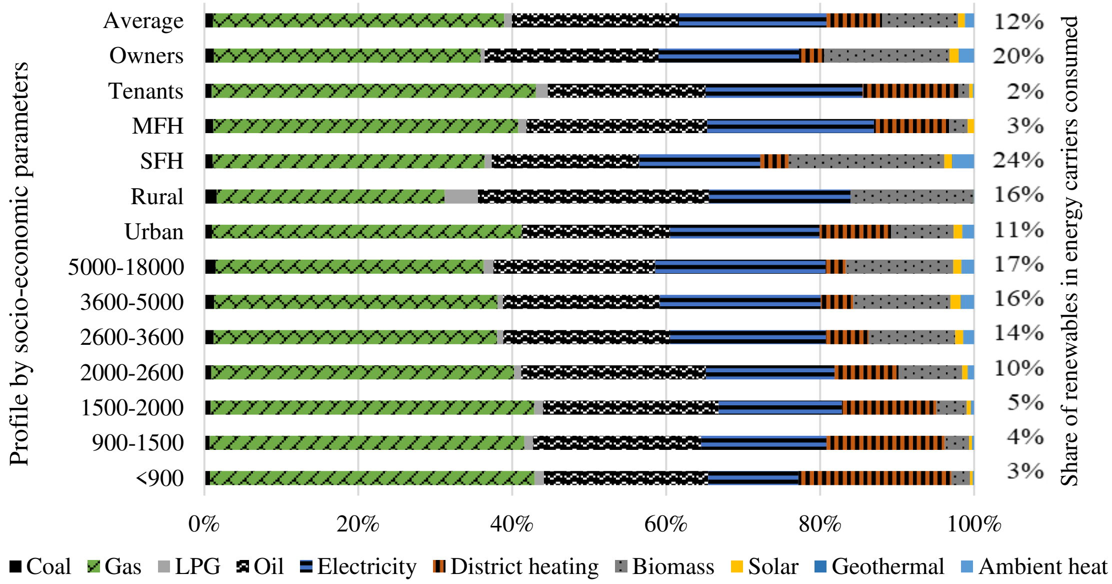

Figure 3-5: Distribution of energy carriers consumed by socio-economic parameters, 2013

Source: own graph and calculations based on (Destatis 2013b; BMWi 2021; AGEB 2019), calculations to develop the energy balance for the base year, 2013, are further described in Appendix C

On the European level, the specificities of these challenges are acknowledged and incorporated into the most recent legislative changes with particular directives on energy efficiency, buildings performance, governance and electricity calling for action on energy poverty and support for lower income households and tenants especially those residing in the worst performing building stock, as already outlined in Chapter 2. Plans and progress are to be reported in the Long-Term Renovation Strategies and the National Energy and Climate Plans. However, a European Commission evaluation of Germany's final National Energy and Climate Plan towards achieving the 2030 climate targets found that sector-specific targets do not align with the overall reduction targets, nor are the renewable energy policies and measures specific enough to evaluate their expected contribution against the renewables objectives. The same outlook pertains to the energy efficiency policies and targets (European Commission 2020b). It is expected that these Acts will be revised in the near future (BMWi 2020b). The influence of policies and measures are only one piece that goes into the final investment and decision-making behaviour of consumers.

3.1.2 Investment decision-making and consumption behaviour

Key to ensuring the success of the energy transition's objectives is the mobilisation of capital from the private sector. However, investment behaviour is not linear and not always rational. The investment and consumption behaviour of different actors are defined along socio-economic characteristics, preferences, financial capacities, techno-economic aspects and guided by policy. The influence of these policies and measures on the investment and consumption behaviour of particular low carbon, energy efficient and/or renewable technologies can be further attributed to individual ideals and limited by purchasing power. In classical interpersonal behaviour theory, this behaviour is understood to be shaped through moral beliefs and further structured by emotional drivers and cognitive limitations (Triandis 1976; Weber 1999). Theories to explain investment behaviour and decision-making regarding energy (Hauser 2013; Triandis 1976; Weber 1999; Wilson and Dowlatabadi 2007; Chatterton 2011) can be summarised into four categories:

- *Economic theory* – energy is a commodity and consumers will adapt usage in response to price signals
- *Psychological theory* – energy use can be affected by stimulus-response mechanisms and by engaging attention, e.g. home energy displays or transparent billing information
- *Sociological theory* – energy use is largely invisible, energy systems are complex and daily practices are significant: energy services are more important
- *Educational theory* – energy use is a skill that is learned through experience in specific situations

While no one theory can truly cover the reality of behaviour, the first two theories assume the individual will make a rational decision and the second two put more emphasis on the structures surrounding these as an influence on the decision (e.g. families, households, energy companies, marketing campaigns, access to technologies). The required capital to upgrade or replace the existing energy infrastructure will demand investment decisions by various actors, but the private sector will want to ensure that assets maintain or maximise utility and profits (Blaug 1985). The objective for this thesis is to apply investment and consumption behaviour into an energy system model in a way to 1) reflect realistic behaviour patterns, highlighting the differences in equality, and 2) enable flexibility to allow for differences in decision-making. However, the aim of this thesis is not to optimise individual decision-making, but rather to consider preferences and social norms as they apply to the overall averages of the profiles defined according to designated socio-economic characteristics. The emphasis is then on economically rational decision-making under policies and measures influencing investment decisions, which is sufficient to examine the effects within an energy system approach, as will be described further in Chapter 4.2.

3.2 Socio-economic disaggregation of population into profiles

In order to improve the representation of differentiated investment and consumption behaviour, analyse opportunities to reduce energy consumption and emissions and to harness the participation from households within the energy transition, and ensure the ability to analyse energy poverty, the households were disaggregated into specific profiles. The disaggregation of the heterogeneous actors within the household sector were categorised considering the major drivers of energy demand in the household sector, such as demographics, income and expenditure, tenure, location, building type, heating systems and appliances.

Therefore, the characterisation of the household sector in this study included first establishing the distribution of the population and households for the base year 2013 into distinct profiles based on socio-economic characteristics beginning with building type (single family and multi-family homes), tenure status (owner/tenant), location (urban/rural), and then income group (disposable income, savings) as shown in Figure 3-6.

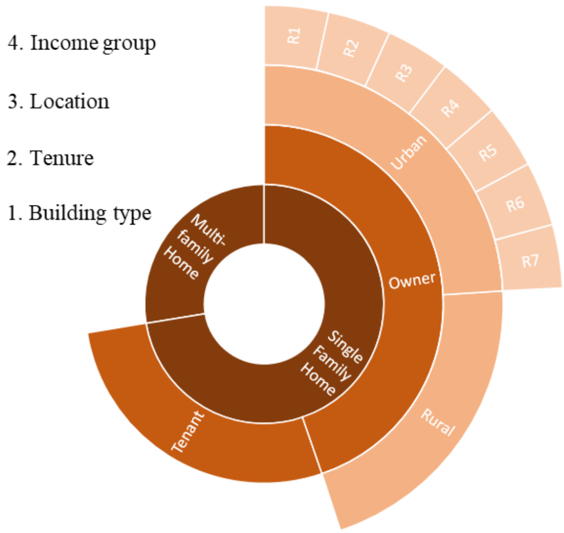

Figure 3-6: Classification of households by key characteristics

The disaggregation of the residential sector by income groups for the purposes of modelling is not often undertaken, but income has been recognised as a key driver of energy consumption as well as a limit for households to achieve a certain level of energy services in the home (Cayla et al. 2011). The income groups are aligned to the income group categories according to Destatis statistical surveys given in Table 3-2 per household and month for the base year, 2013 (Destatis 2013b). The disaggregation of the population into income groups rather than deciles offers a finer insight into energy consumption and financial capacity of households since deciles would again merge the population from different characteristics. As a comparison, the population and household distribution, and median income per decile is given in Table 3-3. In a decile assessment, the share of households is skewed by the even population distribution, where the lowest income group in the first decile represents 10% of the population and 9% of households compared to 3.7% of the population and 7.5% of the households in the lowest statistical income group. This means that while the trend that the number of people per household increases with income, the decile distribution is shifted in the lower income deciles thereby distributing the assessment across fewer households and reducing the emphasis of the single person household in lower income households and the greater burden carried. Within the context of energy consumption, this results in more aggregated and therefore similar consumption profiles across deciles in comparison to income groups which have greater variations (see Appendix C.5 for a comparison of the energy consumption between this thesis based on income groups and studies based on deciles). For this reason, the bottom-up calculation per income group performed in this thesis is deemed to better represent the situation on a household basis.

Table 3-2: Distribution of population, households, and median income by income group, 2013
Source: (Destatis 2013b)

	Pop. (million)	Share of pop.	Share of households	Median income per person and year	People per household
R1 = <900€	2.9	3.7%	7.5%	8,976	1.0
R2 = 900-1500€	7.8	9.9%	15.7%	12,047	1.3
R3 = 1500-2000€	7.9	10.0%	13.4%	14,200	1.5
R4 = 2000-2600€	10.0	12.7%	14.2%	15,513	1.8
R5 = 2600-3600€	15.2	19.3%	17.6%	17,002	2.2
R6 = 3600-5000€	15.8	20.0%	15.5%	19,855	2.6
R7 = 5000-18000€	19.1	24.2%	16.2%	28,408	3.0
Total/Average	78.9			18,733	2.0

Table 3-3: Distribution of population, households, and median income by deciles, 2013
Source: (Held 2019a) and own calculations based on (Held 2019a)

	Pop. (million)	Share of pop.	Share of households	Median income per person and year	People per household
Decile 1	7.87	10.0%	9.0%	9,458	2.0
Decile 2	7.87	10.0%	8.5%	13,444	2.2
Decile 3	7.89	10.0%	8.8%	16,520	2.1
Decile 4	7.86	10.0%	9.2%	19,319	2.0
Decile 5	7.88	10.0%	9.7%	21,991	1.9
Decile 6	7.87	10.0%	9.9%	24,772	1.9
Decile 7	7.87	10.0%	10.5%	28,030	1.8
Decile 8	7.87	10.0%	11.1%	32,104	1.7
Decile 9	7.87	10.0%	11.8%	38,351	1.6
Decile 10	7.87	10.0%	11.5%	58,509	1.6
Total/Average	78.73			26,249	1.8

The detailed methodology for the distribution of the population, including a comparison with studies using deciles, is given in Appendix C-5. Based on this population distribution into the actor groups, an energy balance was developed for each of these 56 profiles that took into account the differentiation of various actors or groups within the household sector where it was first necessary to characterise the drivers of energy consumption. While some of the drivers of household energy consumption are interlinked and cannot be distinguished which influence on energy consumption they have from one another, they can nonetheless be summarised into the following key categories: i) demographics, ii) income and expenditure, iii) dwelling characteristics (including tenure, location, building type and heating structure), iv) access and use of self-generation technologies, v) appliance stock and use, and vi) energy efficiency – current status and potential. Decisive to all of these demand categories is also the access to infrastructure for specific fuel types and the price signals that may shift households to alternate between different options. Each of these categories is elaborated in the following sections and forms the basis for the development of the energy balance for the disaggregated household sector.

3.2.1 Demographics

The basic demographic development of Germany is the main driver of energy consumption as this determines the number and size of homes as well as the associated energy service demands (BMU 2019c; Möller-Ühlken and Kuckshinrichs 2007). Taking these demographic features forward to incorporate further parameters requires the harmonisation of several datasets. To ensure consistency, household and population data were restricted to those stemming from official European and German national statistics. In 2013, there were 78.9 million people living in 39.3 million households with an average household size of 2.01 people per household. In 2018, the population increased to 80.3 million living in 40.7 million households with an average household size of 1.97 people per household (Destatis 2013b; EUROSTAT 2020).

3.2.2 Income and expenditure on energy

Income and expenditure are a central component of the socio-economic characterisation of households and determinant of their energy consumption. Disposable income determines the availability of capital which enables (or restricts) a household to invest into technologies and consume energy (Cayla et al. 2011; Kaza 2010; Longhi 2015; Alberini et al. 2011; Vassileva et al. 2012). Figure 3-7 shows the average shares of direct (operating costs of consumption) and indirect (investments) monthly energy-related expenditures and shares of income by income groups per household and per capita in Germany in 2018 (Destatis 2018a).

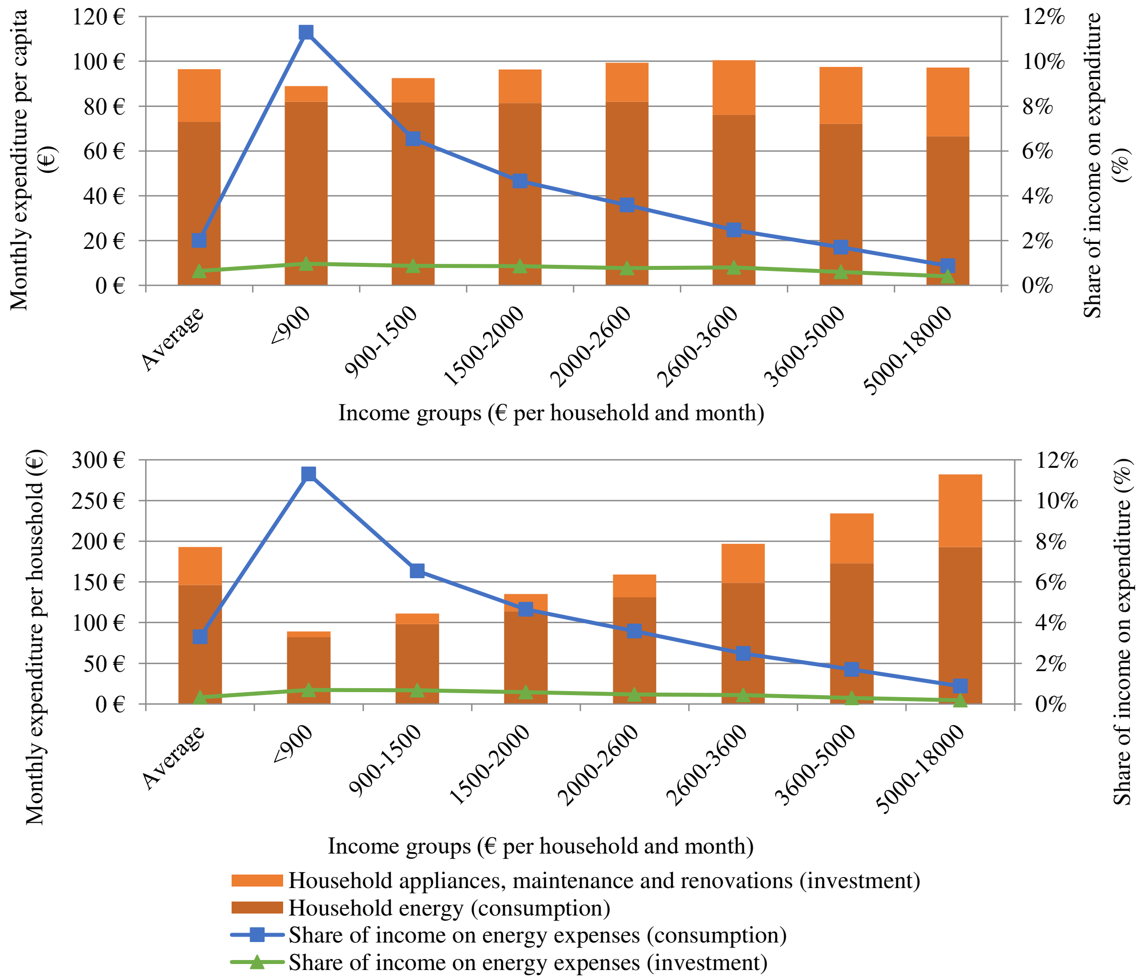

Figure 3-7: Income and expenditure by income group per capita (upper) and per household (lower) in Germany, 2018

Source: own graph based on (Destatis 2018a)

The indirect investments include expenditure on appliances, energy-related home maintenance and renovations. On average, each person spends a total of about 100€ per month on direct and indirect energy expenditures. However, the distribution varies within income groups. The average person spends around 74€ representing 2% of their monthly income on energy consumption (direct energy expenditures), but while a person from the lowest income group would spend 82€ or just over 11%, a person from the highest income group would spend around 67€ and or under 1% of their income. On average, people from all income groups spend less than ~1% of their income on indirect energy expenditures (energy-related investments). These expenditure patterns reveal that the spending on the upgrading of appliances and the home (indirect expenditures) enable lower energy bills. This reflects that higher income households have more disposable income to spend on energy efficient technologies, thereby translating into savings on current energy expenditures. Investments on indirect energy (i.e. investments in household appliances or housing maintenance and renovations), increase with income as visualised in Figure 3-8 (Destatis 2018a).

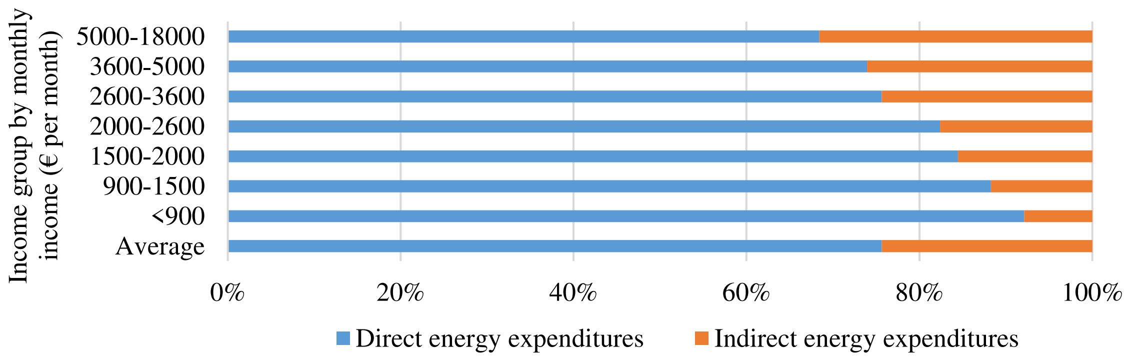

Figure 3-8: Distribution of expenditure on direct and indirect energy expenditures by income group, 2018

Source: own graph based on (Destatis 2018a)

The potential to afford the high upfront investment costs is examined by compiling the potential monthly financial savings accumulated per income group as presented in Figure 3-9, together with the disposable income and average savings per household as presented in Table 3-4.

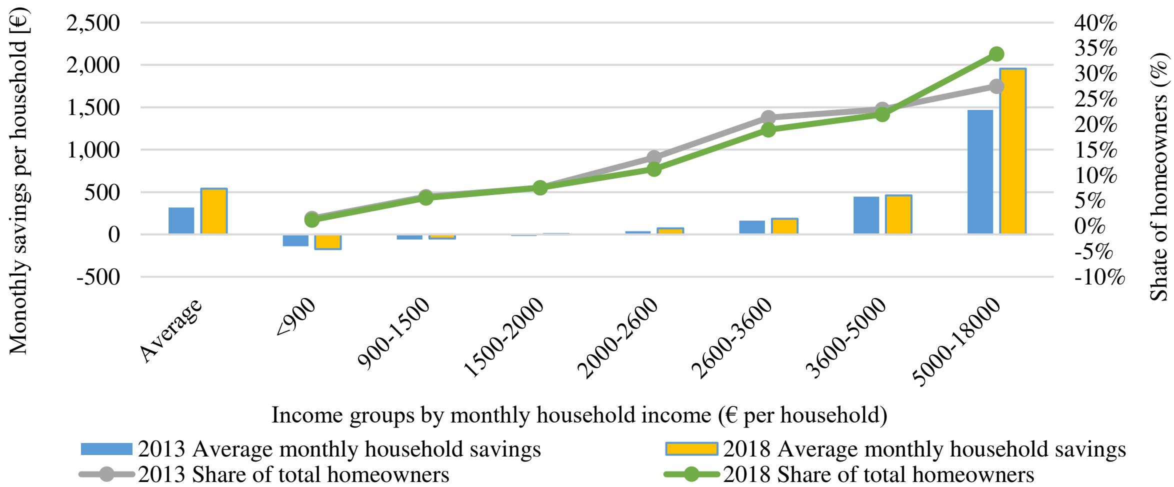

Figure 3-9: Potential of households to afford high investment costs according to available monthly savings by income group and total share of homeowners in Germany, 2013 and 2018

Source: own graph based on (Destatis 2013b, 2018a)

Less than a third (31.6%) of all households save more than the average household with approximately 319€ per month in 2013 (22.2% and 539€ per month in 2018) which could be considered theoretically available for investments in renewable energy and energy efficient technologies or building upgrades. While, the share of homeowners in the upper income groups has increased by 42.4% between 2013 and 2018, the households which both have higher than average savings and are homeowners reduces by 22.4%, which suggests that the number of households with decision-making power and the necessary financial capital is decreasing. Furthermore, homeowners with the potential savings to undertake investments represent just 22.3% of all households in 2013 (compared to 16.7% in 2018) underscoring the limitations in the potential of these actors to be able to carry the whole burden. It also highlights the larger share of households who, in addition to lack of capital, also lack the decision-making power as tenants to make investments, and the substantial role tenure has on potential investments.

Table 3-4: Overview of the household sector by income groups, 2013
Source: (Destatis 2013b)

Income group		**R1 <900€**	**R2 900-1500€**	**R3 1500-2000€**	**R4 2000-2600€**	**R5 2600-3600€**	**R6 3600-5000€**	**R7 5000-18000€**	**Total/ Average**
Households	*M*	2.94	6.17	5.27	5.58	6.93	6.08	6.37	39.33
Population	*m*	2.94	19.66	7.91	10.04	15.24	15.8.	19.1	78.85
Disposable income	*€/HH/month*	748	1,274	1,775	2,327	3,117	4,302	7,102	3,130
Savings	*€/HH/month*	-139	-59.5	-18	39	162	445	1470	319

3.2.3 Tenure

Home ownership is a significant determinant of energy consumption, which is typically characterised by greater living space and appliance ownership (Li and Just 2018; Schlomann et al. 2004; Frondel and Kussel 2018; Destatis 2014a). The greatest potential for energy savings in the household sector lies in buildings, but one obstacle to increased uptake of decentralised energy supply systems and energy efficiency of the building envelope could be the ownership structure (Scott 1997; Bird and Hernández 2012; Kockat and Rohde 2012; Frondel et al. 2015b). In 2013, 55.5% of all inhabitants of Germany lived in rented apartments or houses (Destatis 2013d). As a result, many households are not directly able to invest in energy savings related to the building envelope because they do not have the final decision-making power. Little data is publically available to determine the specific bottom-up calculation of energy consumption between owners and tenants, where differences will be based not only on the building type, available income but also on the types and numbers of appliances as well as their efficiencies.

Expenditure data in Germany based on the census data indicate that overall owners spent 1.71 times more on energy consumption per household and month than tenants in 2014 (Destatis 2014b). In France, tenants consumed 21-22% less than owners, except in multifamily homes, where the difference was only 7% (Belaïd 2016). The landlord-tenant problem (or split-incentives) can result in a range of issues including increased consumption in the rental sector due to a lack of energy efficiency investments on the part of the landlord, or disregard for high energy consumption because the energy bills are paid by the landlord (Castellazzi et al. 2017). A range of policies have been documented to address this phenomenon, but largely require government intervention through the application of financial incentives and or innovative business models (e.g. tax deduction schemes or ESCo investment), or compliance regulations (e.g. Energy Performance Certificates) for the landlords (Trotta et al. 2018).

3.2.4 Location

Location influences the energy demand and the types of technology investments made in residential buildings due in large part to the access to different energy sources, such as grid-based energy sources like district heating and gas, or some renewable energy carriers (Druckman and Jackson 2008; Kramer 2010; Satterthwaite 2009). The level of access, determined through the level of urbanisation, drives the dependency on specific fuel types to fulfil energy service demands, such as space heating and will, therefore, result in different consumption patterns (Kramer 2010; Kleinhückelkotten et al. 2016; Arbabi and Mayfield 2016).

3.2.5 Building typology and space heating structure

The building stock is the main determinant of the overall energy consumption in the household sector due to the significance of space heating consumption in overall household consumption. The energy consumption of the residential building stock is mainly characterised through the number of units per building (building type), the age and floor area. The building typology is commonly confined to two main building types: single-family homes (SFH) and multi-family homes (MFH) (Kockat and Rohde 2012; TABULA 2015; IWU 2012; Diefenbach and Clausnitzer 2010; Cischinsky and Diefenbach 2018). In 2013, just under 4 billion m^2 of floor area is distributed across 21.4 million residential buildings and 39 million residential units, of which 31.3% are in SFH and 68.7% are in MFH (dena 2016; BMWi 2014; Destatis 2013a). About 66% of all existing dwellings were built before 1979 when energy efficiency standards for buildings in Germany were first adopted and therefore only 35.6% of all existing residential buildings meet these higher energy efficiency standards (BMWi 2014; dena 2016). The age of the building is the chief determinant for the dominant heating system. While older buildings rely on gas (47.9%) and oil (37.2%), newer buildings tend to heat with gas (58.8%) electricity (22.3%) and biomass (9.5%), as well as represent 85% of installed heat pumps, as shown in Figure 3-10 (Cischinsky and Diefenbach 2018). Predictably, dwellings built before 1979 are therefore responsible for 68% of the total space and water heating energy consumption, of which the majority is consumed in SFH and two-family homes (dena 2016).

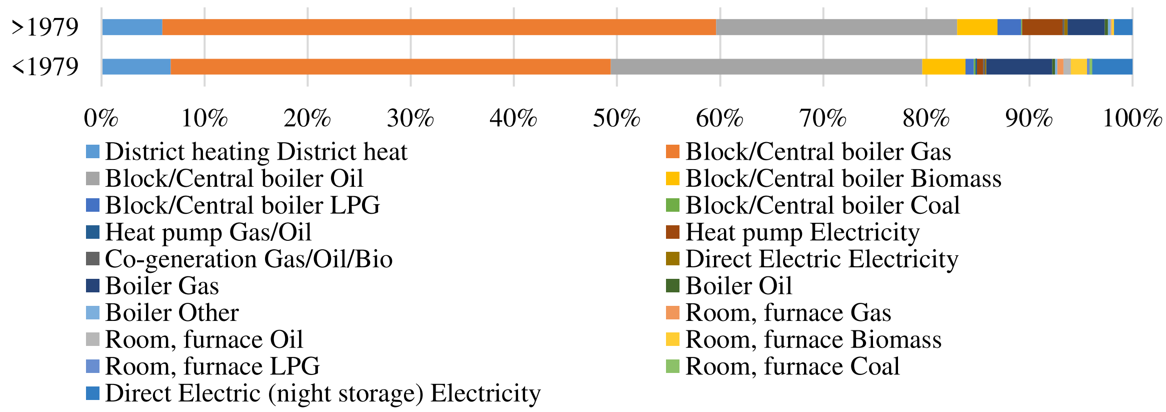

Figure 3-10: Heating technology distribution by building age, 2016
Source: (Cischinsky and Diefenbach 2018)

The potential for improvements in domestic heating is great. As space heating and electricity consumption are key for the energy transition, these end-uses are specifically targeted in achieving the overarching objectives for residential buildings and are in line with the new Buildings Energy Act by incorporating space heating, water heating, cooling, lighting, ICT, process heat and cooling but exclude mechanical energy (Thamling et al. 2020; BMI 2020). The choice of heating technology when modernising is influenced by socio-economic parameters but vary considerably across different countries (Li et al. 2018a; Braun 2010). The high upfront costs of a more efficient heating system remain a considerable barrier, especially for lower income households and to landlords.

Beyond personal preferences and economic limitations, measures directed through policies also guide technology choices. The Renewable Energies Heat Act requires that newly constructed buildings incorporate heating and cooling technologies based on renewable energies, and as such in addition to biomass boilers, heat pumps are forecasted to increase (BMWi 2020a). An additional overview of demand drivers for heating consumption by profile as well as the indicative potential to harness the energy efficiency potential in buildings is provided by profiles and building type for further use in this thesis (see Table E-1 in Appendix E).

3.2.6 Self-generation: PV

The overarching energy transition targets aim to increase the shares of decentralised renewable energy systems, which includes prosumers in the household sector. The financial incentive for households to invest in rooftop PV technologies is to offset the increasing electricity prices. In 2015, the household sector generated 13,135 MW, representing 44.6% of the total self-generated electricity in Germany (JRC 2019; Tash In preparation; Trend: research GmbH 2017; Holstenkamp 2013). The potential for rooftop PV in addition to solar thermal is described further in Chapter 5.1.2.2

3.2.7 Appliances

Appliances and white goods make up 70.5% of the total electricity demand in households and appliance ownership is largely driven by income levels with a greater share of higher income households not only exhibiting a higher prevalence of appliances but also more appliances per household (Vassileva et al. 2012; Schleich 2019; Frondel et al. 2017). While higher income households, driven in part by higher electricity prices, will invest in more efficient appliances, lower income households are unable to afford the high upfront costs and will then either purchase less efficient technologies (which have much lower investment costs) or turn to the second-hand market (Boardman 2010; Caritas 2015).

Particularly households dependent on social welfare are faced with complex hurdles when the need to purchase a first appliance or replace a household appliance arises. Households will typically obtain appliances through donations (second-hand) or are often required to make use of payment plans (which leads to higher overall costs) to pay for the investment into a replacement appliance. The SGB II law dictates that households drawing social welfare benefits are afforded the costs of initial investments, but that replacement investments must be paid through a different fund, which is usually insufficient for a new appliance (HartzIV 2019). Although there are no statistics available indicating which households purchase second-hand appliances, we can assume there is a large sector of society that does make use of this market given the law described and the prevalence of various platforms available to purchase second-hand appliances (e.g. ebay-kleinanzeigen and quoka platforms). Second-hand appliances also have implications on suppressed demand. When households first enter the market for a previously unowned appliance (e.g. dishwasher, dryer), they may first purchase a second-hand appliance which has lower investment costs but higher operation costs in terms of electricity due to the lower efficiency compared to a newer appliance. Energy efficient appliances have a key role to play in driving household energy demand by reducing the amount consumed, and increasing the opportunity for lower income households to meet previously unmet household service demands. A cost-comparison of the high upfront costs for refrigeration is calculated in Chapter 4.4.2. The dynamic of the use of second-hand appliances for lower income households is further described in Appendix F as the basis for the case study to be evaluated in Chapter 5.2.4.

Variations in appliance ownership according to income and tenure will have an impact on the overall energy consumption and potential for the investment in energy efficient appliances, and will have a key role in the household electricity demand.

3.2.8 Energy efficiency and the effect of suppressed demand

Increasing energy efficiency is an overarching objective of the energy transition. There are various reasons leading households to invest in energy efficiency (e.g. environmental concern, status, economic savings) (Barr et al. 2005; Li et al. 2018a), as well as numerous barriers to investment (e.g. tenant status, lack of capital) (Weber and Wolff 2018; Nair et al. 2010; Kastner and Stern 2015), but energy efficiency also has multiple benefits including reduced energy bills and increasing economic development (IEA 2015). The adoption of energy efficient appliances and building retrofit measures generally increase with income and home ownership (Schleich 2019). The potential of the energy efficiency of buildings is described in Chapter 4.4.

However, the investment into energy efficiency can also result in the rebound effect, where households actually increase their energy consumption. This is largely due to the monetary savings of energy efficiency allowing the unmet energy needs – the suppressed demand – to become affordable. Estimates put the rebound potential in Germany between 0 and 30% (Sorrell 2007, 2009; Sorrell et al. 2009). These estimates link back to the estimated 17.2% of households in Germany underspending on energy, which implies that some households do not meet their energy needs (see Chapter 2.4). In addition to statistics related to energy disconnections (see Chapter 2.4), this is also a parameter for the share of households that could be expected to rebound in their energy consumption.

In relation to the concept of allowing households who currently do not meet their energy needs the freedom to be able to increase their consumption is a growing debate on the "Right to Energy" and the deliberation about setting minimum energy service consumption standards (ENGAGER 2019). While this topic is not a focus of this thesis, there is room to explore this issue within the energy system model developed by exploring the implications of minimum energy standards particularly within the context of reducing energy demands in order to achieve climate objectives.

3.3 Disaggregated energy balance by socio-economic profiles

The methodology in this thesis builds on other documented methods to develop energy balances with varying parameters garnered through interviews and surveys conducted (e.g. (Frondel et al. 2015b)). This information was used to extract key data points to construct the energy balance for the profiles of the household sector in this study. The distribution relies on empirical data available through national statistics, government agencies and supported and validated through literature. The scope of this study covers households on the national level of Germany using the base year of 2013, owing to the availability of key statistical sources for the household sector to conduct the disaggregation, which are collected on a five-year basis (Destatis 2013b, 2018b). In each distribution step of the energy balance development, an additional layer is added to the previous step and is validated with various sources and indicators as will be described. The distribution of the final energy consumption is based on key determinants of energy consumption in the household sector, as described in more detail in Chapter 3.2, and takes place as shown in Figure 3-12 in the following 5 distribution steps, with the detailed calculations and validation of the final energy balance given in Appendix C: i) fuel type and end-use, ii) building type, iii) tenure, iii) urbanisation and iv) income group

In Step 1, the total final energy consumption for all households for the base year in 2013 (BMWi 2021) is disaggregated by fuel type and end-use into categories applied in the energy system model. These include 10 fuel types (ambient heat, biomass, coal, district heat, electricity, gas, geothermal, LPG, oil, solar) and 12 end-uses (clothes drying, cooking, cooling, clothes washing, dishwashing, freezer, lighting, other electric appliances, refrigeration, refrigeration/freezer combination, space heating and water heating) according to (BMWi 2021; AGEB 2015; Frondel et al. 2015b; Haasz 2017; UBA 2011; Destatis 2014a, 2014b). In Step 2, the energy consumption by fuel type and end-use is further disaggregated by two building types, namely single-family homes (SFH) and multi-family homes (MFH) in line with common classifications (Diefenbach and Clausnitzer 2010; European Parliament 2012), taking into consideration energy characteristics corresponding to the age of the building, floor area, heating system types, and user profiles (Destatis 2013a; Cischinsky and Diefenbach 2018; Diefenbach and Clausnitzer 2010; dena 2016; Frondel and Ritter 2013b; Frondel et al. 2016b). Step 3 further disaggregates the energy consumption by fuel type and end-use for each building type across tenure status by owners and tenants (Destatis 2013d, 2014a, 2014b), accounting for the typical distribution of appliance ownership and heating systems (Rehdanz 2007; Frondel et al. 2015b; Destatis 2014a). Step 4 disaggregates the energy consumption by fuel type, end-use, building type and tenure status by location: urban and rural according to the population and household distribution (Destatis 2011; EUROSTAT 2020; United Nations 2018).

The distribution in this fourth step is based on typical assumptions for consumption patterns for end-uses per capita, per household or per m^2 (BJZ 2020) and validated for specific end-uses (Kleinhückelkotten et al. 2016) and fuel types (Kramer 2010; Arbabi and Mayfield 2016; Döring et al. 2020; Groenenberg et al. 2011). The final step in the disaggregation distributes the energy consumption by fuel type, end-use, building type, tenure and location across the 7 income groups. Similarly to the distribution for location, the consumption is first distributed according to assumptions and validated by statistical expenditure data(BMWi 2021; Destatis 2013b) and conferred through literature (Cludius et al. 2018; Held 2019a).

As described in Chapter 3.2, accounting for income as the key point of departure becomes essential in order to better assess how households will invest in technologies and spend on energy consumption. Accordingly, in 2013 the households in Germany (39.3 million households; 79.5 million people) were distributed with the method and shares corresponding to these characteristics (Destatis 2013b). The method for the distribution of the households and population into these profiles is detailed in Appendix B.4. Figure 3-11 portrays the distribution of households according to income groups by location, building type and tenure.

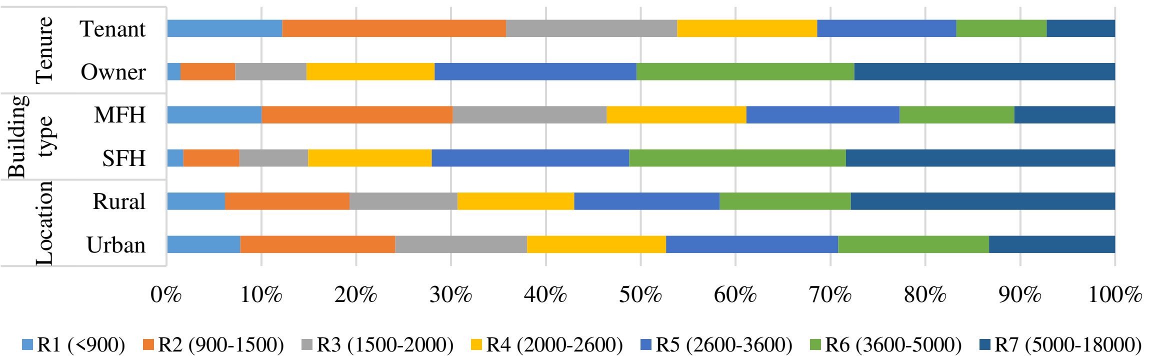

Figure 3-11: Household distribution by income groups by location, building type and tenure, 2013

Source: (United Nations 2018; Destatis 2011; EUROSTAT 2017, 2020; Destatis 2013b, 2013d, 2013c)

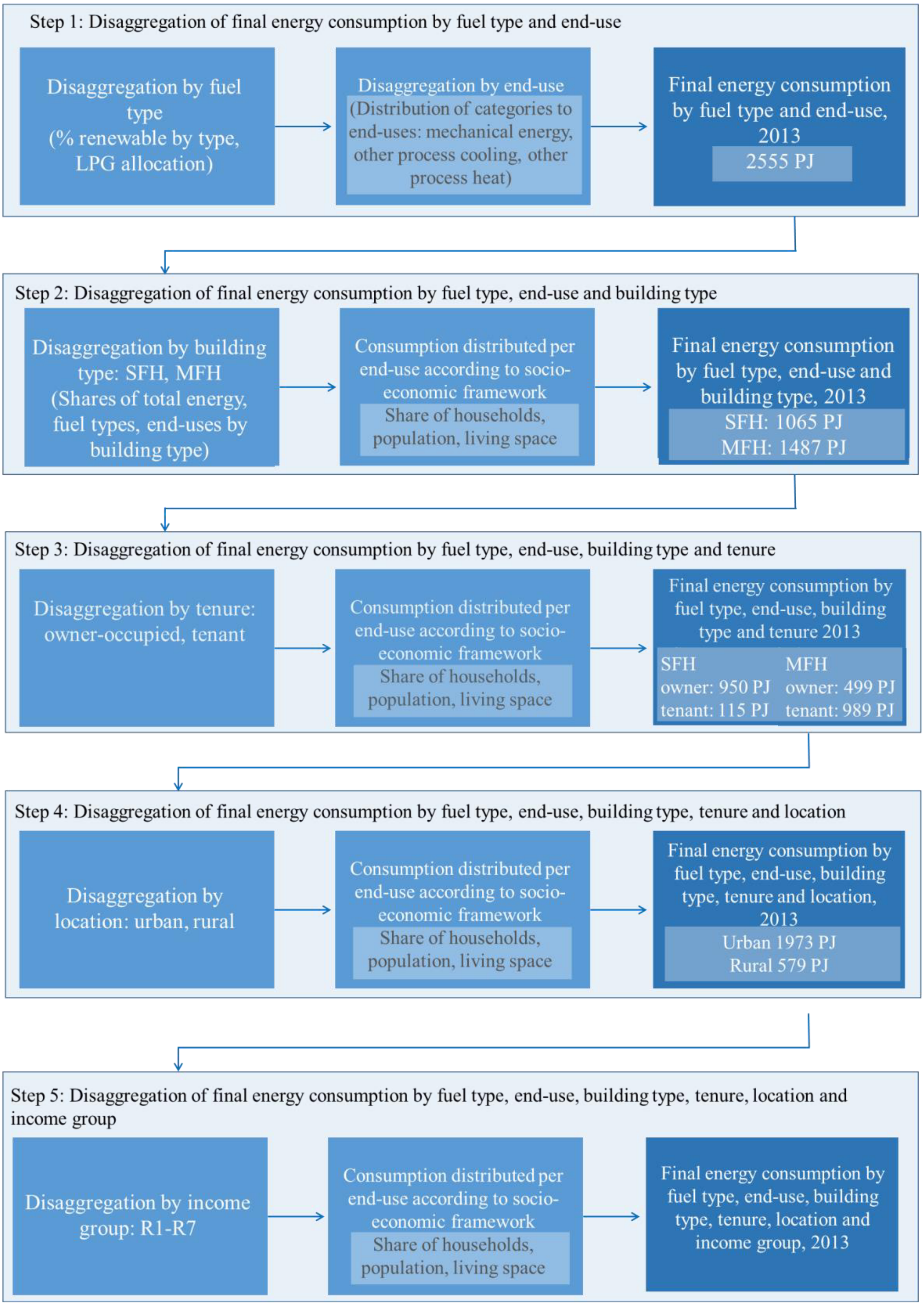

Figure 3-12: Method for the distribution of final energy consumption by energy carrier and end-use and final demand profiles (location, ownership, building type, income group)

The ownership ratio increases with increasing income. 85% and 41% of households with a monthly income of less than 900€ (R1) or 5,000-18,000€ (R7), respectively, are tenants. Furthermore, these distributions show that about 39% of households in the top income group live in a single-family house (SFH), 89.8% of which are also its owners. In the lowest income group this figure is 7.6%, of which 74.8% are owners. About 93% of the lowest income group live in multi-family houses (MFH), 10.1% of which are owners of owner-occupied flats. In the group with the highest income, 61.1% live in multi-family houses, 39.4% of which are owners. The distribution of the energy consumed per capita for heating, electricity and renewable energy is presented in Figure 3-13.

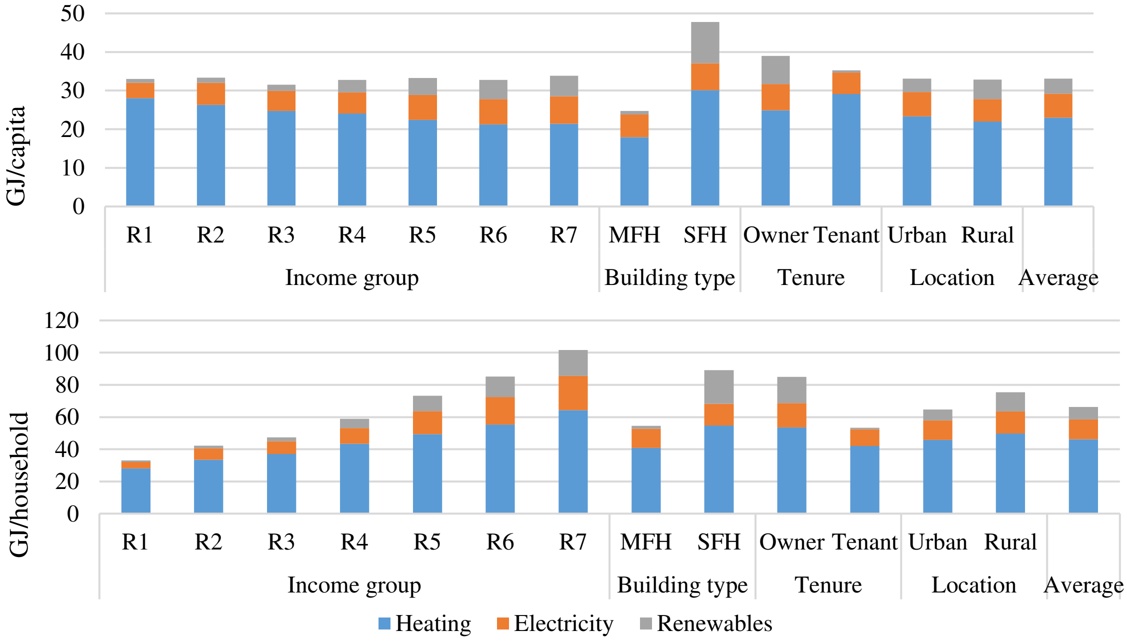

Figure 3-13: Energy consumption per capita (upper graph) and per household (lower graph) for heating, electricity and renewables by characteristic, 2013

Income groups by monthly income per household: R1=<900, R2=900-1500; R3=1500-2000; R4=2000-2600; R5=2600-3600; R6=3600-5000; R7=5000-18000

The lowest income group (R1) consumes the highest amount of energy for heating per capita (28 GJ/capita), which decreases as income increases. Since household sizes increase with income, the heating per household increases from 28 GJ per household in the lowest income group to 64 GJ per household in the highest income group. Tenants, SFH and urban households consume more heating than their counterparts, with the most significant divergence by building type with SFH consuming 30.1 GJ/capita (55 GJ per household) while MFH consume only 18 GJ/capita (41 GJ per household) on average. Electricity consumption reveals similar distribution patterns for location, tenure and building type, but the opposite pattern according to income group where the highest income group consumes the most electricity per capita (7.1 GJ/capita, 21 GJ/household) and the lowest income group consumes 4 GJ/capita and household. Renewable energy consumption decreases as income decreases and exhibit vast differences in consumption according to the other parameters with greater consumption in SFH (7 GJ/capita or 21 GJ/household), rural (5 GJ/capita or 12 GJ/household) and owner-occupied buildings (7 GJ/capita or 16 GJ/household). An average household consists of 2 people per household, which equates to 23 GJ, 6.3 GJ and 3.9 GJ per capita of heating, electricity and renewables, respectively.

These are important findings for the potential and expected investments of household contribution to the achievement of energy and climate targets, as the active participation of households is an important element in achieving the energy and climate targets. A better understanding of the opportunities of different consumer types will help facilitate the achievement of specific targets when the access to and affordability of measures is identified (e.g. home owners, technology or energy shares). The energy system could be tailored towards providing subsidies to specific actor groups according to various parameters (e.g. location, building type or tenure). These profiles take investment and consumption decisions better into account according to the specifics of the profiles as categorised allow for an analysis of the cost-optimal solutions for the overall energy sector as well as to each particular actor group.

3.4 Conclusion: Disaggregated assessment

The energy transition through its energy policies is decidedly shaping the energy system. Households have a significant role to play and are expected to contribute to renewable energy and energy efficiency targets. While the 2020 renewable energy targets were achieved, the energy efficiency targets have lagged behind. The majority of cost-optimisation modelling exercises are based on averaged households. To better understand how different actors within the household sector invest and consume energy, the household sector needs to be characterised in a way to be able to further study the possibilities and opportunities with respect to the limitations households might face.

Income is a key factor in affordability of energy services, be this for the investment in appliances, home refurbishment or the consumption of fuels to meet household energy service demands. Lower income households will prioritise their energy needs differently and as such the energy intensity for each income group varies greatly such that a top-down assessment would render inaccurate information, which is crucial to have when projecting the future energy needs of the region. The building type has a considerable role in determining this final energy demand, particularly for space heating and lighting, and is a major factor in influencing comfort level. Higher income households as well as owners are more likely to live in better insulated buildings as opposed to lower income households or tenants, which can greatly influence the amount of energy required to achieve a certain level of comfort. Furthermore, different income groups will have access to different energy carriers, either by choice, location or building type. Given these opportunities and limitations for investment, strategies should be developed to tap into this potential and support investment where barriers exist. The form of implementation of current strategies is shown to disproportionately affect lower income households in their execution with these households paying more on carbon taxes, benefiting less from social compensation measures and not being in the financial or decision-making position to take action on improving their situation going forward.

This thesis has disaggregated the population into households by income group, location, building type and tenure status resulting in 56 distinct profiles to account for these differences within the household sector. Each of these profiles are characterised with specific household energy consumption as it relates to the overall German energy system. The main objective of this thesis was to develop a basis for the disaggregated assessment of households within the context of energy poverty and the energy transition. The methodology was developed to account for the differences in investment and consumption patterns according to specific socio-economic parameters (including income, location, building type and tenure) and included a detailed evaluation, which comprised of the triangulation of various datasets and literature to enable a disaggregated study of the various households based on the outlined socio-economic parameters and aligned into a systematic structure that can be applied within an energy system modelling analysis. This baseline assessment emphasises the role the household sector can make towards achieving the objectives of the German energy transition. In the following chapter, an energy system model will be developed to accommodate the differentiated characteristics of the household sector with the objective to enable the assessment of strategies aimed to improve the energy welfare of households.

"Always plan ahead. It wasn’t raining when Noah built the ark"

Richard C. Cushing (1895 – 1970)

4 Methodology to assess energy poverty within the German energy system

This chapter describes the methodology undertaken towards assessing the significance of energy poverty on the German energy system within the context of achieving the energy transition targets. Chapter 4.1 reflects on the current representation of the household sector within the overall energy planning process in Germany, and further describes the basis for the model then further developed for this thesis. This is followed by an overview of the modelling features required to include consideration for energy poverty in such a model, and a review of the options to integrate these into an energy system model in 4.2. Chapter 4.3 describes how these methods are then incorporated or adapted into the TIMES-Actors-Model-Households (TAM-Households) model expanded in this thesis focussing on incorporating disaggregation, access and affordability. Chapter 4.4 provides a techno-economic characterisation of the various household technologies. Finally, this chapter validates the model method with the calibration of the TAM-Households model in Chapter 4.5 and summarises the overall novelty and importance of this model structure for this thesis in Chapter 4.6.

4.1 Current representation of the household sector in modelling

Typically, the household sector in Germany is represented in energy system optimisation modelling exercises as one homogeneously defined average household representing all households, disaggregated only by building type or location (BMWi 2018), which oversimplifies the situation and leads to one technology identified as the most cost-effective solution to meet a particular demand. The expected contribution from the household sector towards achieving the targets hinges on energy system analyses which are performed using average households. Despite increased granularity of various attributes in the building sector (e.g. such as investor-specific barriers, ambience heat distribution, and uptake of policies and measures), recent assessments have found that the building sector does not now nor will it meet the expected targets for 2030 (Repenning et al. 2020). These additions still do not allow an assessment of energy poverty and therefore may still underestimate the impact on lower income households and overestimate the possible contributions from the household sector towards achieving the overall objectives of the energy transition. With the aim of finding a least-cost solution to reaching these targets while also meeting the energy needs of all households, this thesis builds on existing research and begins with examining the model structure commonly applied to the household sector in Germany on the basis of the TIMES-D model (Haasz 2017; Fais 2015).

The TIMES (The Integrated MARKAL-EFOM System) model generator is a least-cost optimisation, bottom-up, technology-rich, linear-programming energy system model that can be applied to analyse the implications of a range of pathways for long-term energy investments and to identify least-cost measures to realise the climate and energy objectives of a particular region through the integration of relevant energy policies and technologies under a detailed technical and socio-economic framework (Loulou et al. 2016b; Loulou et al. 2016a). TIMES can be employed to assess the entire energy sector or to single sectors, such as households. The TIMES modelling framework has a detailed representation of energy technologies and their linkages across sectors (or actors) and considers the interdependencies of the energy system. This enables the analysis of the competition and substitution effects between technologies and provides detailed results of the energy flows, capacity investments, emissions and costs. However, this framework is based on a partial equilibrium and as such does not study the effects of energy policies on the remaining economy since only one sector (the energy sector) is considered. As input data, this model requires information around techno-enviro-economic descriptions of technologies including energy prices, technology investment and operating costs, efficiencies and emissions. The socio-economic and political framework also needs to be characterised around the energy demands, technology uptake curves and climate and energy objectives, which may include measures targeting specific fuels or technologies. Further information on the TIMES model generator can be found in (Loulou et al. 2016a).

Figure 4-1 depicts the extracted common structure of the household sector in the TIMES-D model (Fais 2015; Haasz 2017). Here, the structure includes urban households with 2 building types (single-family homes (SFH) and multi-family homes (MFH)) and only one building type in rural areas (SFH), with each of these variants given as an existing building and a newer more efficient building (resulting in 6 profiles in total) and includes the opportunity to invest in energy efficiency measures to meet/reduce heating demands. The energy demands are defined as the total demand for the whole sector for cooking, lighting, freezer/refrigeration and appliances, and specific to the building type (urban/rural SFH, existing/new, MFH, existing/new) for space heating, water heating and cooling. These demands are supplied through energy carriers and technologies (including measures for energy savings on space heating, i.e. renovation options) specific to the building type or the sector on a whole.

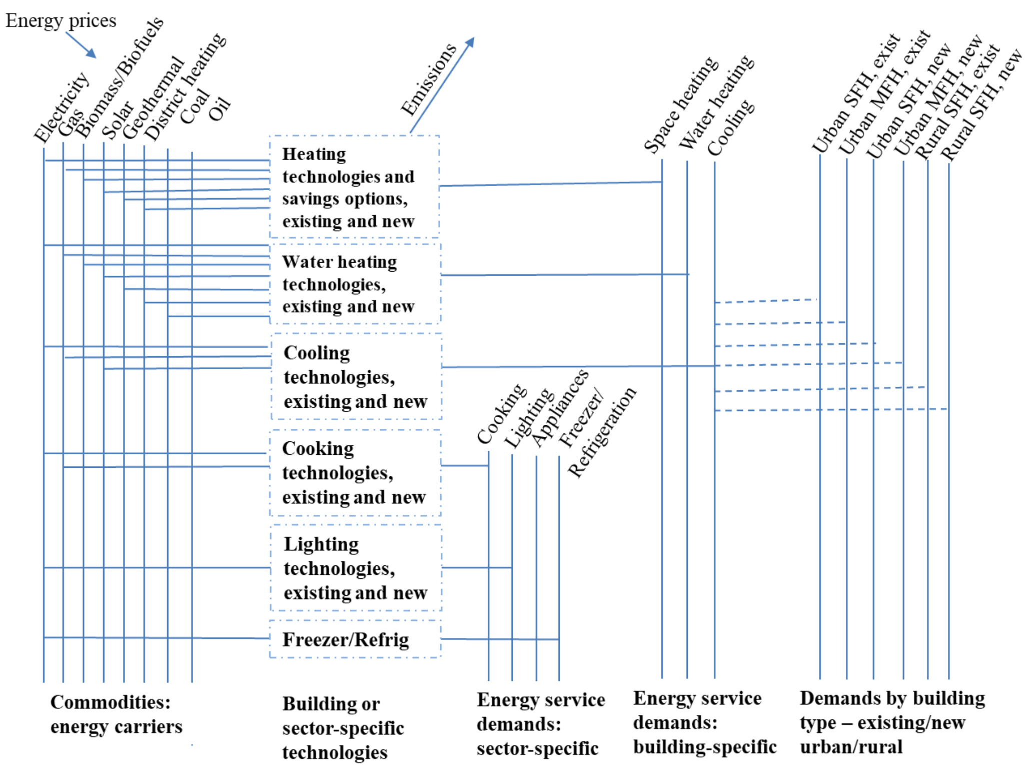

Figure 4-1: Reference energy system for the common modelling approach for the household sector, TIMES-D
Source: (Haasz 2017; Fais 2015)

However, an average household does not adequately capture the observed technological diversity and the differences in investment decisions and consumption behaviour across different types of households and also does not account for barriers to actual investment behaviour on the part of this sector, such as the limited urban and rural characterisation of the building types and the corresponding access to resources and energy networks. Therefore, there is a need to distinguish the household sector through additional characteristics that can explain differing investment and consumption behaviour by varying consumer groups, as described in Chapter 3. A refinement of this sector is necessary to improve the estimates of the decision-making behaviour of actor groups in particular to account for the financial ability of households to be able to afford to make optimal decisions, and to acknowledge the limitations in decision-making power for new investments in distinctly defined household actor groups.

4.2 Requirements and options to assess energy poverty in an energy system model

This thesis focusses on extracting the household sector out of the TIMES-Germany model and further expanding the household sector model beyond the objective of minimising costs to also include maximising benefits. This expanded household sector model is called the TIMES-Actors Model-Households (TAM-Households). The TIMES model is well-suited for the research questions in this thesis as it allows the depiction of the relationship between different commodities (e.g. energy carriers, emissions) and the processes (e.g. buildings, appliances), which will enable the assessment of the distribution of resources and technologies to particular consumers (households) under system constraints, such as energy and climate targets. However, since the common structure represents households in a more aggregated way, adaptations and further development is necessary to allow an investigation of the influence income has on the energy transition in households. The energy demands for the disaggregated income groups varies greatly such that a top-down, aggregated assessment would render inaccurate information, which is crucial to have when projecting the future energy needs and the achievement of targets.

As concluded in Chapter 2.5, energy poverty needs to be considered within the energy planning process to ensure a socially equitable and successful low carbon energy transition. The key parameters that need to be incorporated in order to account for energy poverty in an energy system model are *access* and *affordability*, as described in the common definition given in Chapter 1.1. Access describes the physical opportunity households have to particular energy resources or technologies. Access is limited by a household's location, building type or tenure, while affordability is about the financial capacity households have towards making investments and affording the costs of consumption and maintenance. Affordability is a key cornerstone in the investment decision-making process. Both of these features depend on *disaggregating* the household sector as a foundation for the study, as described in Chapter 3. The integration of policies and measures in the energy system model is also a fundamental part in terms of providing a realistic framework for incentivising or discouraging the adoption of technologies and consumption of specific energy carriers. A review of options to integrate these parameters is described in the next sub-chapters.

4.2.1 Review of options to integrate access

Access can be modelled through clustering by enabling specific actor groups the ability to invest into and consume particular resources and technologies such that, for example, the solar potential is commensurate with the actual roof potential available, or district heating is only available to urban households. Furthermore, for actors living in rental accommodation the access to investment decisions for heating, water heating and building envelope improvements must equally be restricted to reflect the likely investments from the landlords into the properties. Therefore, one key improvement in the model structure will require disaggregation of the household sector so as to better understand and account for the differences in access from different actor groups in the household sector. Improving this behavioural realism will diversify the choices resulting from modelling exercises (Horne et al. 2005). Several studies have implemented disaggregation into energy system models. Heterogeneity of a market segment has also been undertaken through disaggregation to better account for differences in preferences and/or consumption based on characteristics such as socio-economic factors, location, consumer or occupant-related behaviour (Tomaschek et al. 2012; Jaccard 2015a; Reveiu et al. 2015; Li et al. 2018b; Druckman and Jackson 2008; Leroy and Yannou 2018).

Modelling *access* has typically been applied in models applied in the context of developing countries. Here, one application explores the cost-implications of households achieving universal access to modern energy by shifting households from less efficient energy carriers to modern fuels (Pachauri et al. 2013). Another study explored access to electricity and limited biomass resources in a rural village, where different pathways are linked to investment into the resource (e.g. electric grid connection, PV) but limited by the financial feasibility of that resource with further (user) constraints applied on the availability of biomass (Howells et al. 2002).

These methods have been applied across these various modelling exercises as described and should be applied in combination to systematically express the wide-ranging needs and opportunities for access of different households to specific energy sources or technologies, as is necessary in this thesis. Heterogeneity is best represented through disaggregation to enable an analysis for the distinct profiles defined for this thesis (based on socio-economic parameters, location, building type and demand structure), where each defined profile also has designated fuel and technology choices. Coupling this with methods to address the population projection for the disaggregated profiles will account for the monetary development of population groups, where the profiles can be shifted to the next higher income group (and accompanying profile definitions) as income increases. Similarly, identifying segments of the modelled population that will have varying access to resources can be applied to particular profiles thereby specifying differentiated constraints on resource access.

4.2.2 Review of options to integrate affordability

To better reflect *affordability* into energy system models, disaggregation will also be a critical method to adopt into the model. As described in Section 4.2.1, disaggregation is applied in various studies to account for the differences of investment and consumption behaviour of different actor groups. Building on this, by including actor-specific (or income-specific) technologies will allow for the differentiation in affordability of technologies by different household market segments (Tomaschek et al. 2012). Cayla and Maïzi (2015) differentiate between investment and consumption behaviour and describe the various aspects of behavioural economics that contribute to how differently categorised households invest into technologies and consume energy.

Alternatively, to account for varying purchasing behaviour or preferences, a differentiation of discount rates is applied (Daly 2015; Jaccard 2015b; Ameli and Brandt 2015), or preferences are expressed through intangible costs (Jaccard 2015a), or results from external simulation models are used as input to optimisation models to gain insights about more realistic projections of technology transitions with, e.g. discrete choice models (Daly 2015; Horne et al. 2005). Discount rates attribute the value of future savings on investments made in the present (Hermelink and Jager 2015) and the value of present money changes depending on income such that lower income groups would have the highest discount rates to reflect the complexities of lower income groups to access funding (E3Modelling 2018; Schleich et al. 2016). The choice of discount rate will greatly affect the expected investments to achieve a particular target (Earl et al. 2018; Ameli and Brandt 2015), and is difficult to assume appropriately.

Focussing on urban areas, Dias et al. (2019) have explored the optimal system for a municipal energy system by incorporating investment constraints for households to account for limitations in available budget. Budget and time constraints have been included to consider investment and consumption behaviour related to transport and household energy. A limit restricts the allocation of time and budget for investment and consumption for defined actors, which results in more diverse modelling results to better represent, for example, the willingness of particular actor groups to forgo convenience in exchange for more individualised or public transport alternatives (Ahanchian et al. 2019; Tattini et al. 2018; Howells et al. 2002).

Within the Decentral project, (Tash et al. 2019) have included economic limitations to restrict the investments for the supply sector actors, such as citizens, institutional investors and utilities, specifically to explore the uptake of renewable technologies. However, investment behaviour is more commonly integrated in terms of the preferences of the consumer and assessed through their willingness-to-pay (Senkpiel et al. 2020) rather than the ability to pay, and studies fully incorporating actor-specific budget constraints are limited to date where accuracy and inclusion of these into modelling exercises are dependent on reliable data and the plausible processing of these.

As the efficiency of energy consumption improves due to the higher efficiency of technologies, appliances or behavioural impacts, there is often a rebound resulting in higher consumption, particularly for lower income households who are likely suppressing consumption due to affordability (Sorrell 2007). Through disaggregation, these end energy demands can be adjusted based on the demand profiles to account for the rebound effect, or alternatively by fictitiously decreasing the expected efficiency of technologies (Senkpiel et al. 2020; Tomaschek et al. 2012). The quantification of the rebound effect by different actor groups remains a challenge, but reviews estimate that the amount of rebound expected varies by end-use and can range from 10-30% for space heating and less than 20% for other household energy services (Azevedo 2014; Sorrell et al. 2009). The common approach in optimisation energy system models is to keep energy demand constant, adjusted only to accommodate the expected projections of energy efficiency measures and technologies, largely as a means to simplify behaviour which is typically included only in a limited way (Senkpiel et al. 2020; Daly 2015; Kavgic et al. 2010).

The model in this thesis builds on the disaggregated model structure developed which inherently accounts for individualised investment needs (due to expected energy efficiency and rebound developments). Additional features would improve the methodology, whereby individual discount rates can be applied to specific profiles (e.g. tenant buildings to represent hesitancy in landlords to undertake investments). Another key feature will be to constrain the total available budget for each of these profiles to reflect ability to pay. Expected improvements in efficiencies will be incorporated and can also be differentiated by users to account for rebound, such that lower income households would experience lower efficiency improvements over time than higher income households. All of these methods must be combined together into the model to effectively address the research questions in this thesis.

4.2.3 Review of options to integrate policies and measures

As described in Chapter 3.1.1, policies and measures related to energy in households aim to influence investment and consumption behaviour and as such need to be included in the modelling framework to simulate or optimise their effects. Policies and measures, therefore, are widely represented in energy system models with scenario frameworks typically defining energy and emission reduction targets as hard constraints set either globally or on a sector-by-sector basis. When the regulations, policies or measures target specific energy carriers or technologies, these can be expressed by putting bounds or user constraints to include or exclude their use at or from a certain period of time. Hurdle rates are applied to express the acceptance and encourage the adoption of particular technologies. Carbon taxes can also be added to fossil fuel consumption according to the consumer group defined

(Senkpiel et al. 2020). Modelling energy efficiency requires more than just a cap, because as specific technologies or end-uses become more efficient over time, the required energy decreases and potentially results in a rebound in energy demand due to suppressed demands where these are typically calculated exogenously. Energy efficiency can then be enforced through energy and/or emission constraints or forcing specific technologies and altering the demand projections accordingly (Fais 2015; Shi et al. 2016; Calvillo et al. 2018). Energy efficiency improvements in appliance standards are inherently assumed in future projects for available technologies (BMU 2019c).

The policy instruments that have been applied in TIMES-D outline the targets, requirements for laws, restrictions from regulations as well as incentives and taxes. The renewable energy surcharge is included via an iterative process whereby the effects on the payment and demand sides is balanced in terms of ensuring grid extension costs as well as feed-in tariff payments are aligned (Fais 2015). These methods reflect the overarching targets, such as emission, renewable or energy efficiency targets, defined directly via lower and upper capacity bounds and can be applied simply into the TAM-Households model. Similarly, carbon taxes can also be incorporated to carbon-based fuels at different rates for different consumers.

4.3 Modelling to include consideration for energy poverty in the TAM-Households model

This section will describe the methods employed in the newly expanded household sector model, TIMES-Actors-Model-Households (TAM-Households), to account for the heterogeneity of the household sector, access and affordability with a view of building a model capable of investigating the impact of energy poverty on achieving the objectives of the energy transition and vice versa. This analysis is based on adapting the TIMES-D model (see Chapter 4.1) and begins with Chapter 4.3.1 by including a disaggregated representation of households into heterogeneous groups based on socio-economic characteristics (see Chapter 3.2) and details the residential building sector and the types of appliances used. This is followed by Chapter 4.3.2, which outlines how the role of access to resources and technologies is integrated into TAM-Households. Affordability is the cornerstone of this assessment and how this is incorporated into TAM-Households is described in Chapter 4.3.3, which consist of the dynamics of socio-economic groups, budget constraints and coping mechanisms to meet household service demands, such as the purchasing of second-hand appliances or using technologies beyond their technical lifetime. Finally, the inclusion of policies and measures is detailed in Chapter 4.3.4.

4.3.1 Modelling disaggregation

Disaggregating a model to more specific user profiles is very data-intensive, especially in the case of this bottom-up energy system model, where each actor will need to be defined in terms of demands, technologies, buildings and the associated socio-economic projections. Disaggregation is also the cornerstone for integrating consumer investment and consumption behaviour, particularly with regard to developing policies to improve the electricity consumption of households through energy efficiency measures (Jones et al. 2015; Gouveia et al. 2015; Sütterlin et al. 2011). The basis for modelling households as actors is the statistical investment and consumption behaviour of technologies by end-use for households in order to adequately capture and assess the socio-economic parameters (Chapter 3.2).

As shown in Figure 4-2, the final model disaggregation includes location, income group, tenure status and building type specific profiles, energy service demands and technologies. The energy service demands are determined exogenously in both the original TIMES-D and in TAM-Households. In TAM-Households these are given as inputs for each profile-defined building and are based on techno-economic assumptions (Chapter 4.4) for the development of technologies and the political and socio-economic framework (Chapter 5.1) as the key drivers for demand. This model is dynamic in that the population can shift into other income groups and buildings over time, thereby allowing a better representation of the shifts in energy demands precisely because the demands are directly related to the defined socio-economic profile within that building. A summary overview of the system boundaries of the TAM-Household model is given in Table E-4.

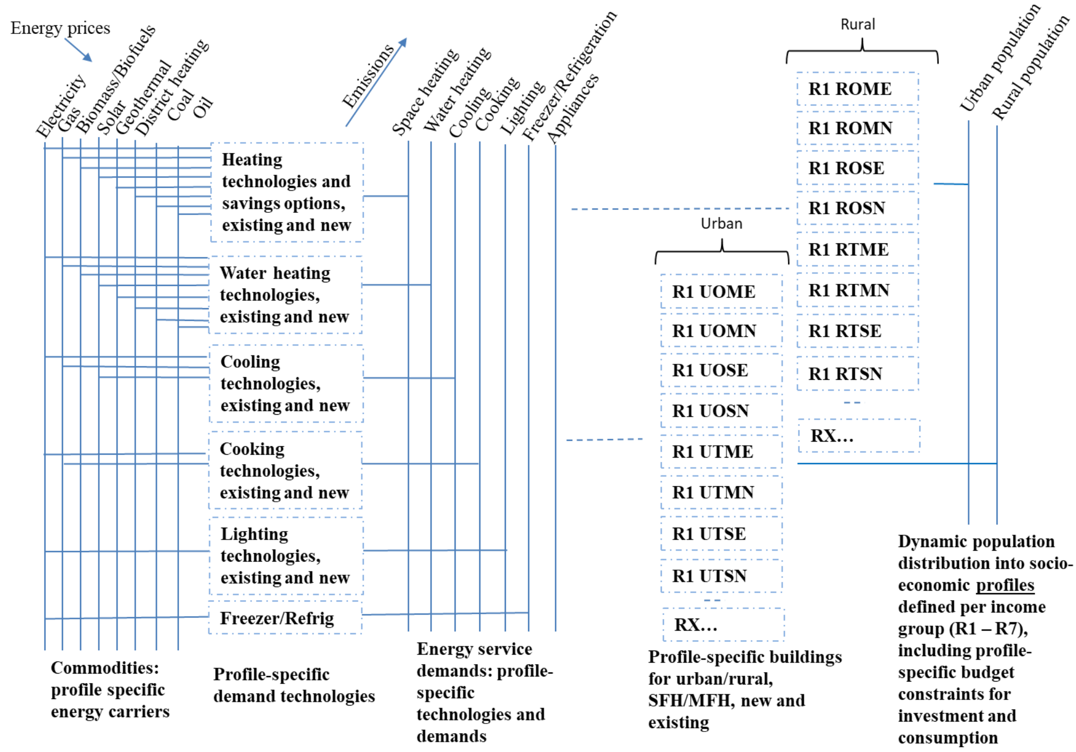

Figure 4-2: Reference Energy System for the household sector in TAM-Households

Abbreviations: Income groups are disaggregated by monthly income per household R1: <900€, R2: 900-1500€, R3: 1500-2000€, R4: 2000-2600€, R5: 2600-3600€, R6: 3600-5000€, R6: >5000€; Location by U= Urban, R= Rural; Tenure by O=Owner, T=Tenant, Building type by M=Multi-family home, S=Single-family home, and by E=Existing, N=New.

4.3.1.1 Residential buildings

Depending on the objective of the modelling exercise, the level of detail regarding residential buildings varies and is contingent on available data. (Kavgic et al. 2010) reviewed the portrayal of residential buildings in 9 bottom-up energy system models into two categories: statistics or building physics-based. While both methods yield a different level of detail in terms of results, the study found that generally a lack of data limits the outcomes of bottom-up models. To estimate the energy consumption and emissions related to a building, the building should be defined around parameters that determine the energy consumption, such as age, type, tenure and heating system.

Models based on building physics will define the energy consumption around the building materials and elements as well as their thermal characteristics based on the occupants and their energy-consumption behaviour. Yet, this will require extensive knowledge about the actual state of the buildings and, for national models, the aggregation of these characteristics will be inevitable as they depend on many assumptions. Statistical models use regression analyses for energy consumption by energy carrier for specific sectors, building types or locations. TIMES-PanEU and TIMES-D use a statistical approach to model energy demand in buildings in the household sector, where the demands for particular end-uses are derived from regression analyses and centred on exogenous parameters like projections for residential buildings, population, household size and floor area (Haasz 2017; Korkmaz et al. 2019). Disaggregating residential buildings by their occupants will be difficult without extensive knowledge of the building stock as well as the energy demand according to the disaggregation of the actors (Montenegro et al. 2020). The method developed in the TIMES-GEECO model is to define energy demands profiled within a building type for the existing building according to energy consumption statistics and allowing the model to choose more energy efficient building types (which have lower energy demands) for future years (Tomaschek et al. 2012).

A similar method is applied in the TAM-Households model, where the existing buildings are defined according to an aggregation of the characteristics for the building stock for each profile given as a typical building. As described in Chapter 3.2.5, this study constrains the study to two types of buildings (SFH and MFH) but remain unique in their characteristics for each profile defined in this thesis resulting in a total of 56 building types defined for the base year. The population is disaggregated by income groups and allocated to each building typology, which is located either in a rural or urban area (see Chapter 3.2 for the definition of the profiles). As incomes increase over time, the population shifts into the higher income groups and, therefore, to higher (different) energy demand profiles. Demolished buildings are replaced with a building of the same category (SFH/MFH) but with an adapted energy demand profile based on the expected higher energy efficiency standards of the building with an additional 56 building types to represent a new build. Based on the disaggregation of the final energy consumption as described in Chapter 3.3, a comparison of the average floor area and final energy consumption per square meter of living area by various parameters is presented in Figure 4-3, with additional detail regarding the disaggregation given in Appendix C.

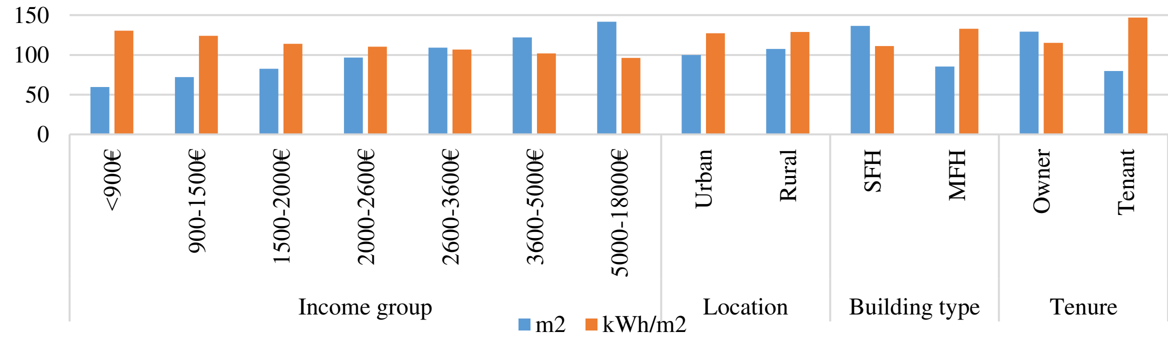

Figure 4-3: Comparison of average living area and space heating consumption by parameters, 2013

Source: own graph based on (Destatis 2013b, 2013d, 2013a; Frondel et al. 2015b; Cischinsky and Diefenbach 2018)

As income increases, the average energy consumption for heating decreases, reflecting the overall higher efficiencies of buildings and heaters. While there is no great difference in patterns by location, building type and tenure play a significant role such that smaller, MFH and rental properties require more energy for heating over their counterparts. This highlights the potential for improvement, particularly in lower income, tenant and MFH buildings, which is given as upper and lower bounds according to the expected renovation/demolition rates and the maximum energy efficiency potential available per profile. An overview of the statistical reference energy consumption values for residential building values is provided in Table E-1 in Appendix E.

4.3.1.2 Household appliances

A similar approach can be taken for modelling appliances. The typical household appliances (and the corresponding energy carriers) modelled are those to meet heating, water heating, cooking, lighting, freezer, refrigeration, and cooling needs, using the common naming convention from the TIMES family of models as shown in Table C-1 (Tomaschek et al. 2012; Cayla and Maizi 2015; DeVita et al. 2018; DeLaquil 2016). The market shares of household appliances are typically distributed to a sector, sub-sector or specific actors or building types through the use of user constraints and are derived through regression studies, or via soft-linking to another model (e.g. agent-based or discrete choice models) to derive more realistic technology adoption pathways, or through empirical survey data (Senkpiel et al. 2020; Horne et al. 2005; Li et al. 2018b).

While some data is available regarding types of fuels consumed, there was limited data available specifying exactly which technologies different household actors use and how occupant behaviour varies, so the preferred method would be to combine statistical and engineering methods to distribute the energy consumption by end-use according to statistics for a standard technology and to allow the model to choose future appliances for each actor group according to the framework conditions for that actor group (i.e. defined costs, efficiencies, energy carriers, market shares) (Tomaschek et al. 2012; Swan and Ugursal 2009; Destatis 2013d, 2014a). Similarly, this method is applied in the TAM-Households model for existing technologies where available data is supplemented with plausible assumptions through literature to allow for the appropriate distribution across all parameters used to define the disaggregated profiles for this thesis as given in Chapter 3.3 and further detailed in the development of the energy balance in Appendix C.

However, due to suppressed demand the impact of rebound should be anticipated and included in the model structure. As stated in Chapter 2.4 and 3.2.8, 17.2% of households in Germany are estimated to be underspending which indicates that energy efficiency improvements in certain households may actually still lead to an increased demand. The basis for integrating differentiated demands and accounting for unmet needs is disaggregation, which allows the inclusion of rebound and different demand responses to energy efficiency improvements. This is accounted for in the model through a shift in the number of households into other demand categories over time (as income increases). Further detail on the energy efficiency potential and how this is distributed across the profiles for inclusion in the model is given in Chapter 4.4.1. Future technologies in Germany are physically available to all households irrespective of income (e.g. washing machine, dishwasher), while others are tailored to correspond to the particular building type such that the model will be able to select the technologies based on the investment and consumption costs limited only by the available budget of each income group to afford these. More detail on the specific technologies modelled is given in Chapter 4.4.

4.3.2 Modelling access

Access to technologies and measures can be limited by various characteristics such as location, tenure, building type and income, as described in Chapter3.2. A range of methods have been applied in various studies to account for different aspects of investment behaviour in modelling, as described in Chapter 4.2.1. The TAM-Households model specifically has delineated access to specific resources through user constraints for each actor group by location and building type, with district heating only available to households located in urban areas and a larger share of the biomass potential is assumed to be available and used in rural areas with lower shares to multi-family homes in both rural and urban areas. Furthermore, the rooftop potential for PV is calculated based on the actual useful areas by building type and income group. This limits the availability of the rooftop potential to the specific actor group and reduces the overestimated exploitation of the overall residential PV potential. The actual assumptions and distribution of the potential per actor group is described in Chapter 5.1.2.2.

4.3.3 Modelling affordability

Income, expenditure patterns and available savings are key factors in affordability of household energy services as highlighted in Chapter 4.2.2. Available capital is essential to cover the costs of consumption as well as the investment costs of new or alternative technologies and measures. Modelling affordability is about: i) understanding and incorporating the dynamics within income groups and within the profiles, ii) reflecting the affordability of each profile according to the budget constraints, iii) reflecting the present value of future cash flows through the application of appropriate discount rates, and iv) incorporating the applicable coping mechanisms to meet needs with limited budget, such as extending the technical lifetime of technologies and/or buying second-hand appliances – which have lower upfront, but higher operating costs. The model restricts the financial ability of households to invest in the high upfront cost of appliances to better reflect the actual potential in overall capital investments by determining the overall available budget per profile based on statistical analysis of the disposable income, savings, GDP and typical investment patterns (Destatis 2018c; IMF 2019b, 2019a).

The GDP per capita increases by 81.4% between 2013 and 2060 from 36,948 €$_{2015}$/cap to 67,0715 €$_{2015}$/cap (IMF 2019a). With a total available capital (actual investment and consumption expenditure plus available savings) of 179 billion €$_{2015}$ in 2013, the distribution across income groups is projected to increase to 631 billion €$_{2015}$ in 2060, as shown in Figure 4-4. The majority of the wealth in the household sector resides in the upper two income groups. This available capital is further distributed per defined profile within each income group according to projections of the shares of households and population. These figures are used to define the budget restrictions for each actor group in the model described in the next section.

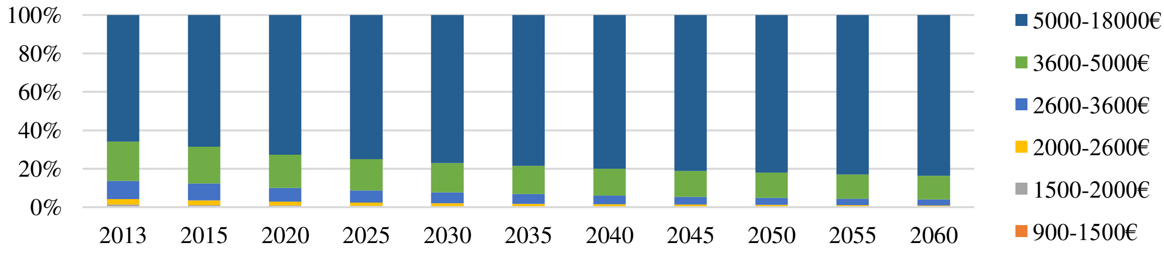

Figure 4-4: Distribution of total available capital in the household sector by income group, 2013-2060 in €$_{2015}$

4.3.3.1 Implementation of budget constraints

The overall household budget is considered by including this into the assessment for household service needs. This additional disaggregation better reflects the holistic financial and decision-making power of specific actors in the household sector and is previously not reflected in modelling assessments for long-term energy planning in Germany. The financial limitations are represented with household budget constraints for each defined profile based on the statistically available funds according to energy-related investment spending patterns for each income group. This budget constraint is considered as the potential available budget that households could invest in more efficient or renewable-based end-use technologies (heating, water heating, lighting, other appliances), retrofit the building and small-scale PV rooftop power generation (playing a role as prosumer).

The model takes into account the limitations in available budget to each actor group through the implementation of profile-specific budget constraints. The budget constraints for each profile are calculated based on available statistics on income-specific typical investment in energy appliances, energy improvement investments and savings (Destatis 2013c). The budget restriction is applied to each profile through a user constraint on the investment and consumption costs (Ahanchian et al. 2020). The mathematical formulation is represented in Equation 1 for an example profile, A.

$$\sum_{r=1}^{R} \sum_{y \in YEARS} \sum_{t \in TECHS_A} new\_cap_{r,y,t_A} \cdot inv\_cost_{r,y,t_A} + fuel_{costr,y,t_A} \cdot act\_cost_{r,y,t_A} \leq Budget_A \qquad \text{Equation 1}$$

where:

new_cap_{r,y,t_A} is new capacity of a technology of profile *A* built in year *y* in region *r*;
inv_cost_{r,y,t_A} is the specific investment cost of the above (equal across regions/profiles);
act_cost_{r,y,t_A} is the operating and maintenance costs of the above (equal across regions/profiles);
$fuel_{costr,y,t_A}$ is the fuel consumption cost of the above (equal across regions/profiles);
$Budget_A$ is the maximum yearly budget available to profile *A* (e.g. households);

This budget constraint is applied to all investments in owner-occupied households. By adding this feature into the model, the algorithm now solves to maximise the welfare of each profile in addition to minimising the overall system costs under specific objectives (i.e. energy and climate targets). Similarly, the budget constraint is included for tenants, but applies only to technologies which they have the decision-making power to replace and therefore excludes heating, water heating and PV technologies as well as building renovations. Instead, these investments include a higher discount rate to represent the apprehension of landlords to make costly investments in properties from which they may not derive a benefit, as outlined by the landlord/tenant dilemma (Bouzarovski et al. 2018; Griffiths and Causse 2010; Hermelink and Jager 2015).

4.3.3.2 Implementation of extended lifetime of technologies

Particularly lower income households may not optimally use appliances to their theoretical technical and economic efficiency, as described in Section 3.2.6. While all household appliances have a specific estimated technical lifetime, some households that are unable to afford the high upfront costs of a replacement appliance may continue to use an appliance until it actually becomes defective. However, the appliance itself will reduce in efficiency over time, thereby resulting in higher energy consumption and related energy bills. For this reason, the model has also incorporated the extension of the lifetime of technologies, whereby a technology can be purchased at no cost to be used for an additional period of time, but at a lower efficiency. As described in Chapter 3.2, TAM-Households has 56 different profiles represented in Figure 4-5 as a simplified example with the refrigerator/freezer demand for “Profile 1”, “Profile m”, “Profile n” through to “Profile 56”. The Profile 1 demand in the base year (2013) is met by an existing technology (BASE1). In subsequent model periods (e.g. model period 1), the base technologies (BASE1) which have come to the end of the expected technical lifetime, can be replaced with profile-specific, more efficient technologies (A1 B or A1 C, where “B” and “C” are appliance energy efficiency classes), extension of the technical lifetime (BASE1 + y) – where y represents the additional years of use for the appliance – or sold in the second-hand market (described further in Chapter 4.3.3.3) to another profile. For further modelling periods, in addition to the option of replacing an appliance with a more efficient model, each of the newer appliances can also be extended by additional years. This same procedure is possible for the other defined profiles and technologies.

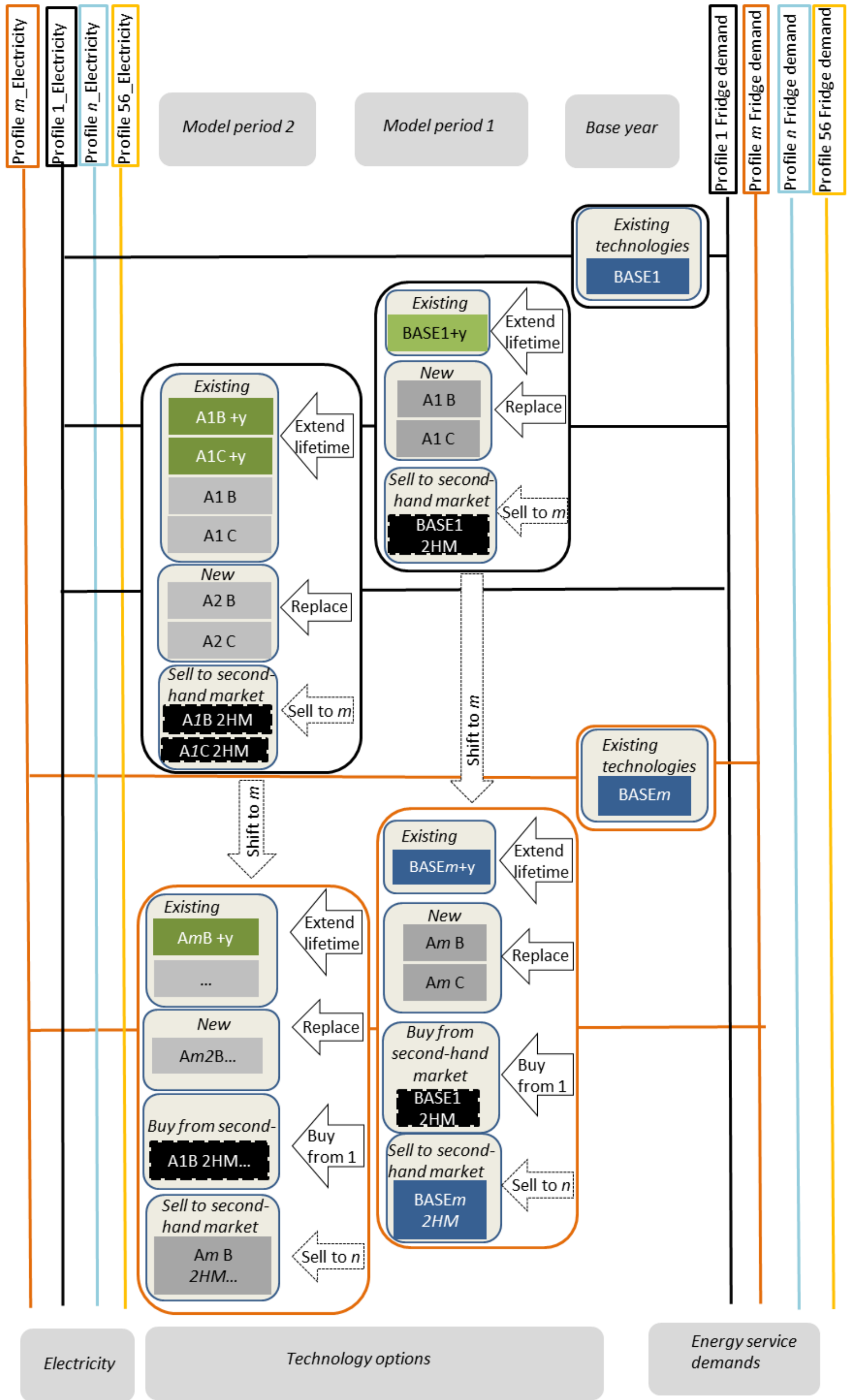

Figure 4-5: Modelling method for lifetime extension and the second-hand (2HM) appliance market

4.3.3.3 Implementation of the second-hand market

Another way households increase their affordability of new investments is to purchase second-hand appliances. This is particularly relevant for refrigeration and freezer appliances. This is modelled in TAM-households by allowing one income group to sell an appliance (thereby gaining an income) and a second income group to purchase this appliance at a lower price (but also lower efficiency), as shown in Figure 4-5. The second-hand appliances is also applied as an example to refrigeration and freezer demand with the sample profiles, "Profile 1", "Profile *m*", "Profile *n*" through to "Profile 56". Similarly, the demand for Profile 1 in the base year (2013) is met by an existing technology (BASE1). In subsequent model periods (e.g. model period 1), when the base technologies (BASE1) need to be replaced, one option is with profile-specific, more efficient technologies, extension of the technical lifetime of the existing appliance (as described in Chapter 3.2.7) or selling it in the second-hand market (BASE1 2HM) to another profile (e.g. Profile *m*). For further modelling periods, in addition to the option of replacing an appliance with a more efficient model, each of the newer appliances can also be sold in the second-hand market. This same procedure can be replicated for the other profiles and technologies defined.

4.3.4 Modelling policies and measures

Methods to model energy-related policies and measures are largely adapted from TIMES-D (Fais 2015) and further developed within the Decentral project (Ahanchian et al. 2020). As described in Chapter 4.2.3, policies and measures are modelled as constraints according to particular targets. These constraints were modelled in TAM-Households in line with the policies and measures influencing energy use in the household sector and relevant to this thesis outlined in Chapter 3.1.1, such as targeted greenhouse gas emissions. In TAM-Households, it was necessary to apply constraints (e.g. renovation rates, market shares for specific technologies or energy carriers) to achieve these targets for the whole sector or according to the profiles defined (e.g. homeowners, building type, location). Measures, such as subsidies, grants (financial incentives) and taxes can be included through a price reduction on the fuels or technologies for specific actor groups (e.g. income group, homeowners).

Specific policies and measures modelled, therefore, include the decarbonisation targets and carbon taxes implemented in the scenarios described in Chapter 5, which provides more detail. The decarbonisation target applies a zero emissions target in 2050 whereupon the model finds the least-cost pathway to achieving this target given other variables and constraints in the model, such as the budget constraints. Environmental taxes, such as carbon taxes, are added to carbon-emitting fuels and related to the consumption by each specific actor groups represented in TAM-Households. The development of the carbon price per ton of CO_2-equivalent was developed according to the tax scheme developed for the Climate Protection Strategy 2030 (Vermittlungsausschuss 2019) resulting in a CO_2 tax in 2035 of the upper boundary of 200 Euro per tonne of CO_2-equivalent (Harthan et al. 2020), and reaching 250€ per tonne of CO_2-equivalent in 2050 to account for the expected damage cost for climate change, thereafter with a linear extrapolation to 260€ per tonne of CO_2-equivalent in 2060, as shown in Figure 4-6.

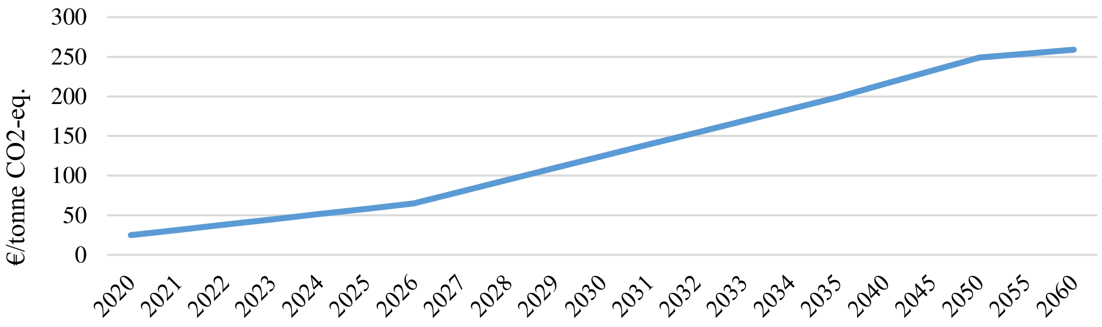

Figure 4-6: The development of the carbon tax as applied in Germany
Source: (Vermittlungsausschuss 2019; Harthan et al. 2020)

Current policies include the implementation of the steadily increasing carbon tax on the consumption of all fossil together with a reduction in the electricity price through the EEG levy alleviation. With the aim of ensuring a more socially just energy transition, the levy on electricity is reduced (as described in Chapter 5.1.2.1). These coupled price signals aim to reduce fossil fuel consumption and encourage a shift towards energy efficiency, renewables, or electricity-coupled consumption (e.g. in heat pumps). The overall impact of how much carbon tax is paid and how much EEG relief gained per household and socio-economic parameter in 2025 is shown in Figure 4-7. As can be expected, lower income households pay more carbon tax than is compensated through a levy relief. As household sizes increase in medium income households, the carbon tax burden increases as does the electricity levy compensation. Since higher income households consume more electricity and emit less carbon overall, these households are compensated to a greater extent, which shows that the social compensation of the EEG levy relief is disproportionately distributed.

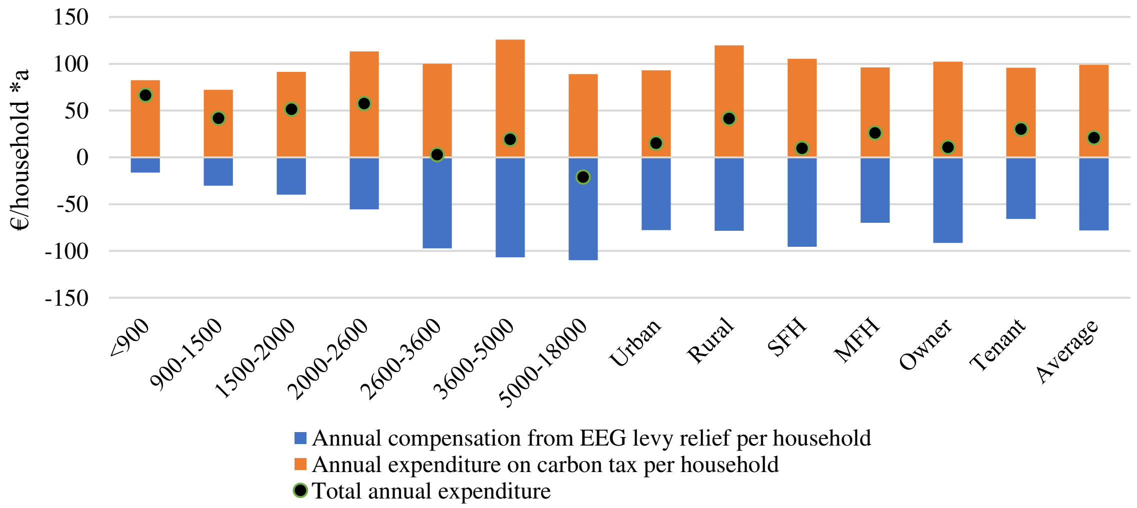

Figure 4-7: Comparison of annual expenditure on carbon tax and EGG levy relief per household by socio-economic parameters, 2025

However, these findings are partially contradicted by findings in (Bach et al. 2020) and (Kalkuhl et al. 2021). Kalkuhl et al. (2021) find that lower income households have a higher electricity consumption as a share of their overall consumption resulting in net benefits. While Bach, et al. (2020) concur that lower income households are negatively impacted by the carbon tax, they find the EEG levy relief makes up for this financial impact. The input for both of these findings are based on (Held 2019a) with assumptions that the amount of electricity consumed per capita across deciles does not increase significantly (as discussed in Chapter 3.2 and shown in Figure C-4), whereas this thesis is based on a bottom-up assessment of energy consumption by income groups which accounts for household sizes (in addition to appliance, building type, location) (cf. Figure 3-13 which gives the average consumption per capita and per household showing that the consumption of electricity varies by income group, namely 4 GJ in the lowest income group and 7 GJ in the highest income group). This is crucial since whether a household has one or more occupants, several electric appliances will consume the same amount of energy and this electric consumption is then distributed across each person in the household. Furthermore, the consumption (and payment) of electricity in TAM-HHs is differentiated by electricity and heat pump electricity, of which the latter is consumed to a greater degree in higher income households (i.e. lower electricity price per GJ, but higher levy relief) such that these households benefit more. The decile assessment does not take the different household sizes into account and thereby averages the consumption across statistical income groups. This indicates that results evaluated per income group rather than per decile would represent a closer reflection of the actual situation facing households.

4.4 Techno-economic assumptions: Fuel and technology options in TAM

The TAM-Households model includes technologies differentiated largely by the building type and location, and allows the model to choose the cost-optimal technologies based on the economic limitations imposed. Technologies and appliances for cooking, clothes washing/drying and lighting are the same across all profiles, adjusted only to accommodate the capacities required to meet the profile energy demands. Technologies used for cooling, space heating, water heating and freezing/refrigeration are building and income-specific. Detailed descriptions include the assumptions for investment costs (€/unit), fixed and variable costs, efficiencies, lifetime and availability factors, with projections of cost and efficiency developments to the end of the modelling horizon in 2060 and can be found in Table E-2 and Table E-4 in Appendix E.

4.4.1 Buildings, energy efficiency and space heating

The distribution of the existing space heating structure by energy carriers in 2013 is shown according to income, location, building type and tenure in Figure 4-8. Particularly the use of ambient heat and geothermal heat pumps increases with income with a combined share of 29.5% in the highest income group, and are more prevalent in urban (91%), single-family (100%) and owner-occupied households (84%) (Destatis 2016). The common method employed in energy system models is to include the additional costs for investments due to the system boundaries represented in the model (Korkmaz et al. 2019; Haasz 2017; DeVita et al. 2018). TAM-Households shifts the focus towards the household expenditure by including a limitation on the total budget available for investments and therefore includes a new methodological framework to include the total installation costs required for space heating technologies. In order to preserve the richness of the technology database based on the TIMES family of models, the investment costs of space and water heating technologies have been updated to include the total installation costs (including any necessary building modifications) based on Eltrop (2020) and validated according to recent assessments (Korkmaz et al. 2019; Eltrop 2020; Mailach and Oschatz 2021) and include 35 different space heating and 12 alternative water heating building and location-specific technologies, while some are dual space and water heating technologies (Haasz 2017) (as further detailed in Table E-2 in Appendix E.

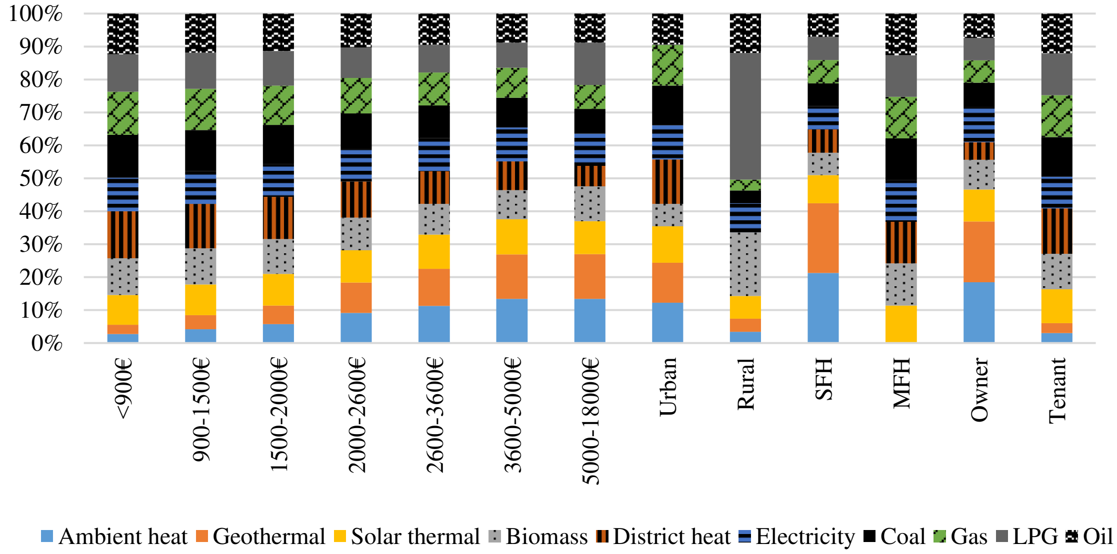

Figure 4-8: Space heating structure by fuel type in 2013 by socio-economic parameters
Source: own graph based on (Destatis 2016)

To illustrate the impact of high upfront costs for a new investment, a comparison of the ca. 20-year lifetime investment and operating costs of installing a new heater is evaluated against maintaining the status quo for an average lower income household living in an urban SFH. This example averages the consumption of an urban SFH (owner and tenant) and assumes constant energy prices over the 20-year period and a carbon tax of 25€ per tonne of CO_2-eq. Table 4-1 details the parameters for the heating systems in terms of efficiencies, investment and operating costs. Replacing the existing oil furnace results in total cost savings over the lifetime of the heating system, owing to the higher efficiency and the mitigation of the carbon tax burden.

Table 4-1: Parameters for the comparison of sample heating systems for a low-income single-family household

		Oil furnace (existing)	Gas boiler	Biomass boiler	Ambient heat pump	Source
Efficiency/ Coefficient of performance	%	75	79.9	65	2.3	(Haasz 2017; DeVita et al. 2018)
Investment costs	*€/GJ*	-	46.9	88.4	85.8	(Eltrop 2020)
Fuel cost	*€/GJ*	24.0	22.8	13.7	65.4	Regression analysis based on (BMWi 2021; Ahanchian et al. 2020; Harthan et al. 2020; BDEW 2020), see Table 5-3
Installed capacity	*kW*	-	6.7	6.7	6.7	Capacity requirements calculated according to energy balance given in Chapter 3.3

The greatest total cost savings occur through an ambient heat pump despite the greater investment costs (which include the costs of any necessary building modifications), as shown in Figure 4-9. The annual operating costs to provide heating is reduced by 76.2% when switching to a heat pump which is 11% more efficient than the current oil boiler and consumes no carbon-emitting fuels and is therefore not subjected to the carbon tax. However, in order to afford the investment cost households would have to pay the equivalent of 13.7 years of the operating costs of the existing heating system upfront, which is often untenable in lower income households without the opportunity to access a loan or financial assistance. The gas and biomass boilers do not provide overall cost savings compared to the oil boiler due to the higher installation costs. Although the gas heater is more efficient than the biomass heater, the gas heater will require the user to pay a carbon tax on the fuel consumption which can vary over the years and is expected to increase. The biomass boiler has 88% higher investment costs and 23% higher fuel input than the gas heater, both of which may also be impacted by price fluctuations and infer that this renewable heating source is not as cost-competitive as the heat pump.

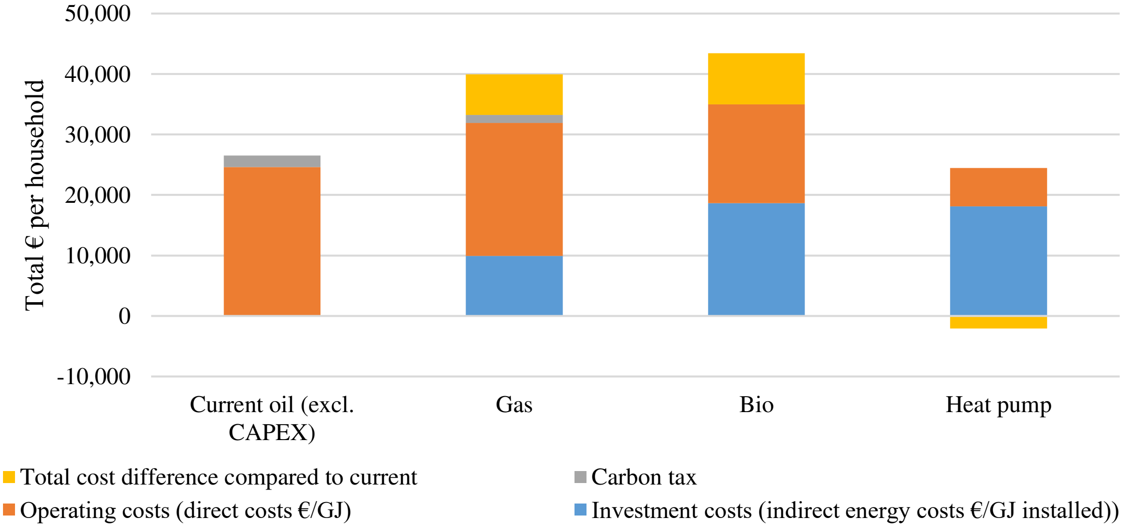

Figure 4-9: Cost comparison of the space heating investment and consumption costs for existing and alternative technologies for the lowest income group over a 20-year lifetime
Source: own calculations and graph based on (Eltrop 2020)

The energy efficiency potential of renovating buildings with regards to heating savings was calculated for the German building stock and distributed to the profiles based on the aggregation of the shares across the building age and associated floor area (Kockat and Rohde 2012; dena 2016; TABULA 2015; Destatis 2014b, 2016, 2013d; Bach et al. 2014). Together with the aggregated heating system structure for each profile (Destatis 2016), the available energy efficiency potential was calculated for each profile based on the difference between the average existing energy rating of the building compared to increasing these to achieve a higher energy efficiency rating according to usual renovation performances (TABULA 2015; BMWi 2015). These were calculated for each profile based on the average net space heating demand for various parameters (income group, building age, building type) in line with (IWU 2012; Cischinsky and Diefenbach 2018). The distribution assumes that of the existing building stock, an average of 35.7% of homes (51.9% of owner-occupied and 19.5% of rental homes) are renovated with at least one energy efficiency measure (BBSR 2016), leading to the assumption that the average net energy demand for space heating per m2 is reduced by 30% compared to the non-renovated equivalent of the same building categorisation (i.e. building type and age, average living area by income group), and have therefore not achieved a completed state of energy-related renovation, implying there is additional potential to be harnessed in these buildings. This bottom-up calculation of the energy efficiency potential reveals that the majority of renovations have occurred in urban, owner-occupied buildings in households with higher income groups (74.6%), as can be expected. Tenants living in urban MFH comprise 26.1% of all renovated homes while owners living in MFH only include 12.6% of all renovations, as shown in Figure 4-10.

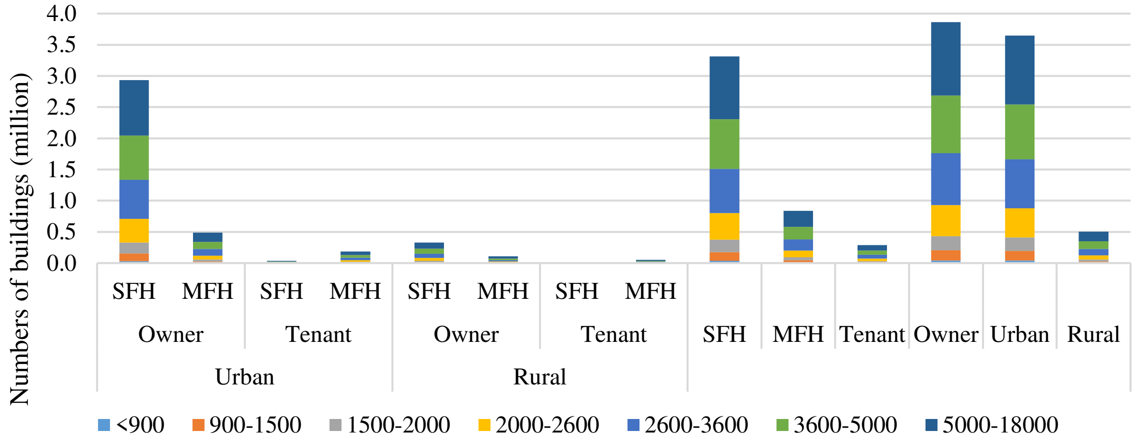

Figure 4-10: Numbers of buildings renovated by income groups by tenure, building type and location

Source: own graph and calculations based on (BBSR 2016)

Taking into consideration the existing renovation status and the remaining potential in the building stock (based on averaged building stock characteristics for each profile considering building age, floor area, location) (IWU 2012; BBSR 2016; Cischinsky and Diefenbach 2018; Destatis 2016; TABULA 2015; Bach et al. 2014; Kockat and Rohde 2012; dena 2016; Destatis 2014b, 2013d) results in a total estimated energy efficiency potential in the base year, 2013, of 771 PJ, based on an average space heating demand of 109 kWh/m^2 corresponding to an average of 126 kWh/m^2 of final energy consumption for space heating. These findings are validated by comparison with other studies, where the average final energy consumption for heating is given to be 169 kWh/m^2 (BMWi 2014), 144 kWh/m^2 (including water heating) (TABULA 2015), 144 kWh/m^2 (net space and water heating demand) (BMU 2019c). The final energy efficiency potential calculated for this thesis across income group by other parameters is shown in Figure 4-11.

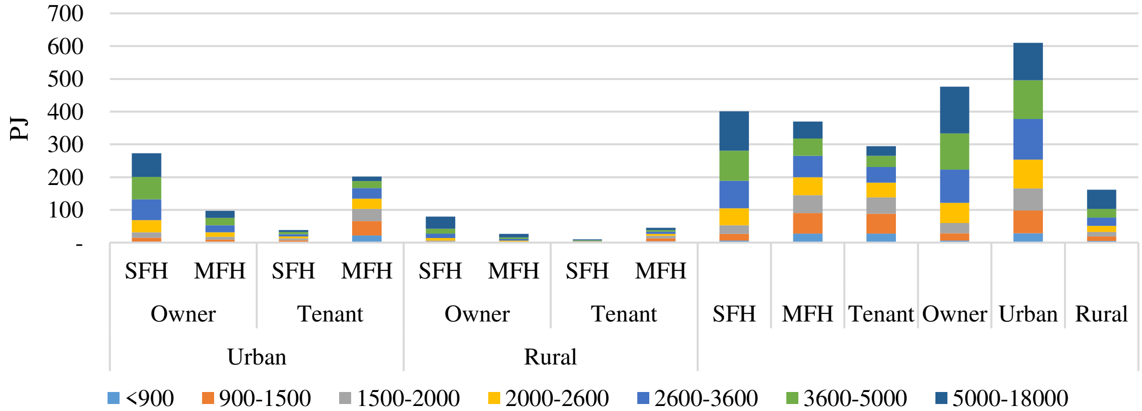

Figure 4-11: Distribution of total energy efficiency potential across income groups by tenure, building type and location

Source: own graph and calculations based on (IWU 2012; BBSR 2016; Cischinsky and Diefenbach 2018; Destatis 2016; TABULA 2015; Bach et al. 2014; Kockat and Rohde 2012; dena 2016; Destatis 2014b, 2013d)

Due to the amalgamation of data sets, it was possible to harmonise the energy balance calculated in this thesis with four building age categories. Differences are also accrued due to the disaggregation by income group, which takes into account different floor areas and energy demand values based on the final energy consumption and the efficiencies of technologies used opposed to the aggregated by building type and age estimations, as well as due to the averaging of the consumption taking into consideration the shares of renovated buildings for each profile. Nonetheless, overall the values taken in this thesis are within the expected range in comparison to the range estimated in the literature.

Figure 4-12 highlights this energy efficiency potential from the perspective of the income groups. Here, it becomes evident that in the upper four income groups, the greatest potential resides mainly in owner-occupied, SFH, while in the lower income groups, the largest potential is in the MFH rental sector for the lower three income groups. This underscores the significance of a differentiated policy approach to achieve renovations in the lower income sector. Energy efficiency options are modelled according to values used in the TIMES-PanEU model, which include four energy efficiency packages are defined to include a range of options to upgrade the thermal envelope and the heating supply system and are based on the TABULA/Episcope project to detail the expected savings for the level of renovation (TABULA 2015; Korkmaz et al. 2019). The packages enable harnessing the potential of the heat savings possible ranging from 19-61% for SFH and 27-55% for MFH. Further details on the techno-economic assumptions for the energy efficiency measures is given in Table E-2 in Appendix E.

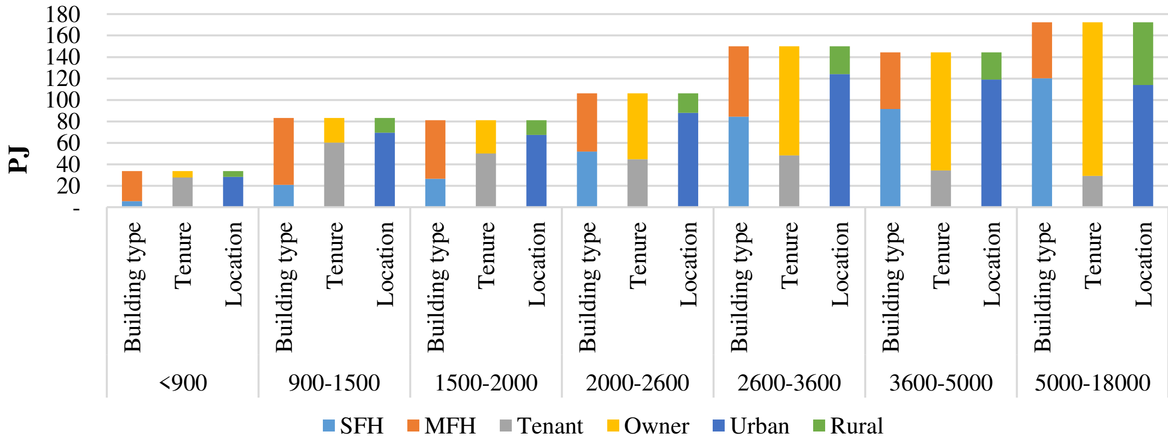

Figure 4-12: Distribution of total energy efficiency potential for existing buildings across income groups by parameter

Source: own graph and calculations based on (IWU 2012; BBSR 2016; Cischinsky and Diefenbach 2018; Destatis 2016; TABULA 2015; Bach et al. 2014; Kockat and Rohde 2012; dena 2016; Destatis 2014b, 2013d)

4.4.2 Appliances

The average efficiency improvement trends in electricity-based appliances are calibrated into the demand projections for these end-uses according to assumptions in (BMU 2019c) until 2035 and efficiency developments compared to the assessments and regression analyses of trends in (DeVita et al. 2018; Braungardt et al. 2014; Korkmaz et al. 2019). The trends were extrapolated based on total expected electricity consumption in the household sector according to assumptions in (BMU 2019c) until 2060 and the final efficiency trends taken in this thesis are shown in Figure 4-13. The range of trends according to these studies for the different end-uses is detailed in Figure E-1. Refrigeration and freezer demand represents a significant share of the total electricity demand with 34.1% in the lowest income group, 15.2% in the highest income group and 18.4% in the average household (Figure 4-14), and therefore a significant opportunity to reduce energy consumption in households. Replacing an existing E/F efficiency class refrigerator-freezer combination with an A or B efficiency class alternative, which are 60% to 53.5% more efficient, respectively, also requires high upfront costs (European Commission 2019; DeVita et al. 2018).

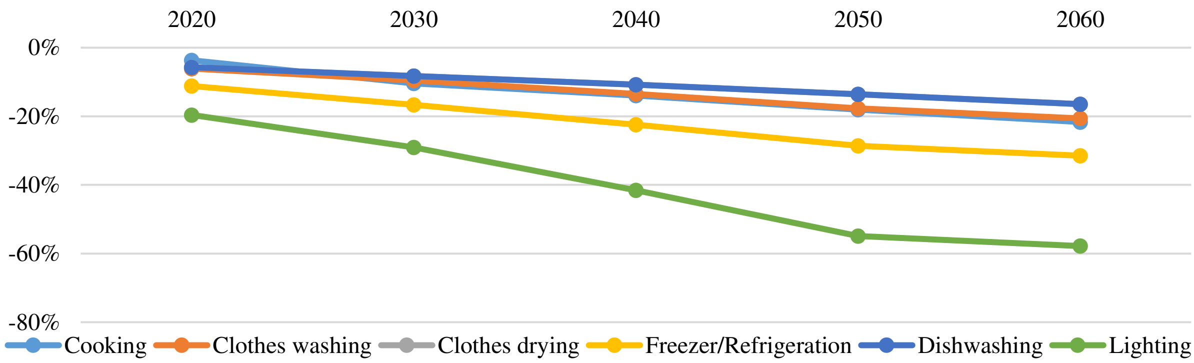

Figure 4-13: Cumulative efficiency improvements in electricity-based household appliances compared to 2013, 2020-2060

Source: own graph and calculations based on (BMU 2019c; Korkmaz et al. 2019; Braungardt et al. 2014; DeVita et al. 2018)

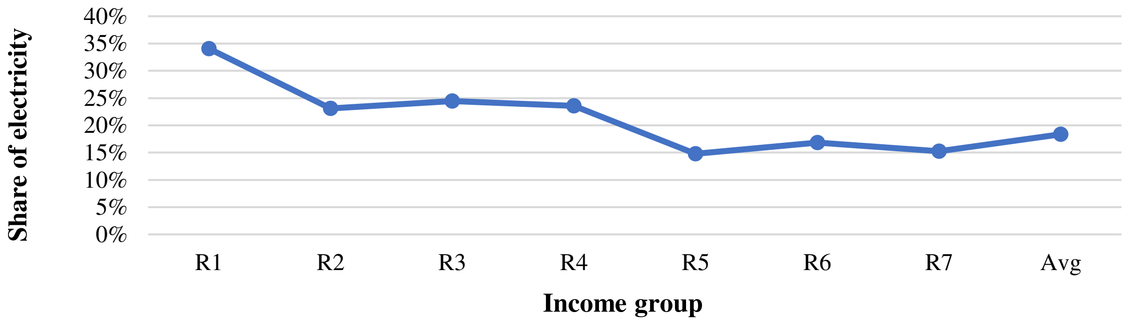

Figure 4-14: Share of refrigeration/freezer electricity consumption of total electricity consumption per income group

Source: own graph and calculations based on (BMWi 2021; UBA 2011; Destatis 2014a, 2014b)

In the example illustrated in Figure 4-15, a lower income household stands to save 305% of the operating costs over the lifetime of the refrigerator if replaced with an A class energy efficient appliance, yet the investment costs represent 4 years of the operation budget upfront.

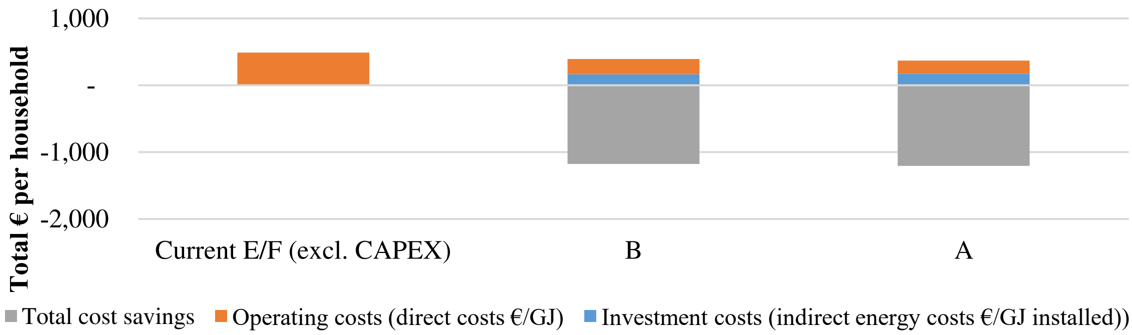

Figure 4-15: Comparison of investment and operation costs for the replacement of an existing refrigerator-freezer combination in a lower income household

Source: own graph and calculations based on (European Commission 2019; DeVita et al. 2018)

The affordability of the higher upfront costs of household appliances and the policies restricting the uptake of new, more efficient technologies in lower income households dependent on social welfare complicates the situation (HartzIV 2019). Without alternative support programmes for lower income households – such as the "Energy savings check" (*Stromsparcheck*) project initiated by Caritas – the affordability of the higher upfront costs of more energy efficient appliances may be untenable and means there is a greater reliance on second-hand appliances despite the longer term lower costs of more efficient, but higher priced alternatives (Boardman 2010; Caritas 2015).

This issue of second-hand appliance use in households was introduced in Chapter 3.2.7 and further detailed in Appendix F as the basis for the case study evaluated in Chapter 5.2.4. The costs and efficiencies of further household appliances for cooking, cooling, clothes washing and drying, lighting, refrigeration and freezing have been updated according to De Vita et al. (2018).

4.5 TAM-Household model calibration

The TAM-Household model is calibrated using the final energy consumption statistics (BMWi 2021) and emissions (BMU 2019b) which details overall energy carriers by end-use for the household sector for the base year 2013, accounting for the overall trends in heating and cooling degree days which indicates a downward trend in heating needs and an upward trend for cooling (see Figure D-1 in Appendix D) (EUROSTAT 2021d). Figure 4-16 demonstrates the calibration of the model for 2015 according to available statistics compared to the outcomes of the TAM-Household model by end-uses and energy carriers. The parameters were aggregated to show the results for the overall energy carriers and end-uses and match up such that the input data leads to robust development in the following years within a standard deviation of ±5%.

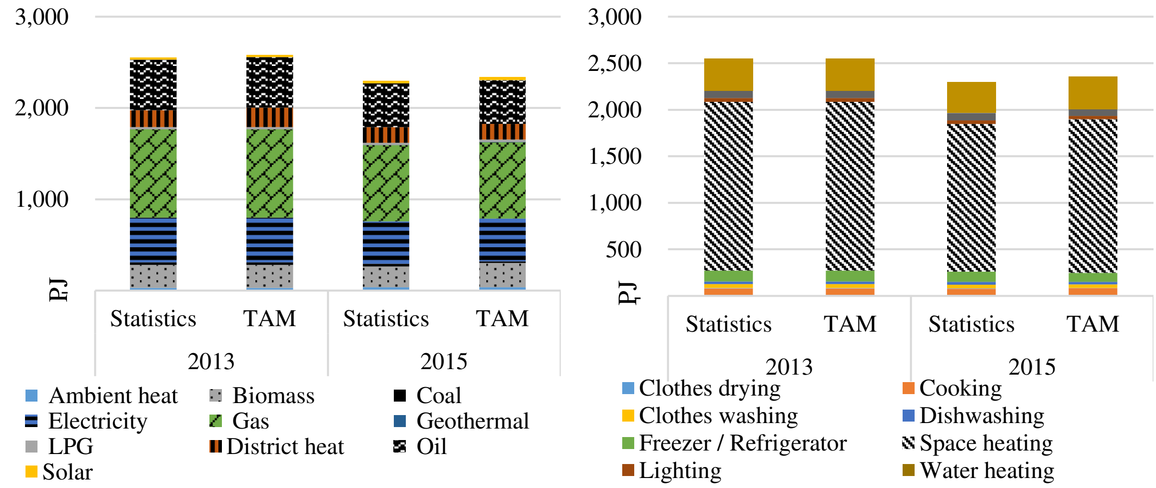

Figure 4-16: Comparison of input data and outputs from TAM-Households for the household sector for the base year 2013 and calibration for 2015 by energy carrier (left) and end-use (right)
Source: own graph and calculations based on (BMWi 2021)

The calibration was also verified by disaggregating the total final energy consumption by income group, location, building type and ownership as shown in Figure 4-17. These values, too, exhibit minimal differences of ±5% to the statistics.

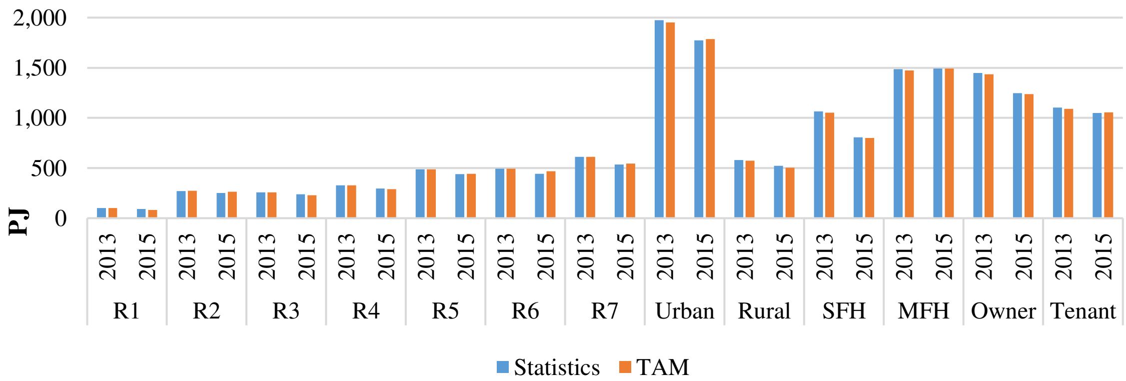

Figure 4-17: Comparison of final energy consumption in TAM-Households with statistics for 2013 and 2015 by socio-economic parameters
Source: own graph and calculations based on (BMWi 2021)

4.6 Conclusion: The TAM-Households model to assess energy poverty in the energy system

This chapter assessed how energy system modelling for the household sector is typically approached and explored methods for a more heterogeneous view of the actors within the household sector with a view of better understanding and incorporating energy poverty into an energy system model. The key attributes to be included into TAM-Households cover the differentiated investment and consumption behaviour of different actor groups in the household sector based on their socio-economic characteristics as well as the access and affordability of specific resources and technologies. Of the methods reviewed in the literature, several were incorporated directly or adapted so that TAM-Households could be applied to the research questions outlined in this thesis.

This thesis is developed based on the household sector of the existing TIMES-Germany model where the household sector is further disaggregated in order to explore the investment and consumption behaviour of different actor groups and the effects on energy use and emissions. The structure is developed in such a way that the energy system model allows a holistic analysis accounting for the heterogeneity of the population and the limitations in investment arising from socio-economic constraints, such as a limited household budget, prioritisation of investment trade-off decisions between different household energy service demands, e.g. second-hand appliance purchases and extending the economic lifetime of appliances beyond their technical lifetime. By capturing this disaggregated view point and considering the role that income has in achieving the necessary investments, the energy welfare of households can be assessed within the context of ensuring energy transition targets are met. This TAM-Households model was developed to determine the least-cost, maximum benefit pathway for households taking into account the investment and consumption behaviour of specified profiles. The methodology includes the limitation of the financial capacity of different actors in the household sector through budget constraints, which converts the modelling algorithm to include a dual objective (minimise costs, maximise benefits) rather than only solving for the least-cost. The methodology developed in this thesis is designed to evaluate not only the energy and emissions of different pathways, but also the distributional and overall impacts of different policies, thereby providing a tool to specifically support the debate about which policies will facilitate a just transition.

In the following chapter, the application and results of the TAM-Households model are assessed in terms of the effects of energy poverty on the energy system and vice versa. TAM-Households will be applied to investigate the energy welfare of lower income households and will better be able to account for the gaps in investment from the different income groups and, in turn, assist in identifying insights for achievable targets and development of policy measures towards the improvement of the energy welfare of lower income households

“The reason that the rich were so rich, Vimes reasoned, was because they managed to spend less money. Take boots, for example. He earned thirty-eight dollars a month plus allowances. A really good pair of leather boots cost fifty dollars. But an affordable pair of boots, which were sort of OK for a season or two and then leaked like hell when the cardboard gave out, cost about ten dollars. Those were the kind of boots Vimes always bought, and wore until the soles were so thin that he could tell where he was in Ankh-Morpork on a foggy night by the feel of the cobbles. But the thing was that good boots lasted for years and years. A man who could afford fifty dollars had a pair of boots that'd still be keeping his feet dry in ten years' time, while the poor man who could only afford cheap boots would have spent a hundred dollars on boots in the same time and would still have wet feet. This was the Captain Samuel Vimes 'Boots' theory of socioeconomic unfairness.”

Sir Terry Pratchett, Men at Arms, 1993 (1948-2015)

5 Integrated assessment of energy poverty

The objective of this chapter is to develop evidence-based policy recommendations through an energy system analysis on how households can meet energy transition targets without compromising their energy welfare. This integrated assessment of energy poverty is evaluated through a scenario analysis using the newly developed TAM-Households model. The scenario analysis forms the basis to apply the modelling method to understand the implications of the methods on the results. The overall scenario framework and the underlying assumptions are described in Chapter 5.1 followed by the three scenario blocks assessed in this study depicted in Figure 5-1: 1) Showcasing the TAM-Households method by exploring the differences between an aggregated and disaggregated model and the impact of budget constraints (Chapter 5.2); 2) Exploring energy poverty parameters of access and affordability (Chapter 5.3); 3) Exploring the improvement of the energy welfare of low income households and the impact of policies and alternative redistribution of energy taxation (Chapter 5.4). An evaluation of the scenarios with respect to the methodology is discussed in Chapter 5.5. Chapter 5.6 concludes with a summary of the key insights.

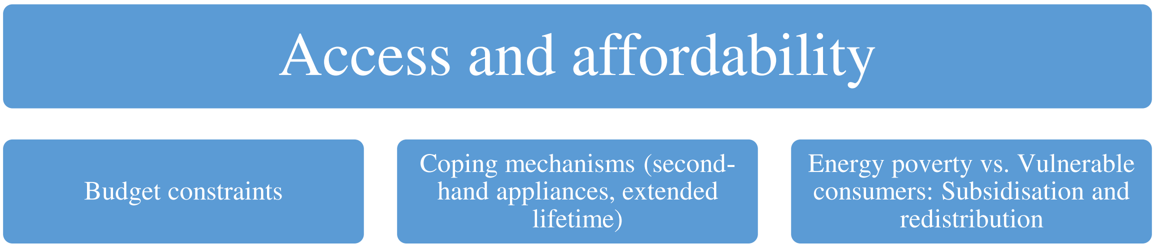

Figure 5-1: Overview of scenarios assessed with TAM-Households

5.1 Overall scenario framework and assumptions

The overarching scenario framework includes common assumptions across all scenarios for the input data and projections of the socio-economic framework and the various techno-economic parameters. These assumptions are based on available data and the consistency is validated as described in the following sections.

5.1.1 Socio-economic and political framework assumptions

A common political framework underpins the scenario assessments and includes achieving the renewable energy and energy efficiency targets outlined in Chapter 1.2. The overarching framework for socio-economic development is assumed across all scenarios. The common methodology implemented to forecast energy demand in the residential sector is based on assumptions around these socio-economic parameters (population, number of households, household size, number of occupants, disposable income, floor area and climatic variables) and provided exogenously to the model (BMU 2019c; Hall and Buckley 2016; Gouveia et al. 2009; Cayla and Maizi 2015; Haasz 2017). In TAM-Households, the projection of the demand for the household sector is calibrated according to the prognosis of specific energy carriers and the related demands by end-use according to the configuration of the drivers of energy demand defined for each building type within each profile developed for the energy balance for the base year of 2013 (i.e. depending on the efficiency of buildings and technologies, number of occupants, location, floor area, as described in Chapter 3.2 and detailed in Appendix C).

Specifically, the development is based on (BMU 2019c) and further projected to 2060 based on a regression analysis for population, numbers of households, floor area and building types given in Table 5-1 (IMF 2019a; Destatis 2019a; dena 2019; Gerbert et al. 2018). The prognosis for the population is further defined for each income group as per the profiles disaggregated and described in Chapter 3.3 with regard to location, building type, tenure and income. The population and number of households is expected to increase and then decrease again over time such that overall in 2060 against 2013 there is an annual decrease of 0.1% and increase of 0.1%, respectively. There is a trend towards more single-family and larger homes (increasing floor area) with these increasing annually by 0.3% and 1.1%, respectively. The total number of multi-family homes first increases then decreases to reach the same total in 2060 as in 2013, and also shrinks in size.

Table 5-1: Socio-economic parameters for the scenario analysis

Source: (EUROSTAT 2017; IMF 2019a; Destatis 2019a, 2018c, 2013a, 2016; dena 2019; BMU 2019c; Gerbert et al. 2018)

		2013	2030	2040	2050	2060	Change (2013-2060)	Avg. annual change (2013-2060)
GDP	*bn €2015*	2,913	3,737	4,150	4,594	5,021	72.4%	1.5%
Population	*m*	78.9	82.6	80.9	78.0	74.9	-5.0%	-0.1%
GDP per capita	*€2015/capita*	36,948	45,246	51,308	58,892	67,015	81.4%	1.7%
Households	*m*	39.3	42.8	43.0	42.4	41.6	5.8%	0.1%
SFH	*m*	12.3	13.5	13.8	13.9	14.0	13.7%	0.3%
MFH	*m*	27.0	29.3	29.2	28.5	27.6	2.3%	0.0%
Total floor area	*m m2*	3.99	4.45	4.48	4.45	4.36	9.2%	0.2%

As such the shift of the number of households in each income group and the shares of the population by tenure, building type and urbanisation is illustrated in Figure 5-2. There is an observed overall decline in the shares of lower income groups due to the shift of the population into higher income groups resulting in a higher average income per capita. While overall the absolute number of households declines due to the corresponding decrease in population, there is an increasing trend in shares of residence in multi-family homes (66%), home ownership (59%) and living in urban areas (74% households, 90.7% population) in 2060.

Validation of the projections are in line with expected overall energy carrier use for each sector given assumptions for 2020 and 2035 (BMU 2019c), and driven by population, households, household size, floor area as well as associated shifts in numbers of households between income groups and across location, building types, household income and expenditure, and available capital for investments (Destatis 2013c; IMF 2019a; Destatis 2019a; EUROSTAT 2020; United Nations 2018; Destatis 2019b). The expected heating and cooling degree days will impact on space heating and cooling demands. Between 2013 and 2015, the heating demand decreased due to the mild winter, whereas this increased again sharply to 2020 with a distinctly colder winter. The further prognosis of the heating and cooling demands are aligned with climate estimates on scenarios undertaken in Germany which are based on estimates made on the European level (Kemmler et al. 2020; European Commission 2020e). The overall tendency is towards milder winters requiring less heating and warmer summers requiring more cooling, such that these demands decrease and increase, respectively, as shown in Figure D-1 in Appendix D.

The development of the available budget for each profile is applied to the model exogenously, and is projected based on GDP developments and allocated to each profile according to the disposable income and savings statistically available to each income group. Demand for particular technologies or end-uses are determined exogenously based on the inherent improvements in the energy efficiency of technologies used by households, which means that as technologies become more efficient through design, the energy demands are reduced, as discussed in Chapter 4.4 (BMU 2019c; Braungardt et al. 2014).

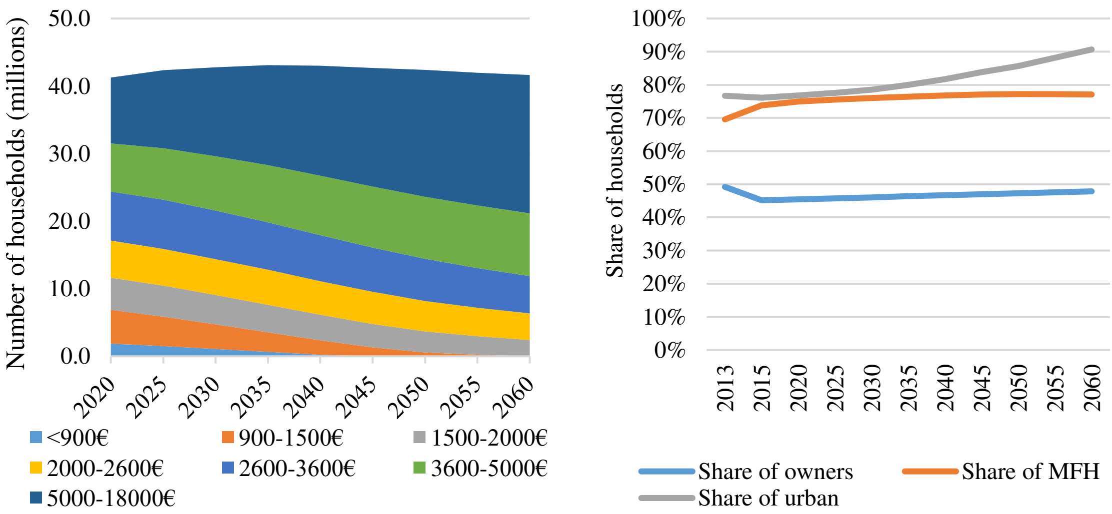

Figure 5-2: Development of households by income group (left) and share of population by ownership, multi-family home and rate of urbanisation (right)

Source: (EUROSTAT 2017; IMF 2019a; Destatis 2019a, 2018c, 2013a, 2016; dena 2019; BMU 2019c; Gerbert et al. 2018)

5.1.2 Techno-economic assumptions

The techno-economic assumptions in this analysis described in this section cover the energy prices, resource and technology potential, and discount rates. Standard emission factors for each residential fuel type in Germany are applied (Juhrich 2016).

5.1.2.1 Energy prices

The initial basis for consumer prices for energy were based on an analysis of global market prices for Germany calculated within the Decentral project (Ahanchian et al. 2020), where overall there is a cross-border price decrease for crude oil of -10% and an increase of 10% for natural gas between 2018 and 2060 and based on the IEA *Sustainable Development* scenario, as shown in Table 5-2 (IEA 2018b; BMWi 2021). The future development of consumer prices of secondary fuels processed from primary fossil fuels and including oil products like LPG and fuel oil are dependent on primary fuel prices (IEA 2018; BMWi 2019a).

Table 5-2: Price assumptions for primary fossil fuels

Source: (IEA 2018; BMWi 2021; Ahanchian et al. 2020)

		2013	2018	2030	2040	2050	2060
Crude oil	*US$$_{2017}$/bbl*	110	67	66	64	62	60
Cross-border prices							
Crude oil	*€2015/GJ*	14.5	10.3	10.2	9.9	9.6	9.2
Natural Gas	*€2015/GJ*	8.6	5.7	7.1	6.6	6.1	5.8
Lignite	*€2015/GJ*	1.0	1.0	1.0	1.0	1.0	1.0

Biofuel prices were based on estimates for the transport sector and compete with light fuel oil prices (Ahanchian et al. 2020). Biomass prices were based on a regression analysis for import wood prices, but it should be noted that as a limited resource, the prices could become more expensive in relation to competitive energy prices (Ahanchian et al. 2020). Hydrogen prices for consumers were adapted from (Bundestag 2020). A linear regression analysis conducted on historical data of primary fuels and consumer prices resulted in the household energy prices shown in Table 5-3, which are the final consumer prices including all additional taxes, with the exception of the carbon tax (see chapter 4.3.4). The renewable energy surcharge (EEG) on electricity is assumed as a cost reduction, which is funded through the BEHG (Vermittlungsausschuss 2019; Bach et al. 2020). These are applied in the model separately as profile-specific so that different energy prices and taxes can be applied to different consumer groups.

Table 5-3: Final household energy prices including taxes (€$_{2015}$ per GJ), 2013-2060
Source: (BMWi 2021; IEA 2018; BDEW 2020; Harthan et al. 2020; Kuhlmann et al. 2020; Kreidelmeyer et al. 2020)

Energy carrier	2013	2018	2030	2040	2050	2060	Source
Fossil fuels							
Coal products	18.1	18.2	18.1	18.0	-	-	Regression analysis according to (BMWi 2021)
Light fuel oil	24.2	16.2	24.7	27.9	31.1	33.8	
Liquefied Petroleum Gas	24.3	18.1	24.7	27.2	29.7	31.7	
Natural gas	23.0	19.3	21.3	22.2	22.8	23.1	
Other fuels							
Biomass	13.8	13.9	14.3	14.3	14.4	14.6	Regression analysis based on import wood prices (Ahanchian et al. 2020)
Biofuel	41.7	33.1	42.2	45.6	49.1	51.9	Regression analysis based on international crude oil prices
District heating	26.0	22.4	27.3	24.3	26.0	26.5	Regression analysis based on (BMWi 2021); forecast linked to base electricity price
Electricity total	81.3	80.8	94.0	91.2	81.7	83.0	Regression analysis based on (Harthan et al. 2020; BDEW 2020)
EEG levy relief	0.0	0.0	-7.3	-6.4	-5.5	-4.6	(Vermittlungsausschuss 2019) financed through the BEHG; forecast based on (Kuhlmann et al. 2020)
Electricity for heat pumps	65.0	64.6	75.2	73.0	65.4	66.4	20% less than electricity price, based on assumptions (BMWi 2021)
Hydrogen	-	-	65.8	48.1	44.1	39.5	(Kreidelmeyer et al. 2020)

5.1.2.2 Resource and technology potential

Several resources are limited due to their availability. This section describes how the potential for biomass, PV, solar thermal, district heating and heat pumps is distributed across the profiles. As described in Chapter 3.3 and 4.3.2, the resource potential is determined through the feasible access of each profile, given their characteristics (e.g. location, building type, useful area), to these resources.

The overall *biomass potential* in Germany is estimated at about 1,200 PJ (Joest et al. 2009). The upper limit available to the household sector was estimated to not exceed 450 PJ in 2060 (Ahanchian et al. 2020). The distribution of the consumption of biomass by the profile characteristics (e.g. location and building type) are given by (Döring et al. 2020). In 2013, the biomass potential is consumed to a larger share in urban areas (63% of the total biomass potential) and single-family homes in both rural and urban areas, representing each 31% and 54% of the total biomass potential consumed, respectively. The shares remain relatively stable into the future, but because the assumption is coupled to the development of the number of each building type according to the location in urban and rural areas, the available potential consumed by each profile changes correspondingly. For example, while the SFH in urban areas declines, the same building type increases in rural areas. The distribution of the biomass potential consumed by various characteristics is detailed in Table 5-4.

Table 5-4: Distribution of consumption of biomass potential by characteristic, 2013-2060
Source: (Döring et al. 2020; Joest et al. 2009)

	Statistics 2013		Projection 2030		2040		2050		2060	
Profile	%	PJ	%	PJ	%	PJ	%	PJ	%	PJ
Total (upper)		252		300		450		450		450
Urban	63%	159	67%	201	65%	294	64%	287	63%	283
Rural	37%	92	33%	99	35%	156	36%	163	37%	167
Owner	94%	236	92%	277	93%	419	94%	422	94%	424
Tenant	6%	15	8%	23	7%	31	6%	28	6%	26
SFH	86%	216	86%	257	86%	387	86%	389	87%	391
MFH	14%	36	14%	43	14%	63	14%	61	13%	59
Urban SFH	54%	137	57%	172	39%	174	38%	173	38%	173
Urban MFH	9%	23	10%	29	6%	28	6%	27	6%	26
Rural SFH	31%	79	28%	85	20%	91	21%	94	22%	97
Rural MFH	5%	13	5%	14	3%	15	3%	15	3%	16
<900€	1%	3	4%	12	1%	2	0%	-	0%	-
900-1500€	4%	11	9%	26	3%	15	1%	4	0%	-
1500-2000€	6%	14	8%	25	5%	22	4%	18	3%	14
2000-2600€	11%	29	14%	43	9%	41	8%	37	7%	32
2600-3600€	20%	49	23%	69	15%	66	13%	60	12%	53
3600-5000€	23%	57	21%	62	15%	68	16%	71	16%	72
5000-18000€	35%	89	21%	63	17%	77	20%	89	22%	97

The *rooftop potential for PV and solar thermal installations* is calculated based on the current market shares of the total available rooftop capacity and projected development for the household sector. The potential for the household sector is distinguished from the total potential for all sectors based on the building type and the maximum potential generation capacities by sector (JRC 2019; Tash In preparation; Trend: research GmbH 2017; Holstenkamp 2013). Estimates put that only 38% of all residential and non-residential building rooftops are suitable for solar installations due to the restrictions such as optimal facing rooftops, hindrances, building permit curbs, heritage status. (Demuth et al. 2013). These aspects are considered and only the total technical potential is elaborated. As such, the aggregated potential is distributed to each income group based on the final total useful area of each building type resulting in the shares shown in Table 5-5 (Destatis 2016). In 2013, the majority of the potential is in urban areas (78%), where the greater potential is in SFH (78%). The potential increases with income group due to the proportionately increasing share of useful roof area. Into the future, the majority of the potential is in the higher income households as the lower income household wealth increases thereby shifting the population into the higher income groups, where the size of the home and the corresponding rooftop potential increases. The decline of the potential towards 2060 is linked to the availability of rooftop space according to the overall decline in the number of residential buildings and the development of rooftop sizes in line with building areas (Destatis 2013d, 2018c).

Table 5-5: PV rooftop potential by characteristic, 2013-2060

Source: (JRC 2019; Trend: research GmbH 2017; Holstenkamp 2013; Demuth et al. 2013; Tash In preparation; Destatis 2013d, 2018c)

	Statistics 2013		Projection 2030		2040		2050		2060	
Profile	%	**PJ**	%	**PJ**	%	**PJ**	%	**PJ**	%	**PJ**
Total (upper)		263		301		300		298		297
Urban	78%	205	77%	231	76%	226	75%	222	74%	220
Rural	22%	58	23%	71	28%	73	25%	76	26%	77
Owner	77%	202	80%	176	94%	180	84%	184	86%	186
Tenant	23%	61	20%	125	20%	119	16%	114	14%	111
SFH	78%	206	80%	114	94%	112	85%	112	87%	112
MFH	22%	57	20%	187	20%	187	15%	186	13%	185
Urban SFH	60%	159	61%	85	71%	83	63%	82	64%	81
Urban MFH	18%	46	16%	145	15%	143	12%	141	10%	139
Rural SFH	18%	47	19%	29	23%	29	22%	30	23%	31
Rural MFH	4%	11	4%	42	4%	44	4%	46	3%	46
<900€	2%	6	1%	2	0%	1	0%	0	0%	0
900-1500€	7%	18	3%	10	2%	5	0%	1	0%	0
1500-2000€	8%	20	5%	17	5%	13	3%	10	2%	7
2000-2600€	12%	33	10%	31	10%	26	7%	22	6%	18
2600-3600€	20%	52	18%	55	18%	47	13%	39	11%	34
3600-5000€	22%	57	25%	75	30%	79	27%	82	29%	86
5000-18000€	29%	77	37%	111	49%	128	48%	144	51%	151

The *district heat potential* applied in this thesis is related to the theoretical projected extension of the network and the related availability for the residential market. The entire district heating potential is available only to households located in urban areas. The lower and upper bounds are taken from (Blesl et al. 2018) and represented in Table 5-6 until 2050, with a continued expected trend extrapolated to 2060.

Table 5-6: District heat potential for the total residential sector, 2013-2060

Source: (Blesl et al. 2018)

PJ/a	2020	2030	2040	2050	2060
Total max. potential	320	560	490	460	450
Min. household potential	143	113	98	86	79
Max. household potential	240	420	368	345	338

The *heat pump potential* is considered from the point of view of bounds on both the supply and demand sides, which include, for example, the limited resource availability or grid access. This means heat pumps are also limited by the possibility to install these based on the building type as well as the housing density although the differentiation is not given for urban and rural, simply the aggregated shares based on the assumption of a certain national housing density. The maximum potential for heat pumps by energy source and building type is modelled as an upper bound by technology and building type as shown in Table 5-7 (Bubeck 2017).

Table 5-7: Maximum potential for heat pumps by energy source and building type

Source: (Bubeck 2017)

Energy source	SFH		MFH	
	existing	new	existing	new
Geothermal	60%	80%	30%	50%
Ambient heat	70%	90%	50%	70%
Geothermal or ambient heat	70%	90%	50%	70%
Solar thermal	80%	80%	50%	50%

5.1.2.3 Discount rates

The role of the discount rate is to discount future cash flows and to account for different characteristics of investment and consumption behaviour, such as preferences, income or lack of decision-making power, as outlined in Chapter 4.2.2 and 4.3.3, for the selection of actor groups included in the model through monetarisation. Aside for the global discount rate for the household sector of 10% (which is in line with literature ranging from 9%-14.1% (Fotiou et al. 2019; Nijs et al. 2015; E3Modelling 2018; García-Gusano et al. 2016), different actor groups have alternative discount rates for specific technologies to reflect the diverse values each actor groups gives to technologies (e.g. energy efficiency) and decision-making as well as the perceived cost of equity and debt (Fotiou et al. 2019; Ameli and Brandt 2015; Mundaca et al. 2010). For example, since tenants do not use their own budget restrictions for certain investments the discount rate should be higher for landlords as the perceived higher initial investment cost (Tomaschek et al. 2009; Bouzarovski et al. 2018; Griffiths and Causse 2010) and can be as high as 35% to reflect the split incentives problem of landlords unwilling to invest into tenant properties as applied in France (Hermelink and Jager 2015). To represent this, the hurdle rate for investments into tenant properties (e.g. for space and water heating, PV and insulation) is higher for landlords than into their own properties and is given in Table 5-8. For lower income households, this same type of hesitation or limitation to invest is represented through the budget constraint. For landlords who speculate that investments would increase the value of the property and invested costs would be recouped through increased rental prices, the discount rate would be lower (Leskinen et al. 2020; Ameli and Brandt 2015).

Table 5-8: Actor-specific discount rates

Source: (Hermelink and Jager 2015; Tomaschek et al. 2009; Fotiou et al. 2019; Nijs et al. 2015; E3Modelling 2018; García-Gusano et al. 2016)

Actor group	%	Source
Global	10%	Based on (Fotiou et al. 2019; Nijs et al. 2015; E3Modelling 2018; García-Gusano et al. 2016)
Landlords (heating, water heating, PV)	35%	(Hermelink and Jager 2015; Tomaschek et al. 2009)

5.1.3 Indicators

The status of the energy system as well as the respective changes assessed with TAM-Households can be estimated through specific indicators. Given the complexity of the energy poverty lived experience and without survey information, it is difficult to link directly the impact of scenarios since the typical energy poverty indicators are a mix of subjective and consensual statistics (see Chapter 2.2). In this thesis, the indicators are calculated by correlating the potential impact of the scenario pathways with energy expenditure, investment expenditure and energy prices and as they relate to the projection of the median income for each profile as was undertaken by (Pye et al. 2019). While these indicators may not reflect the definitive pathway towards reducing energy poverty, they can give an indication of the tendency of various parameters and the potential to affect energy welfare over time, since the concept refers to a households being able to meet energy service demands at affordable cost (see Chapter 2.1). The indicators included in this thesis are applied to assess issues related to energy poverty, affordability of meeting energy needs, and evaluating a just transition (as outlined in Chapter 2.1 and 2.2) while achieving objectives outlined in the energy transition (i.e. carbon and energy intensity, share of renewables for heating, share of access to self-generation and heat pumps), specifically as shown in Table 5-9. These are estimated as follows:

- Carbon intensity (GHG-I) is the CO_2-eq per capita calculated according to the fuels consumed and the correlating emission factors
- Energy intensity (EU-I) is the ratio between energy consumed and energy required (based on energy balance developed described in Appendix C)
- Renewable energy (%RE) is the share of renewable energy consumed for heating
- Access/Prosumers (%PV) is the share of self-generation of total electricity consumption
- Affordability (%INV) is the share of income spent on energy-related investments (indirect) (statistical calculation)
- Affordability (%EXP) is the share of income spent on energy consumption (direct) (bottom-up calculation)
- Inability to keep comfortably warm (%Warm) is the statistical share of population unable to keep their homes warm (EU-SILC statistics) – correlated to energy expenditure and income
- Arrears in utility bills (%Debt) is the statistical share of population in arrears in utility bills (EU-SILC statistics) – correlated to energy expenditure and income
- Hidden energy poverty (2M) is the statistical share of population spending more than twice the median (2M) in 2015 (HBS statistics) – correlated to energy expenditure and income
- Hidden energy poverty (M/2) is the statistical share of populations spending twice less than half the median (M/2) in 2015 (HBS statistics) – correlated to energy expenditure and income

In the base year, the carbon and energy-use intensity increases with decreasing income, which reflects the greater dependency on fossil fuels in lower income households. In relation to income, the energy welfare is severely impacted as the lower income households perform worse than the average household and are consuming markedly less self-generated electricity or renewables for heating, and spending more on energy. The energy poverty markers are, as can be expected, significantly worse for lower income households. Less variation can be found when comparing the energy poverty markers by physical parameters, but SFH and owners are stronger prosumers and consumers of renewable energy than their counterparts.

Table 5-9: Baseline indicators, REF scenario, TAM-HHs, 2013

Source: own calculations as described, (EUROSTAT 2018b, 2018a; EPOV 2021)

Indicator	Greenhouse gas emissions: CO_2 intensity	Energy efficiency: energy use intensity	Renewable energy: renewables for heating	Access: self-generation of total electricity consumption	Affordability: income spent on energy-related investments	Affordability: income spent on energy consumption	Inability to keep comfortably warm	Arrears in utility bills	Hidden energy poverty: overspending	Hidden energy poverty: underspending
	GHG-I	EU-I	%RE	%PV	%INV	%EXP	%Warm	%Debt	2M	M/2
Unit	*CO_2-eq/ capita*	*Ratio*	*% RE in heating*	*% PV self-generation*	*% income*	*% income*	*%population*	*%population*	*%population*	*%population*
<900	1.42	0.98	3.2%	0.0%	0.5%	11.4%	16.6%	9.0%	51.7%	24.6%
900-1500	1.42	1	4.5%	0.0%	0.3%	9.3%	14.1%	8.6%	47.2%	23.2%
1500-2000	1.39	0.94	5.7%	0.0%	0.7%	7.3%	8.5%	6.4%	30.8%	20.2%
2000-2600	1.36	0.91	12.1%	12.6%	0.8%	6.3%	4.8%	3.2%	20.1%	19.2%
2600-3600	1.25	0.89	17.9%	9.4%	0.7%	5.9%	2.3%	1.9%	13.7%	20.0%
3600-5000	1.19	0.89	20.7%	8.5%	0.6%	5.0%	1.2%	1.2%	9.4%	16.2%
5000-18000	1.22	0.86	23.0%	7.6%	0.6%	3.6%	0.5%	0.5%	5.7%	14.3%
Urban	1.25	0.89	13.3%	7.5%	0.4%	5.4%	2.3%	1.9%	-	-
Rural	1.39	0.75	22.4%	8.4%	0.3%	4.6%	8.5%	5.0%	-	-
SFH	1.63	0.67	30.3%	16.2%	0.3%	4.9%	5.6%	3.7%	15.8%	17.1%
MFH	1.13	0.99	3.6%	4.1%	0.4%	4.8%	5.2%	3.5%	20.1%	18.0%
Owner	1.44	0.73	24.9%	15.6%	0.3%	4.7%	3.1%	2.6%	-	-
Tenant	1.13	1.21	2.2%	0.0%	0.4%	4.9%	4.9%	3.7%	-	-
Total	1.28	0.89	15.3%	7.7%	0.7%	4.7%	5.3%	3.6%	17.4%	17.4%

5.2 Exploring the TAM-Households model features for the household sector

This section explores the effects of the modelling features included in TAM-Households and the overall investment decisions and consumption profiles. In the first instance, these are compared to an aggregated model to evaluate the effects of these additional features as it relates to the methodology employed. The scenarios for this comparison are described in Chapter 5.2.1. The results analysis begins with a direct comparison of the two models highlighting first the significance of disaggregation on the overall energy and emissions developments in the household sector in Chapter 5.2.2, followed by the impact of including budget constraints in Chapter 5.2.3. This is followed by a case study in Chapter 5.2.4 exploring the impact of second-hand appliances and extending the technical lifetimes of technologies on the overall energy and emissions (as described in Chapter 4.3.3). The chapter concludes with a summary of the insights.

5.2.1 Scenario descriptions

The reference scenarios for each model compare the results of the aggregated model with the TAM-Households disaggregated model as described in Table 5-10. The expected policies implemented are identical and the socio-economic framework differs only due to the level of disaggregation in the respective models, where the aggregated model has 6 aggregated actors (3 base year profiles + 3 additional new profiles) (as described in Chapter 4.1) and TAM-households has 112 profiles (56 base year profiles + 56 additional new profiles) as described in Chapter 3.2. While the underlying assumptions around the socio-economic parameters remain the same, the distribution differs due to the averaged living area by building type thereby resulting in different inputs for the demands for the aggregated model compared to the socio-economic framework in TAM-Households, e.g. related to the inclusion of investment and consumption by income groups and development of the total floor area (3.8 bn m^2 in 2013 and decreasing to 3.5 bn m^2 in 2060). The TAM-Households methodology is then compared without the budget constraints in the BUDGET0 scenario.

Table 5-10: Scenario description: Reference scenarios

Socio-economic framework (GDP, population growth, energy prices, etc.)		
Reference scenarios	**Aggregated model (AGG)**	Aggregated household sector with 6 profiles (3 existing + 3 new), all expected policies implemented
	TAM-Households (TAM-HH/REF)	Disaggregated household sector with 112 profiles (56 existing + 56 new), budget constraints, all expected policies implemented
	BUDGET0	Disaggregated household sector *without* budget constraints, *without* increased landlord discount rate, all expected policies implemented

5.2.2 The significance of disaggregation on energy use and emissions

The differences in the distribution of the socio-economic framework lead to disparities in the underlying assumptions for the drivers of demand such that given the requirements to decarbonise by 2050, the development pathways and associated investment and consumption patterns differ significantly. The aggregated model has a steeper exit from oil consumption than in TAM-HHs, but overall has a slower downward trend towards 2060 with a total final energy consumption of 863 PJ, which is around 223 PJ higher compared to TAM-Households, as depicted in Figure 5-3. This decreased consumption in TAM-Households is due to the lower consumption of high input fuels, such as biomass, as well as the consideration of the shift in the population to higher income groups which have greater energy efficiency in appliances and the consideration for lower income households, who have lower demands than the average household. The decline in the aggregated model is reflected in the uniform reduction of the consumption of oil and gas, whereas the budget constraints in TAM-HHs highlights the staggered investments. The aggregated model reduces the final energy consumption to four main energy carriers: biomass (35.3%), district heating (28.9%), ambient heat (14.1%), and electricity (21.6%) in 2050. Whereas TAM-HHs favours biomass (29.7%), district heating (23.9%), electricity (19.2%), ambient heat (17.4%) and biofuels, (9.6%) in 2050.

These differences can be attributed to the consideration of access to specific fuels in TAM-HHs, which are constrained by the location and building type, as well as the lack of capital to invest in infrastructure. While the aggregate model maximises the use of biomass and employs heat pumps as a key component of decarbonisation, TAM-HHs incorporates hydrogen fuel blends and biofuel-based heaters. TAM-HHs takes into consideration the technical and legal limitations of specific heaters based on the required installed capacities and this excludes several technologies from the outset. Additionally, due to the limitation in the availability of expected energy carriers for decarbonisation (e.g. district heating, which is restricted to urban households only), TAM-HHs exhibits a more diverse panel of energy carriers used, such as the technical need to rely on biofuels (and hydrogen) in the short to medium term in order to bridge the transition to decarbonisation. This underscores the urgency of taking action in the next 5-10 years to influence the types of new, costly investments undertaken. In TAM-HHs this also results from the budget constraints limiting the short-term ability to afford the costs of new infrastructure or to replace technologies, so the cost-optimal solution is to blend fuels within the existing infrastructure or to feed existing technologies. While the addition of tax financially discourages the consumption of fossil-based fuels, the CO_2 tax as a price signal alone is insufficient in achieving these desired effects with both models only resulting in full decarbonisation in 2050 when emissions are no longer allowed.

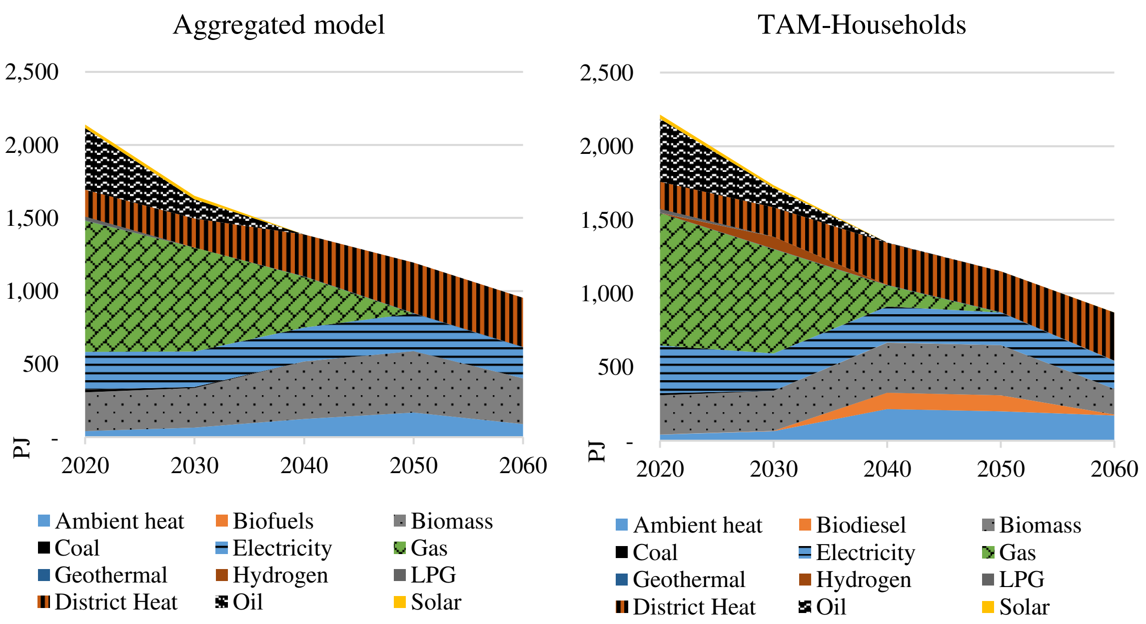

Figure 5-3: Comparison of the development of the total final energy consumption in the aggregated model (left) and TAM-Households (right) by energy carrier, 2020-2060

Space heating represents the majority of consumption across both models with shares in 2050 of 76% and 57% in the aggregated model and TAM-HHs, respectively. To better assess these trends, the final energy consumption by energy carrier for heating in MFH is compared in Figure 5-4. In 2030, the distribution of energy carriers for heating in MFH contrasts starkly, where TAM-HHs shows a greater reliance on gas and district heating and the aggregated model overestimates the energy reduction potential in these building types and favours gas, oil, and biomass. Assumptions around the development of biomass prices could alter the uptake of this fuel as a major component of the solution landscape given that this limited resource still remains competitive to alternative fuels subject to uncertain carbon tax additions. TAM-HHs shows higher trends of consumption when comparing the total MFH consumption throughout the time horizon. This is due to two trends. Firstly, owing to the disaggregation, the average consumption per household in TAM-HHs in 2020 is 37 GJ/HH, declining to 14 GJ/HH in 2060, while the aggregated model averages 38 GJ/HH in 2020, declining to 16 GJ/HH in 2060. The disaggregation means the wider range of household consumption profiles based on socio-economic parameters are considered resulting in variated total consumption and differentiated investments opportunities due to ownership structure. Secondly, due to budget constraints. For example, gas is used longer in MFH in TAM-Households due to this differentiation and because the limit of budget means households tend to keep with the existing infrastructure to meet short-term needs over investing into new infrastructure. This shows the confines and the potential of replacing fuels within the same infrastructure (e.g. with biofuels or hydrogen) over the investment and replacement of new technologies or infrastructure. In the long-term this disaggregation has an impact on investment decisions for particular actor groups and therefore on the choice of technologies and associated energy carriers, which will influence the consumption in the long-run if an investment decision is locked-in. Once an investment in a particular technology type is made, the trend is to continue to use this (Li et al. 2018a).

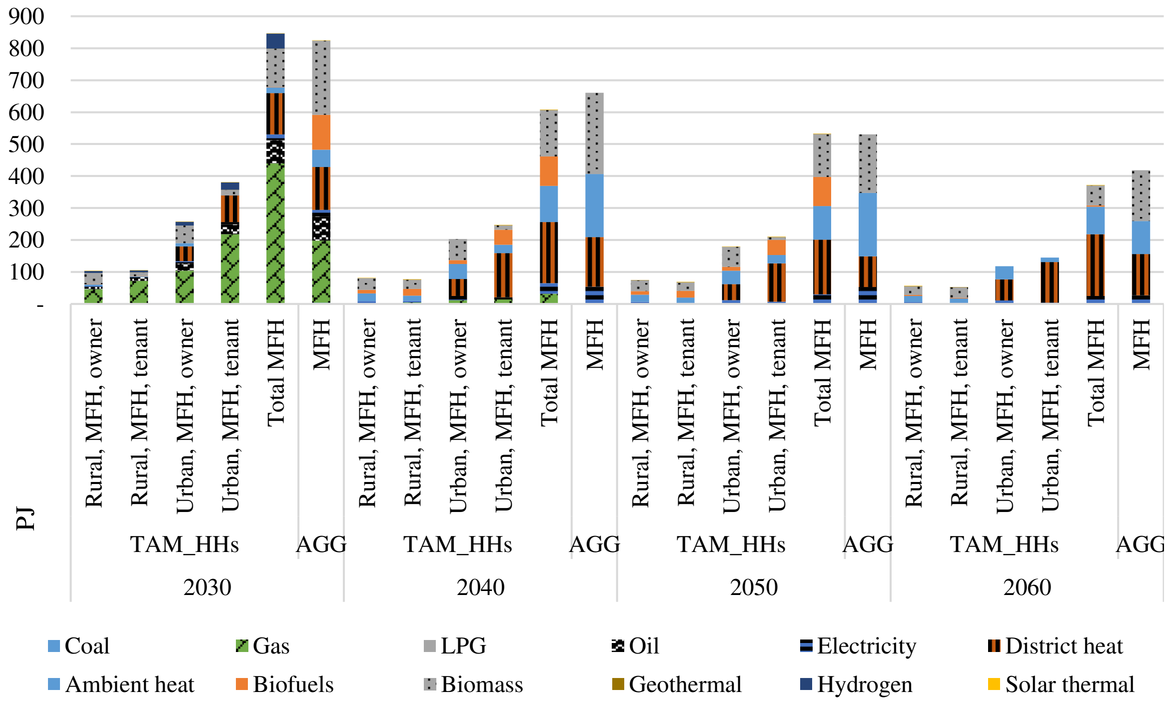

Figure 5-4: Comparison of final energy consumption for heating in MFH in TAM-HHs and the aggregated model (AGG), 2030-2060

5.2.3 The impact of budget constraints on investment decisions, energy consumption and emissions

The financial capacity of the lower three income groups is severely constrained due to the accumulated debt, thereby strictly prohibiting the possibility of these households to invest in the high upfront costs of technologies (see Chapter 3.2.2). This limited financial capacity is included in TAM-HHs as a budget constraint. To assess the impact of the budget constraint, the ratio between the investment to consumption expenditure per household and income group is compared to 2060 with the majority of new investments made in the short to medium-term, in Figure 5-5. Due to the budget constraints, the lowest income group must delay investments to the future (seen as a sharp increase between 2030 and 2040) in favour of consumption in order to meet suppressed demands first. Consumption expenditure remains steady correlating to the investment expenditure with the likely increase in consumption attributed to rebound (an increase in efficiency means the household is able to increase their consumption). After 2040 the households in this income group shift to the next highest income group and are, therefore, no longer represented. The suppressed demand affects approximately 11.3 million people equivalent to energy consumption costs (without the carbon tax) in 2030 resulting in the need for an additional 84€ per capita for those affected to meet these demands. This figure aligns roughly with the 4.8 million customers (considering an average household size of 2.1 people per household) served disconnection notices annually after non-payment equivalent to 100€ (BNetzA 2021).

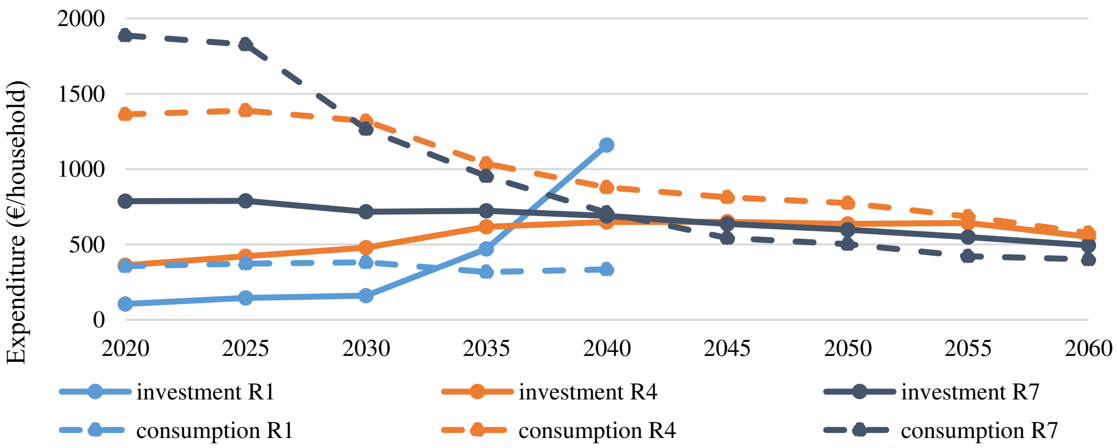

Figure 5-5: Comparison of investment and consumption expenditure per household by income group in the TAM-Households reference scenario, 2020-2060

Per household, higher income household (R7) investment patterns exhibit a steady decline with 37.1% less investments in 2060 compared to 2020, resulting in 78.7% lower consumption expenditure from 2020 to 2060, as a result of increasing energy efficiency levels less investment over time and lower consumption is expected. Lower income households (R1) increase investment expenditure by 52.9% between 2020 and 2030, followed by a sharp increase in investments from 2030-2040 (highlighting the phenomenon that lower income households must accumulate budget to make high upfront investments) and reduce energy consumption expenditure by 10.9% over the same time horizon. Medium income households (R4) steadily increase investment expenditure, levelling off after 2040, with an increase of 52% to 2060. With this increase in investment expenditure, the consumption expenditure decreases by 57.7% to 2060, which shows less rebound in consumption in this income group. This stark difference in investment and consumption patterns can largely be attributed to the difference in larger household sizes as income increases, thereby spreading the costs over more people as well as the delay in investments in lower income households, and the need for lower income households to meet consumption demands with any additional budget accumulated.

Comparatively, the consumption trend of renewable-based energy carriers increases between 2020 and 2060 at a greater rate in lower income households (R1) than medium (R4) and higher (R7) income households, as shown in Figure 5-6. The renewable consumption per household in highest income group (R7) remains relatively stable, with a steadily decreasing trend as the influence of higher energy efficiency becomes evident thereby decreasing overall demand. Consumption in the lowest income group (R1) remains steady until 2040 when the population is shifted into the next highest income group. The medium income group (R4) has a stable consumption of renewables with a steadily increasing trend. This relates likely to the difficulties low and medium income households have with accessing a loan to pay off high investment costs, such that as a result investments are staggered over a longer time period. The end result is that the household sector will take longer to reach the potential this sector has towards contributing to the energy transition targets and reducing their own emissions.

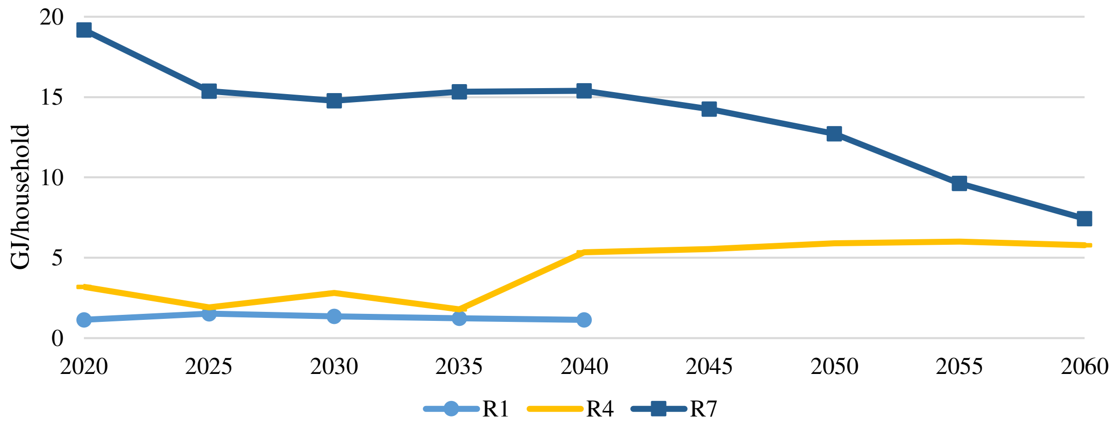

Figure 5-6: Consumption of renewable-based fuels per household by income group in the TAM-Households reference scenario, 2020-2060

Taking a closer view into the investment behaviour of the lowest (R1), the middle (R4) and the highest (R7) income groups with (TAM Households reference scenario (REF)) and without the budget constraint (BUDGET0) reveals that without the addition of the budget constraint investments the model algorithm assumes that investments are made incrementally, and the cost of these are reflected as annual payments over the lifetime of the technology rather than as an upfront cost that a consumer must pay once-off. As shown in Figure 5-7, the majority of investments in the REF scenario occur for the lowest income group (R1) in 2040 as budget is accumulated without accruing benefits to reducing consumption expenditure due to rebound, while for the medium income group (R4) and highest income group (R7) the investment patterns are almost indistinguishable. In the BUDGET0 scenario – without budget constraints – the investments are lower in both time periods for all income groups, but significantly more reduced in the lowest income group (R1), while in the highest income group (R7) the invests amounts per household remain stable as these households are not affected by a budget constraint and are therefore only reduced slightly to reflect the annuity of the payments (the difference is larger for 2020 because in 2020 higher investments are required to replace technologies reaching the end of their lifetime). The crucial difference in the two scenarios is the function of the addition of a budget constraint. Namely, this adds a dual objective in TAM-Households: to minimise costs and to maximise utility. So, whereas REF achieves both objectives, BUDGET0 only minimises the system costs and as such the overall benefits to the energy system are maximised rather than from the perspective of the household.

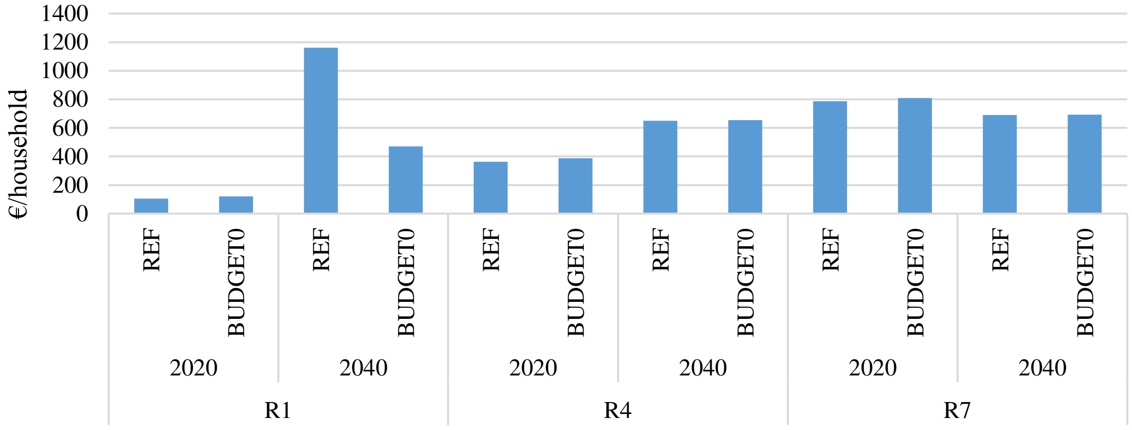

Figure 5-7: Comparison of investment behaviour with (REF) and without the budget constraint (BUDGET0) in an average low (R1), medium (R4) and high (R7) income household, 2020 and 2040

The impact of investment patterns is also visible when comparing the total final energy consumption of all households across the scenarios with the impact on the consumption patterns in the lowest income group (R1), as shown in Figure 5-8.

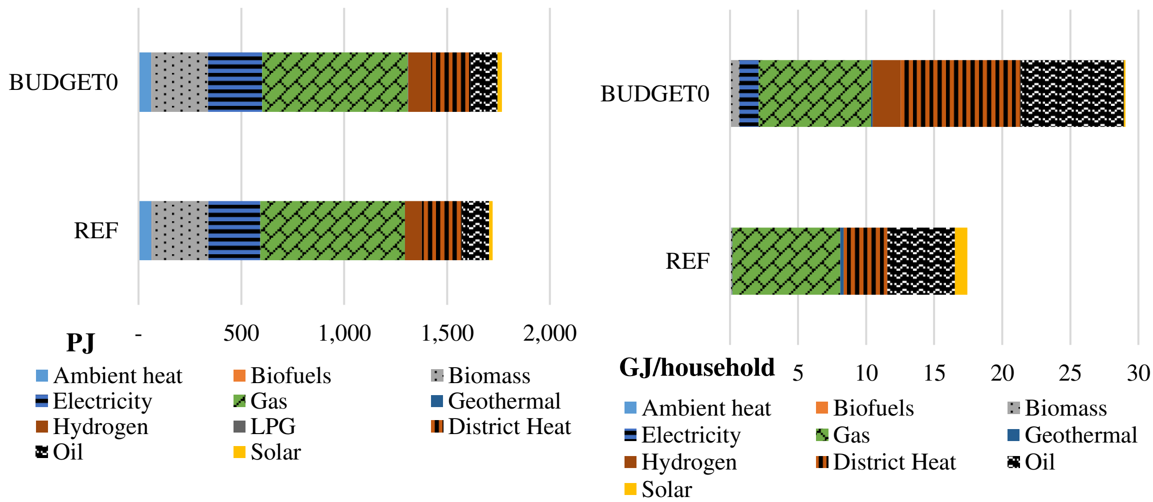

Figure 5-8: Comparison of final energy consumption in all households (left) with the energy consumption per household in the lowest income group (right), by scenario in 2030

Overall, the total consumption in all households is about 45 PJ higher in the scenario without budget constraints (BUDGET0) than in the reference scenario (REF, which includes budget constraints) because investments are made incrementally (the standard modelling method spreads the costs of investments across each time slice over the lifetime of the technology, indicating the shift in the consideration for households' abilities to afford infrastructural investments). Without the budget constraint in the BUDGET0 scenario, the need for fuel blended solutions (with hydrogen and biofuels) is 28 PJ higher. A comparison of the final energy consumption per household in the lowest income group compared across both scenarios varies considerably, limited by the budget constraint, which reflects the inability of households to afford the investments to achieve an optimal system solution. Whereas the BUDGET0 scenario assumes the availability of capital does not play a role, all immediate energy service demands are met. This is reflected in the results showing that the true consumption needs of households in the lowest income group average 29.1 GJ per capita annually. In the reference scenario, households must trade-off investment and consumption expenditure resulting in households pulling back on meeting immediate consumption needs in lieu of investment such that each household cannot meet all energy service demands, resulting in consumption of only 17.5 GJ/capita annually. This translates into a suppressed demand of about 11.6 GJ per household annually. This key outcome highlights also the importance of implementing the full methodology employed in this thesis to evaluate the impact on lower income households. Disaggregating by income groups is not enough to represent the situation in lower income households; the budget constraint must be added. The economic ability of households to participate in the energy system will also impact the rate of achieving energy transition targets due to the slower investment rates. This shows that the lowest income group is incapacitated to take action to reduce their energy consumption and are therefore bound to existing consumption patterns until sufficient capital is amassed to enable the required investments to improve their energy welfare. This implies that energy vulnerable households are delayed in benefiting from the energy transition (energy efficiency and renewable energy) thereby vulnerable to energy poverty. Households already experiencing energy poverty will not alleviate the situation without additional financial support.

5.2.4 Case study: second-hand appliances and extended lifetime of technologies

Two additional, optional features are showcased in two further scenario variations and compared to the TAM-Households reference scenario (REF) as a case study and described in Table 5-11. These features explore the impact of 1) second-hand appliances (2HM), and 2) extending the technical lifetime of a technology (EXT) through a case study on freezing and refrigeration investment and consumption behaviour. In the previous section, the impact of the budget restriction revealed the limited ability households had on participating in the energy transition as a basis for exploring how alternative financing might improve the energy welfare of households. As described in Chapter 2, lower income households implement coping mechanisms to meet their energy needs by making trade-off decisions between different end-uses, investment decisions and consumption behaviour. To illustrate this point, this scenario explores the impact on the overall expected energy and emissions when the use of second-hand appliances or extending the technical lifetime of appliances are employed as a coping mechanism in order to reduce or delay the costs of new investments, respectively.

Table 5-11: Case study descriptions: impact of coping mechanisms

Socio-economic framework (GDP, population growth, energy prices, etc.)	
TAM-HHs/REF	Disaggregated, all expected policies implemented, budget constraints with all investments paid upfront
2HM	REF + lower 5 income groups can purchase a second-hand refrigerator and/or freezer from the upper 5 income groups of the same profile type for existing buildings only; maximum 20% share of demand can be fulfilled
EXT	REF + lower 5 income groups can extend the lifetime of their refrigerators and/or freezers at no cost but with reduced efficiency for a maximum of an additional 5 years with a maximum of 20% share for existing buildings only

Investment and consumption behaviour with limited budget can have implications on the expected, rational, economic choices by certain households when weighing up the untenable high upfront costs. Without access to loans, lower income households will find non-financial means of meeting energy service demands, which could include buying second-hand appliances in order to reduce the investment costs, or using technologies beyond the technical lifetime until they break. The advantage is that the household budget can be extended and used to fulfil energy service demands, but the disadvantage is that the efficiency of second-hand technologies will often be lower than those available on the market which will be in accordance of the latest appliance standards. The concept of second-hand markets was introduced in Chapter 3.2.7 while Chapter 4.4.2 provided an overview of the potential impact refrigeration has on the overall electricity consumption and costs for different income groups. Coping mechanisms are used in households to ensure household service demands can be met despite scarce financial capacity to pay the high upfront costs. These are not modelled in the reference scenario due to lack of data, however a case study looking at the impact of such coping mechanisms on the energy welfare of households was explored in the 2HM and EXT scenarios. The model development, therefore, includes options to extend the technical lifetime of appliances (EXT) as well as introduce a second-hand appliance market (2HM) using the methodology described in Chapter 4.3.3. These two scenarios simulate these coping mechanisms, for which more detail on the significance of freezing and refrigeration demand is provided in Appendix F.

As shown in Figure 5-9, the investments made for refrigeration and freezing per household for the lowest (R1) and the middle (R4) income groups are compared in the graph on the left by scenario in 2025. The results are shown for 2025 in this scenario, because when comparing only the investments for freezing and refrigeration technologies, the majority of investments occur in this time frame due to the technological lifespan of the existing appliance stock. In comparison to the TAM-Households reference scenario (REF), both scenarios enable lower investment costs to the budget constrained lower income households, e.g. in 2025 in the REF scenario, an R1 household invests about 20.2€ annually, whereas this reduces to about 14€ and 19.9€ per household annually in the 2HM and EXT scenarios, respectively. Medium income households (R4) invest about 44€ annually, whereas this reduces to about 43€ and 32€ per household annually in the 2HM and EXT scenarios, respectively. The differences in the investment and consumption patterns for R4 are moderate, which indicates that these households are not suppressing demand and do not rely on lower investment costs of second-hand appliances in order to fulfil this energy service demand.

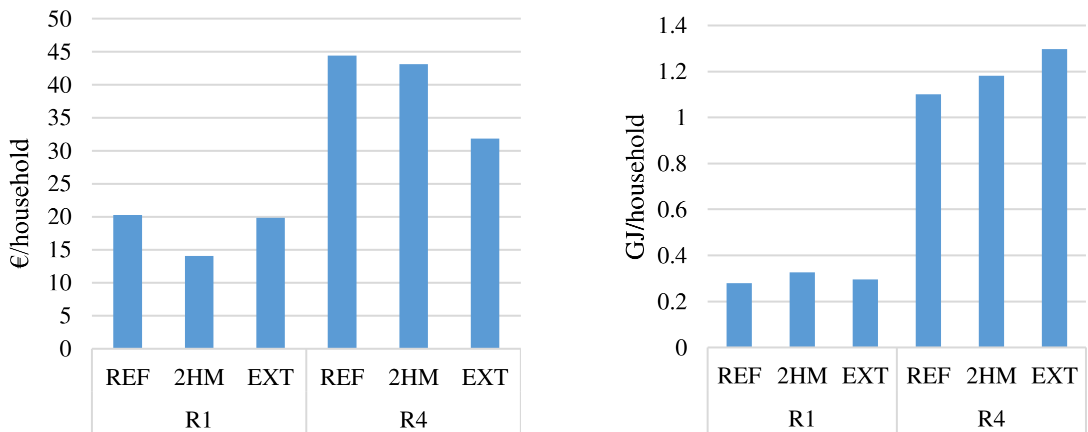

Figure 5-9: Comparison of annual investment (left) and energy consumption (right) for refrigeration and freezing per household by income group and scenario, 2025

However, the energy consumption is higher in both lower income groups (R1, R4) for both scenarios (2HM and EXT) in comparison to the reference case (REF), as shown in the graph on the right. Between the two coping mechanisms, as can be expected extending the technical lifetime of the appliance results in lower investment costs overall but higher energy consumption over buying a second-hand appliance, since the second-hand appliance would typically represent an upgrade to the existing appliance. Since the higher income groups (R5-R7) do not rely on second-hand appliances and assumptions are not incorporated to reflect the continued use of older appliances beyond the technical lifetime (e.g. as a second refrigerator or freezer), neither of these scenarios has any effect on the investment or consumption patterns and are not shown in the results. The implication of these practices is that discounting the impact of coping mechanisms, such as second-hand appliance purchases, could have an effect on the expected total energy (and emissions). The impact of these coping mechanisms are discounted in household energy forecasts likely because in the big picture the differences are negligible, but to a lower income household from their point of view amounts to significant differences in the household budget and energy welfare (i.e. meeting energy service demands at affordable cost). This effect has been demonstrated for freezers and refrigeration, but also could include other household appliances, such as clothes washers, dryers, dishwashers, which are typically lower efficiency but still operational and sold as household upgrades to an appliance of higher efficiency. However, since there is no reliable data on the use of these practices, they are not fully incorporated into the reference scenario and only shown here as a case study to highlight the negative impact of these practices on the household energy consumption patterns in lower income households.

5.2.5 Insights

This section showcased the method employed for the disaggregated TAM-Households model in comparison to an aggregated model. Overall, the disaggregated TAM-Households model allows insights into the differentiated investment and consumption patterns. The methodology applied in TAM-Households makes it possible to evaluate the financial limitations of particular households with regard to the ability to afford the high upfront costs of investments through the two main features: disaggregation (as described in Chapter 4.3.1) and the budget constraint (as described in Chapter 4.3.3). Increasing the resolution on the types of demand profiles results in a divergence in the future pathways between the two models. This highlights that the cost-optimal path to achieve decarbonisation in 2050 for different profiles means unexpected energy carrier patterns, such as biofuels, which would require household infrastructure investments and evaluation of the most cost-effective sector for consumption as this fuel would compete with the transport and industrial sectors for supply. Significantly, lower income households are not in a position to improve their energy welfare (i.e. by meeting both investment and consumption needs) and are only able to make high cost investments once sufficient budget is accumulated, which means that households will continue to live in energy poverty, or may become vulnerable to it given the dynamic changes in the energy supply sector and the addition of financial disincentives, such as carbon taxes. Without the addition of the budget constraint, the modelling methodology shifts to only optimising the system costs rather than also maximising the utility to the households. This underscores the need for the addition of the budget constraint in order to better evaluate the energy welfare of households from their perspective. The inclusion of the budget constraint revealed the magnitude of suppressed demand in lower income households resulting in lower than expected consumption.

Additionally, this section evaluated how the energy system and the energy welfare of households could be impacted with respect to the utilisation of non-financial coping mechanisms such as second-hand appliances and using appliances longer by foregoing higher investment costs that would lower consumption in the long-term, compared to reduced investment costs to enable higher consumption now. Buying second-hand appliances or continuing to use an old appliance has negative impacts on the amount of additional energy consumed in the long-term in comparison with a newer, more efficient appliance, however the lower investment hurdle reduces the required capital considerably. In both alternative scenarios, the investment expenditure decreases compared to the reference scenario, but the energy consumption expenditure increases which indicates that in order for households to minimise their costs and maximise their benefits, the pallet of solutions include compromising future reduced consumption so as to benefit from lower investment costs in the immediate. The employment of coping mechanisms to decrease investment costs to meet freezing and refrigeration demand does not lead to investments in other technologies or energy carriers due to the increased consumption costs to maintain the existing appliances. The analysis of the freezer and refrigeration demand with this model framework allows an insight into the importance of energy efficiency programmes for lower income households to enable affordability and highlights the need to address the rebounding of energy use despite increases in energy efficiency of newer appliances. The influence of the use of second-hand appliances on the energy consumption of the residential sector, especially in lower income households, puts into perspective the lack of improvements in the energy welfare of lower income households and the lack of participation from this sector in contributing towards the nationally defined energy efficiency targets. The perpetuation of the use of second-hand appliances can ultimately reduce the opportunities for the overall energy system to become more efficient and risks leaving lower income households behind in the energy transition. The application of the method showed that there is a need to better assess the trade-off between more efficient appliances and the impact on the energy system as well as on the energy welfare of lower income households.

5.3 Exploring access and affordability

This sub-chapter investigates the impact of energy poverty on the achievement of energy transition targets. The scenarios for this analysis are described in Chapter 5.3.1., which include a direct comparison between the approach to addressing energy poverty and addressing vulnerable consumers as described in Chapter 2. The results are presented in Chapter 5.3.2 followed by a summary of the insights in Chapter 5.3.3.

5.3.1 Scenario descriptions

These scenarios include an assessment of how lower income households cope with meeting energy needs with low incomes, as well as an evaluation of the impact an energy poverty approach can have on household energy use and emissions compared with the present approach for vulnerable consumers, as summarised in Table 5-12. Addressing energy poverty requires similar but different types of support compared to the approach to address vulnerable consumers, as explained in Chapter 2. The benefits of energy efficiency have shown to improve the energy and economic welfare of households (IEA 2015). Energy efficiency directly addresses not only the causes of energy poverty but also services the overarching energy efficiency targets (Dobbins et al. 2019). However, the current approach to address vulnerabilities in the energy sector in Germany is through welfare support often reduced to bill support rather than targeted energy-specific support, as described in Chapter 2.4. As it stands, social welfare beneficiaries are eligible for payment of electricity bills (up to a certain amount), heating bills (adequate for the situation of the beneficiary), and payment of the corresponding carbon tax. However, this approach contradicts the overarching targets to shift away from fossil fuel consumption and directly subsidises its consumption. One scenario compares the costs and benefits of subsidising investment into energy efficiency (EP scenario) with a scenario where the equivalent costs of subsidisation of energy bills (consumption) and the responsibility for payment of the carbon tax are excluded from the budget constraint (VC scenario) in the lowest two income groups. To drive investment in residential buildings, the funding under the Climate Programme has been consolidated as a 20%-35% reduction on the investment cost of renovation measures and heating technologies on specific technologies, measures and renovations that lead towards increasing renewable energy and energy efficiency (BWA 2021). In the Vulnerable Consumers scenario (VC), the electricity consumption is subsidised and the payment of the carbon tax is redirected to a third party for payment (e.g. government agency). The payment for the heating costs remains with the household in this scenario at this time because it was not possible to determine which profiles exactly benefit from this support and would distort the investment results unfavourably without the comparative price signal for the fuel type.

Table 5-12: Scenario descriptions: access and affordability

Socio-economic framework (GDP, population growth, energy prices, etc.)	
TAM-HHs/REF	Disaggregated, all expected policies implemented, budget constraints with all investments paid upfront
EP	REF + financial aid for energy efficiency measures in buildings and space heaters to address energy poverty; technology-specific investment subsidisation at 20%-35% of upfront capital for lowest three income groups (those with negative monthly savings)
VC	REF + financial aid for bill support to maintain vulnerable consumers; electricity consumption subsidised; payment of carbon tax expenses excluded from budget constraint) for lowest three income groups

5.3.2 Exploring approaches to address energy poverty compared to vulnerable consumers

To compare the impact of subsidising investments to subsidising consumption, the energy consumption patterns are elaborated. Looking at the overall energy consumption for all households in 2035 shown in

Figure 5-10. The results are shown for 2035 for this set of scenarios, because the dynamics modelled (accumulation of budget for investments and effect on suppressed demand) presented the maximum impact in this year. Overall, comparing the total consumption in all households shows that the VC scenario consumes oil, gas and electricity to a greater extent and relies less on biofuels resulting in total shares of 32% renewables and 35% fossil fuels. The EP scenario exhibits similar trends to the REF scenario overall, but with 13.9 PJ more solar, 8% more gas, totalling 33% renewables and 36% fossil fuels. The subsidisation of electricity to the lowest three income groups results in electricity consumption overall increasing by 4.2% in the VC compared to the REF scenario. This already highlights the differences in the approach towards providing financial support to lower income households. The impact becomes more visible when narrowing in on the average energy consumption in the lowest three income groups. The average energy consumption per household shows the increased electricity (20% share) in the VC scenario and the increased renewables (22.6% share) in the EP scenario, compared to the REF scenario with 10% electricity and 14.6% renewables. Despite the higher share of solar and biomass in the VC scenario, the VC scenario maintains almost 30% fossil fuels in the end energy mix. The EP scenario incorporates 19.5% fossil fuels and 26.2% renewables, with significantly greater shares of biofuels, biomass and ambient than the REF scenario. Significantly, the average consumption increases by 5 GJ and 8.5 GJ per household in the

VC and EP scenarios, respectively, compared to the reference scenario. This is as a direct result of households unable to afford the costs of required consumption. The phenomenon of suppressed demand is detailed at the end of this section.

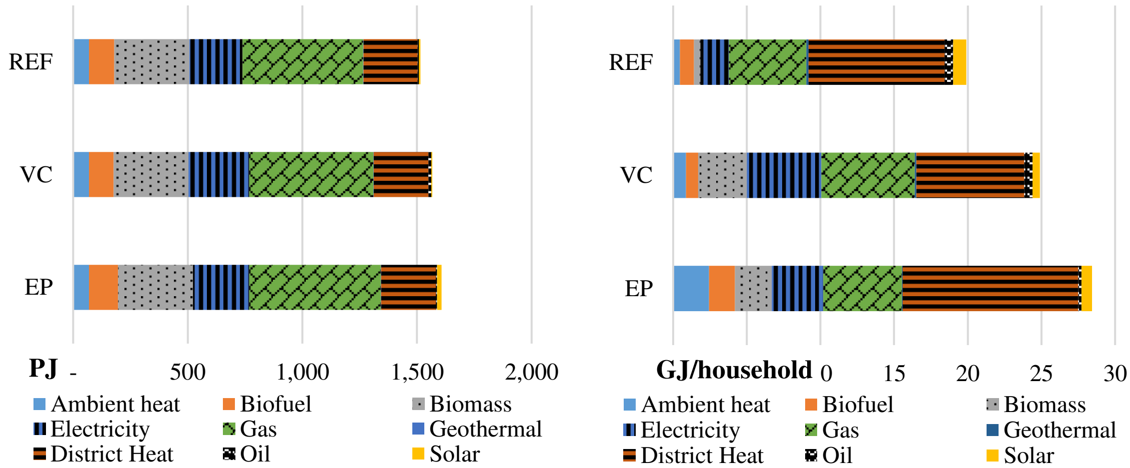

Figure 5-10: Final energy consumption in all households (left) and average per household for the lowest three income groups by scenario, 2035

Figure 5-11 compares the impact on the energy consumption patterns for the lowest three income groups for the Energy Poverty (EP) and Vulnerable Consumers (VC) scenarios compared to the TAM-Households reference (REF) scenario by various parameters. This describes the impact of subsidising the investment costs (EP scenario) compared to the subsidisation of consumption (VC) scenario with the reference case where neither is subsidised. The results show the average energy consumption for owners, tenants, occupants in MFH and SFH, urban and rural households, as well as the average household by scenario.

On average, in comparison to the reference scenario, subsidisation results in 2.7 GJ and 4.5 GJ more renewables per household on average in the VC and EP scenarios, respectively. This includes 2 GJ and 0.4 GJ per household more ambient heat in the EP and VC scenarios, respectively, than in the REF scenario. Fossil fuels make up almost a third of the consumption in each of the REF and VC scenarios, while this share is reduced to 19.6% in the EP scenario. The main fuels in the VC scenario are district heating, and gas and electricity – of which the electricity tariff and the carbon tax are subsidised. The average household in the EP scenario relies chiefly on district heat, incorporating more ambient heat, biomass and biofuels than either of the other two scenarios.

Owners are more likely to make investments into their own properties and the shift to renewables is reflected across all three scenarios compared to tenant properties, where owners in the REF, EP and VC scenarios incorporate 24.7%, 44.7% and 49.1% shares of renewables, respectively. Households in tenant buildings maintain fossil fuel shares of 46.7%, 33.3% and 44.3% in the REF, EP and VC scenarios, respectively, with tenant households in the VC scenario maintaining fossil fuels of 11.7 GJ per households. Biomass remains a key part of the renewable energy landscape because the pricing is competitive with respect to the increasing carbon tax on conventional fuels. However, the price of carbon could also escalate in the future if demand increases.

The REF scenario favours biofuels and district heating, but also heat pumps in SFH and include 34.7% renewables, but 40.1% fossil fuels of the total final energy consumption. With financial support for the upfront investment costs, the EP scenario shows a shift in this same building type towards the integration of renewables to encompass 41% of total consumption with more biomass and heat pumps, also in tenant buildings where the resistance to invest is decreased for landlords, and reduces the total fossil fuel share to 33.1% of the total and renewables to 35%.

Due to the ability to access network fuels, urban households rely on district heating and electricity for 54.5%, 48.3% and 48.9% in the REF, EP and VC scenarios, respectively. Correspondingly, rural households incorporate greater shares of decentralised fuels, such as biofuels, biomass and solar resulting in total shares of renewables to include 53.3% (14.8 GJ per household), 39.5% (14.2 GJ per household) and 35.4% (11.6 GJ per household) in the REF, EP and VC scenarios, respectively. In both the REF and VC scenarios, rural households additionally incorporate the greatest shares of oil.

The results emphasise the differences in energy consumption patterns that may arise when bill support (as given in the VC scenario) is provided to households. Overall, these results support that investment subsidisation would benefit households without decision-making power, such as tenants. The VC scenario shows households' limited financial capacity to invest and therefore continuing to consume fossil fuels to a greater extent, representing almost a third of total final consumption, which is similar to the share of fossil fuels in the REF scenario indicating that providing subsidies for consumption does not shift the share of fossil fuels in beneficiaries without the effective price signal from the carbon tax. Investment subsidies (as given in the EP scenario) result in higher consumption overall with a greater incorporation of renewables compared to the REF scenario.

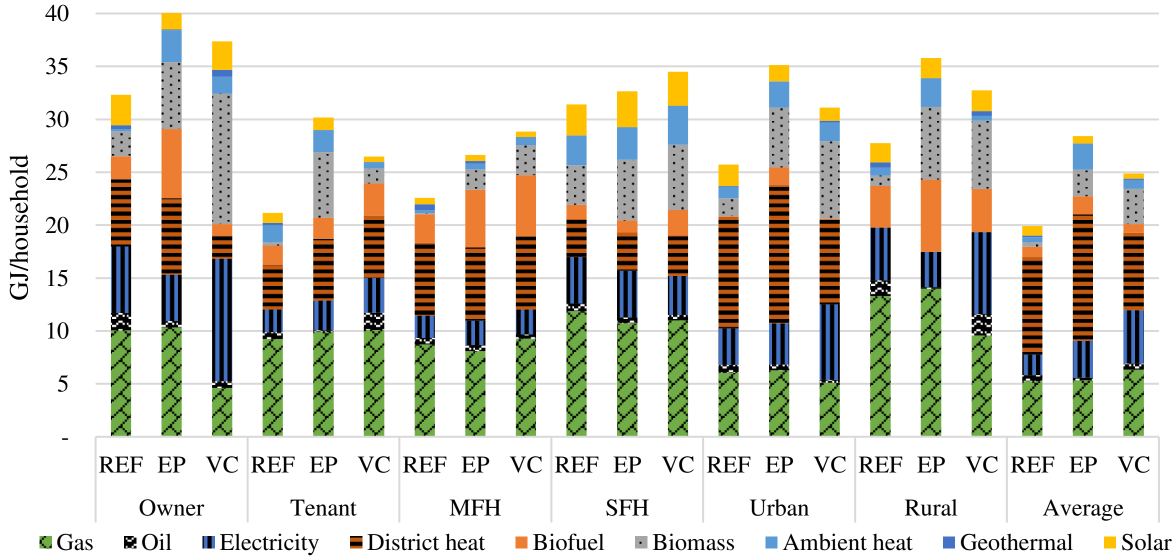

Figure 5-11: Comparison of the energy consumption patterns per household in the energy poverty and vulnerable consumers approach with the reference scenario in the lowest three income groups, 2035

Looking at the lowest three income groups only in 2035, a comparison of the suppressed demand and the impact of the two subsidisation variations with the reference case is undertaken in Figure 5-12. In the reference scenario in 2035, 6.10 million people of the population in the lowest three income groups, which includes 59.8% of this population group, are each in need of about 151€ per capita in order to meet all household service demands. The suppressed demand is reduced in this same population set in the Vulnerable Consumers scenario (VC) due to the subsidisation of the electricity costs and the removal of the burden of the carbon tax such that 6.11 million people (59.9%) within this population subset would each require an additional 74€ per capita to satisfy all household service demands. The greatest impact in reducing suppressed demand is through the Energy Poverty (EP) scenario, which reduces the issue to affecting approximately 9.3% of this population group, equating to 952,000 people. An additional 62€ per capita for this subset of the population is necessary to lift these households out of this energy shortage. A table summarising the outcome of the suppressed demand is provided in Table D-2 Appendix D.

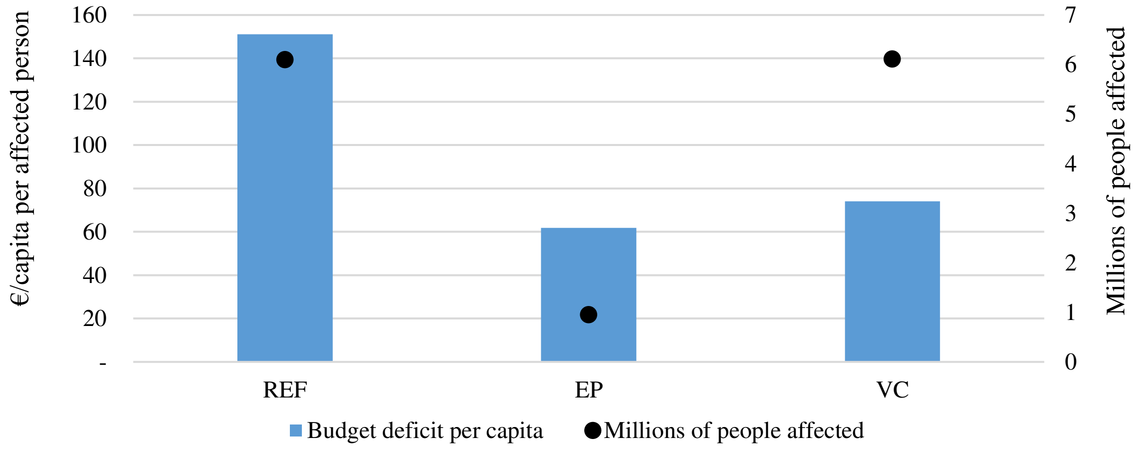

Figure 5-12: Comparison of the suppressed demand by scenario in 2035

5.3.3 Insights

The methodology enabled a comparison of the effect of subsidising investments in renewable and more efficient technologies and measures compared to the approach of subsidising consumption. This showed that lower income households were able to overcome the investment hurdle and shifted their investment and consumption profiles to include more renewables, whereas the subsidisation of electricity consumption and assuming the carbon taxes for lower income households maintains the status quo, which is not in line with the energy transition objectives. The effect on suppressed demand could also be evaluated with this methodology and found a reduction in the Vulnerable Consumers scenario compared to the reference scenario, which indicates that acute bill support is crucial to the energy welfare of households. The evaluation also found that the suppressed demand was reduced further through the subsidisation of investments in the Energy Poverty scenario. The methodology provides a platform that enables the opportunity to assess how best to redistribute the funding to provide acute bill support as well as investment support into the household energy infrastructure so as to ensure energy and emission targets are met while safeguarding household energy service demands.

5.4 Exploring the impact of policies and measures for the improvement of the energy welfare of households

This section explores the influence targeted policies and measures have on the energy welfare of households. The scenarios for this assessment are described in Chapter 5.4.1. Chapter 5.4.2 assesses the effects of a 50:50 distribution of the carbon tax between landlords and tenants, followed by an evaluation of the effects of alternative redistribution schemes for the redistribution of collected funds in Chapter 5.4.3. The chapter concludes with a summary of the insights.

5.4.1 Scenario descriptions

These scenarios assessed the effects of various taxation and subsidisation options. As a starting point, one scenario (CO2TO) explored the condition where landlords and tenants shared the carbon tax equally, as was debated (Schultz 2021) (and subsequently shelved (Spiegel 2021)) on the national government level. Another area currently debated is the redistribution of environmental taxes collected. While the current method to be deployed is to collect a carbon tax according to the consumption of fossil fuels and then to redistribute this through a tax relief per kWh electricity consumed (Vermittlungsausschuss 2019), other options discussed include reallocating the funds through a “climate bonus” at 100€ per capita (CB scenario) as explored in other studies (Kalkuhl et al. 2021). One alternative distribution method is explored in the CBLI scenario where the climate bonus is provided to the lower half of the population only but increased to 200€ per capita annually. Additional scenario assumptions about the share of population targeted by income group is given in Table D-1 in Appendix D.

Table 5-13: Scenario description: Improving the energy welfare of households

Socio-economic framework (GDP, population growth, energy prices, etc.)	
TAM-HHs/REF	Disaggregated, all expected policies implemented, budget constraints
CO2TO	REF + carbon tax is shared among tenants and landlords 50:50
CB	Climate bonus; 100€ per capita; carbon tax; EEG surcharge without levy relief
CBLI	Climate bonus only for half the population (lower incomes); €200 per capita annually; carbon tax; EEG surcharge without levy relief

5.4.2 Carbon tax burden shared among landlords and tenants 50:50

One measure debated by the national government (and subsequently shelved largely due to criticism from landlord and owner associations, and the government perception that this would disproportionately affect families and the elderly (JUDID-Redaktion 2021)) was the equal distribution of carbon taxes between landlords and tenants. Figure 5-13 depicts this distribution of the carbon tax burden per capita by income group, owners and tenants, the average household and for commercial and government owners in 2025, where the distribution of landlords by income group is based on assumptions by (Bach et al. 2014). The results are shown for 2025 to facilitate the comparison with the other studies presenting results for 2022, as introduced in Chapter 4.3.4. In the CO2TO scenario, half of the tenant emissions are redistributed across the owners by the share of owners per income group as well as to commercial and government landlords, while in the REF scenario the emissions remain entirely with the emitter. The high share of tenants and lack of landlords in the first two income groups lead to less expenditure on the carbon tax for these income groups as the burden is alleviated by owner responsibility. Here the carbon burden decreases from 71€ per household to 41€ per household annually for the lowest income group. Estimates of the share of landlords increases with income where over 40% are in the highest income group resulting in a higher carbon tax expenditure, increasing from 87€ per household to 104€ per household. The overall burden on an average owner increases from 111€ to 172€ per household, while the burden on the average tenant is almost halved from 93€ to 48€ per household annually. The greater shift in tenants is due to the greater share of tenants in lower income households. The additional cost burden in owners incentivises a shift in the investments to reduce emissions in owner-occupied properties such that in comparison to the reference scenario the overall emissions in this profile are reduced from 40 Mt CO_2-eq to 32.5 Mt CO_2-eq.Commercial and government landlords make up about 34% of rental properties thereby taking the responsibility for the equivalent share of tenant emissions and result in a carbon expenditure of 94€ per rental property within their jurisdiction annually.

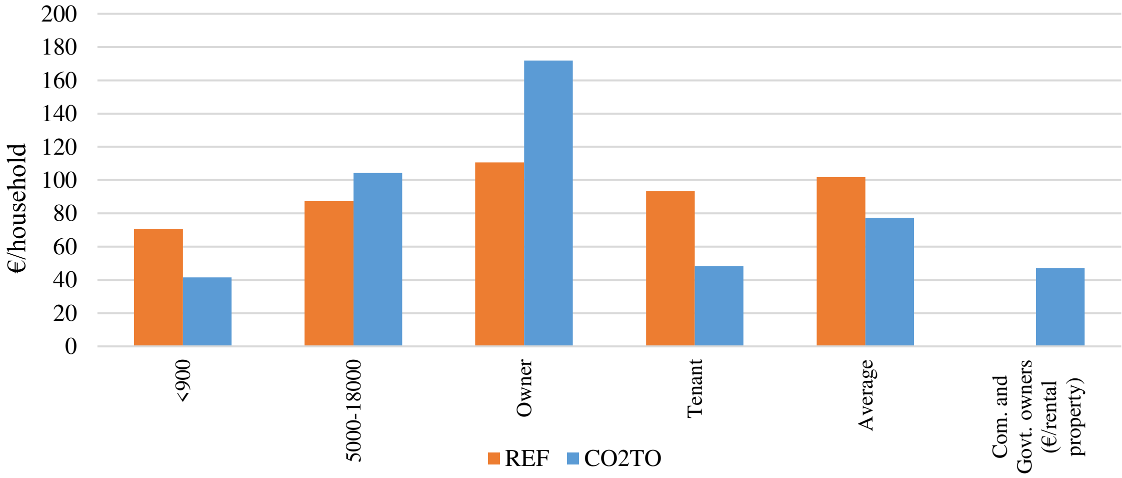

Figure 5-13: Carbon tax burden per household by profile and scenario, 2025

Overall, this distribution has a subdued impact on the final energy consumption, where overall the household consumption in the CO2TO scenario decreases by 149 PJ with about 47 PJ more electricity and 1 PJ less solar is consumed in 2025 than in the reference scenario, as shown in Figure 5-14 on the left. This trend has marginal impacts on the energy consumption profiles for both tenants and owners, as shown in Figure 5-14 on the right, which highlights that owners invest slightly more into ambient heat and electricity and reduce reliance on district heating in the CO2TO scenario. Tenants sees the greatest increases in district heating, biomass and electricity compared to the reference scenario.

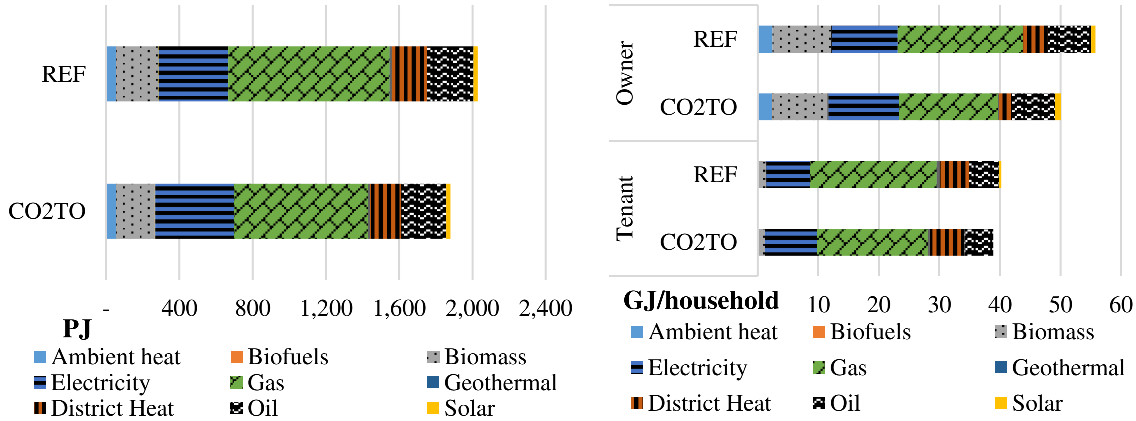

Figure 5-14: Final energy consumption for the household sector (left) and per capita by ownership (right) by scenario, 2025

Neither scenario results in significant reductions in oil consumption in the short-term despite the increased carbon tax with 0.2 GJ and 0.15 GJ per household less in tenants and owners, respectively, in the CO2TO scenario compared to the REF scenario. Gas consumption decreases in owner profiles by 4.4 GJ per household in the CO2TO scenario. This slower decline in exiting from fossil fuels across all income groups is as a result of the budget limitations on the investment capabilities, particularly of owners that must now also ensure costs in tenant properties do not become an additional cost burden. In comparison to the reference scenario, the cost-optimal path of the CO2TO scenario sees a similar trajectory as fossils decline towards the decarbonisation target in 2050, as shown in Figure 5-15. The trajectory of the other profiles follow a moderate declining path.

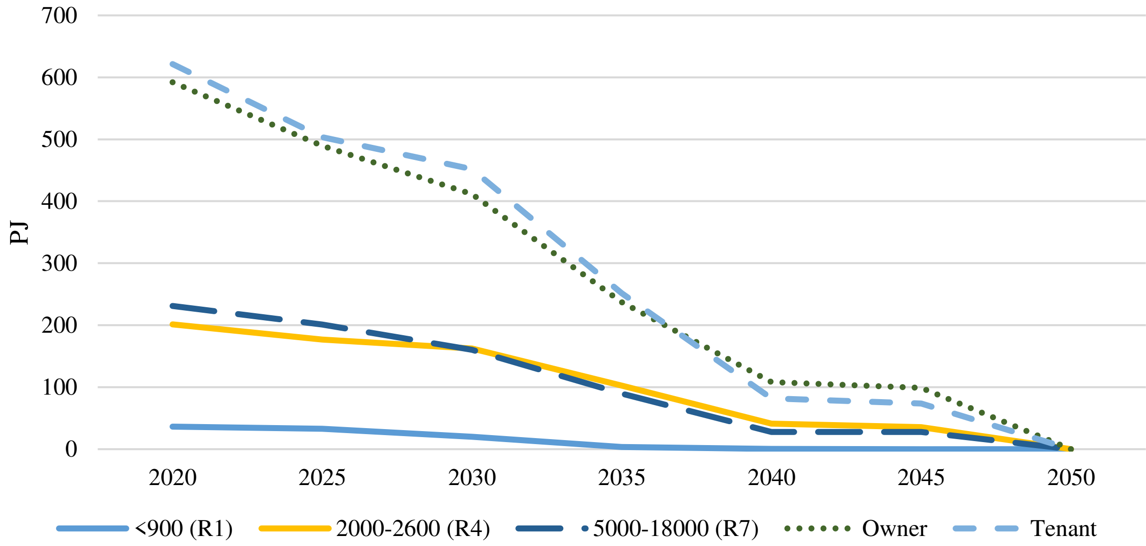

Figure 5-15: Final energy consumption of fossil fuels by income group and tenure, CO2TO scenario, 2025-2050

With the distribution of the carbon tax, there is no suppressed demand in 2025 in the CO2TO scenario, but as the carbon tax increases so does the suppressed demand. However, only the lowest two income groups are affected in the CO2TO scenario, whereas in the reference scenario, the first three income groups are affected. For example, in 2035, 15.5% of the R1-R4 households in the CO2TO scenario are in need of 24€ each annually, compared to the REF scenario where 44% of the households in this group require an additional 151€ each annually, as shown in Figure 5-16.

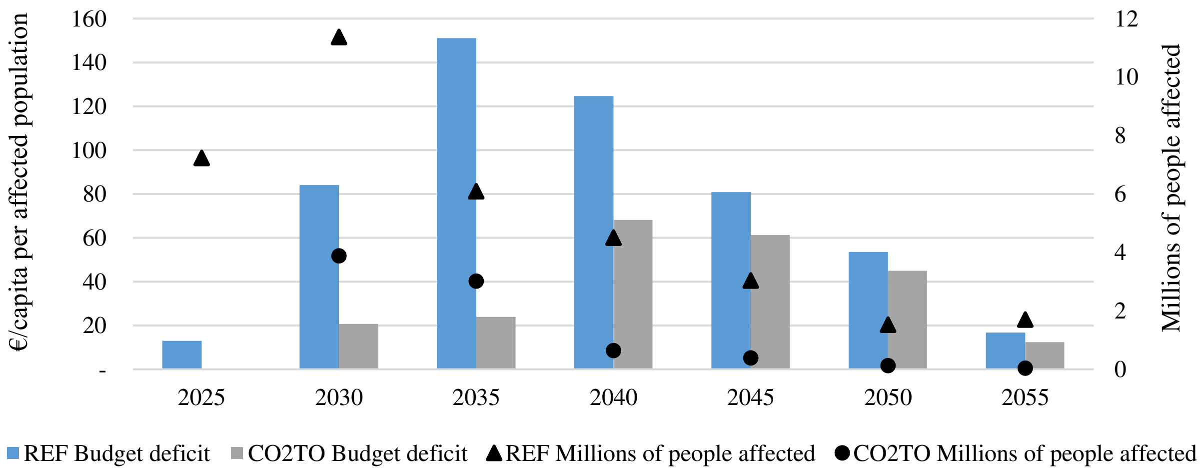

Figure 5-16: Comparison of suppressed demand in the four lowest income groups by scenario, 2025-2055

The highest income group owned 51.6% of the tenant properties in 2025 and therefore represent 44.4% of the responsibility for the emissions in the household sector (29.5% without tenant properties). The impact of this carbon sharing policy may also have an impact on the energy use and emissions for the owners within this profile type, and are therefore presented in Figure 5-17. Due to the particular significance of this income group to the total final energy consumption of all households, the patterns are similar to the total consumption of all owners presented in Figure 5-14. Overall consumption reduces by 22.2% with an increase in solar by 2.8 GJ per household, contributing towards an overall share of 34% renewables. While oil remains the same, gas consumption increases by 10.3%, and district heating is reduced by 73% compared to the reference case, the overall fossil share is 47% compared to 37% in the reference case.

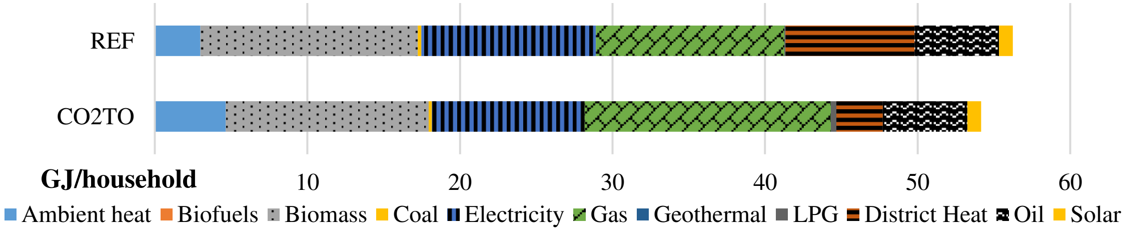

Figure 5-17: Final energy consumption per household in owners of the highest income group, 2025

This indicates, on the one hand, that as the financial obligation increases in the CO2TO scenario, owners become more proactive in terms of investing in owner-occupied buildings to reduce emissions by shifting towards renewables. On the other hand, there are also indications that these higher investments are countered with an increased reliance in existing infrastructure as highlighted by the higher gas consumption in the short-term, before the influence of the increasing carbon price takes effect. As presented in Figure 5-18, the annual investments per household are consistently higher which also result in lower consumption per household in the CO2TO scenario compared to the REF scenario. This suggests that the additional financial burden in this income group may shift the investment and consumption patterns towards an accelerated decarbonisation.

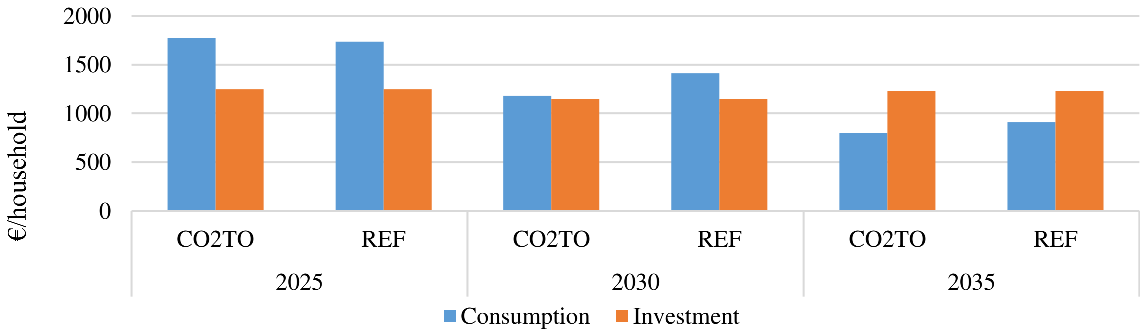

Figure 5-18: Annual investment and consumption patterns per household in owners of the highest income group (R7) in the medium-term by scenario, 2020-2035

5.4.3 Redistribution of the carbon tax without the EEG levy relief

Two methods to redistribute the collected carbon tax through a climate bonus were investigated. The Climate Bonus (CB) scenario allocated 100€ per capita whereas the Climate Bonus for lower incomes (CBLI) scenario distributed funding scheme to half the population, starting with the lowest income groups, but doubled the amount to be redistributed (i.e. 200€ per capita), applied from 2025. This additional capital to the available budget[2] per household in each income group, which increases with income due to the larger household sizes, as shown in Table 5-14. The lower income groups remain below the average additional budget in the CB scenario due to the amount of debt and inability to accumulate savings while the higher income households have greater incomes and savings at disposal.

[2] The available budget is calculated based on a statistical regression analysis of actual spending and savings (or debt) according to Destatis (2013a) and projected according to GDP and population prognoses based on (IMF 2019a), with the implementation in the model further described in 4.3.3

Table 5-14: Average additional budget per household by income group and redistribution scheme (€$_{2015}$)

Scenario	<900€	900-1500€	1500-2000€	2000-2600€	2600-3600€	3600-5000€	5000-18000€	Average
CB	101	128	152	183	228	217	202	193
CBLI	203	257	303	367	456	11	-	182

The effect that is compared with this method is the difference between adding a carbon tax and in exchange subsidising electricity consumption as is the case in the reference scenario (REF), with adding a carbon tax, foregoing the electricity subsidy and redistributing the collected funds across the population as an increase in budget per capita. Overall, the environmental impact varies little between the two distribution variations where in 2030 the final energy consumption in the CB scenario results in 1,781 PJ (52 Mt CO_2-eq) and the CBLI scenario results in 1788 PJ (54 Mt CO_2-eq), compared to the Reference scenario with 1,736 PJ (54 Mt CO_2-eq), as shown in Figure 5-19. The electricity consumption is about 10% higher in the REF scenario than in both Climate Bonus scenarios due to the lack of reduction on the electricity levy in the Climate Bonus scenarios resulting in lower electricity consumption. The addition of the carbon tax without the EEG levy relief on electricity, however, results in higher demand to use the existing gas infrastructure together with a hydrogen or biofuel blend in favour of replacing existing technologies with alternatives in both Climate Bonus scenarios. The shares of renewables shifts only slightly from 20.6% in the REF scenario to 19.8% in both climate scenarios, while the share of fossil fuels reduces only slightly from 48.5% in the REF scenario to 47.6% and 47.2% in the CB and CBLI scenarios, respectively. Biomass continues to play a significant role in the fuel mix because the pricing is competitive in relation to the increasing carbon tax on fossil fuels. With increasing demand on biomass as a central fuel, the price could increase thereby influencing the overall fuel landscape.

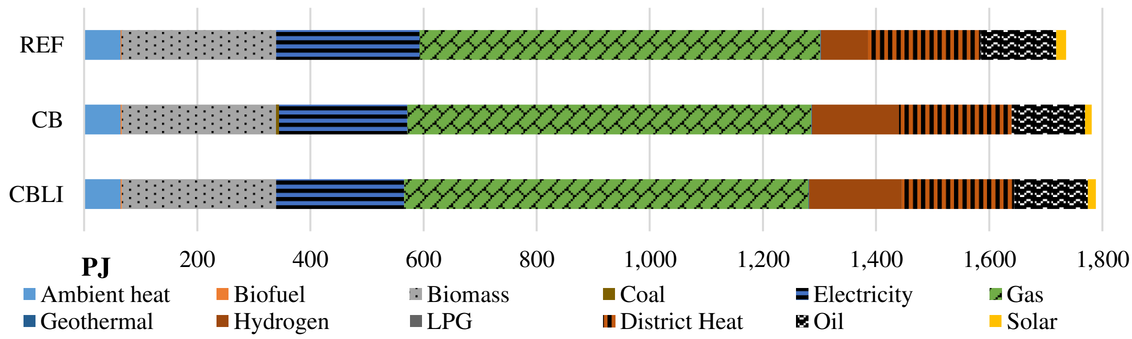

Figure 5-19: Final energy consumption in all households by energy carrier and scenario, 2030

While the overall picture of energy consumption across all households sees minimal shifts from either redistribution scheme, the average energy consumption per household in the lower four income groups sees more considerable shifts in the total consumption with an average of 31 GJ, 34 GJ and 35 GJ per household in the REF, CB and CBLI scenarios, respectively, as shown in Figure 5-20. The REF scenario incorporates shares of renewables and fossil fuels of 7.2% and 63.2%, respectively, while in the CB scenario the shares are 5.6% and 62.1%, respectively, and 7.9% and 58.8% in the CBLI scenario, respectively. This indicates a greater shift for the lower income households in the CBLI scenario towards renewables and away from fossil fuels compared to both other scenarios. In 2030, the end of the technological lifetime of the majority of space heaters is reached and require replacing. Since insufficient budget has been accumulated in the lower four income groups to this date to afford infrastructural changes, the key bridging solution is to blend fuels, for example with hydrogen or biofuels. In subsequent modelling periods, sufficient budget is accumulated for alternative investments and the use of hydrogen and biofuels disappears again. While the CBLI scenario shifts a greater extent of the demand to network supply, such as district heating and gas, and higher input fuels, such as biomass, the CB scenario reduces carbon-intensive fuels, including gas and oil, to a greater extent than in the other scenarios. None of the scenarios exhibit substantial investments into energy efficiency measures where the REF scenario incorporates an energy efficiency equivalent of an average of 0.07 GJ per household and each of the climate bonus scenarios an average of 0.1 GJ per household. However, an analysis of the energy consumption alone does not render sufficient information about the energy welfare of households.

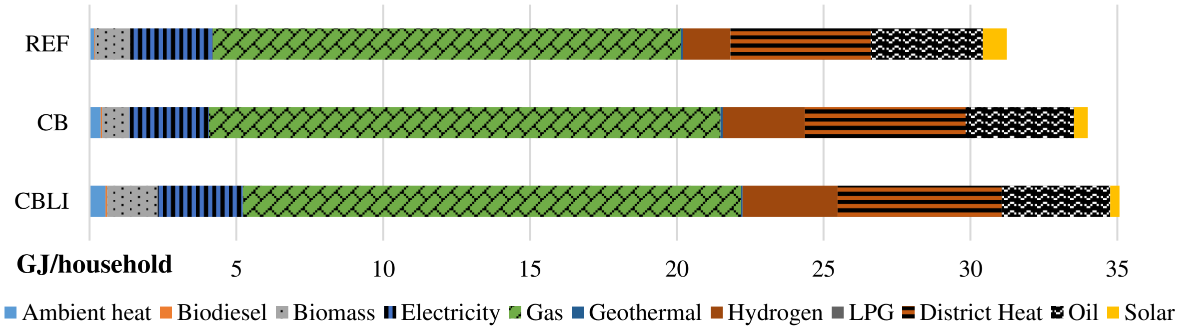

Figure 5-20: Average energy consumption per household for the lower income groups R1-R4, 2030

The suppressed demand can also be assessed to provide a more holistic picture of the energy welfare of households. In this scenario comparison there is suppressed demand prevalent in both the REF and the CB scenarios. Within these scenarios, households continue to compromise on their energy welfare by suppressing demand. In both the REF and the two Climate Bonus scenarios (CB, CBLI), energy consumption was suppressed in the lower four income groups of the population restricting consumption to varying degrees in 2030, as shown in Figure 5-21.

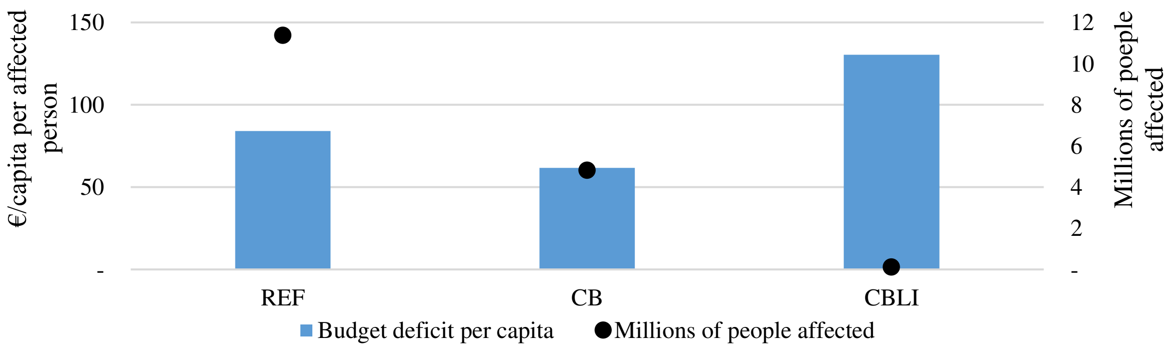

Figure 5-21: Average suppressed demand per capita for the affected population by scenario, 2030

In 2030 in the REF scenario, 11.4 million people are in need of an additional 84€ per capita for the affected population. The addition of the climate bonus from 2025 of 100€ per person in the CB scenario saw an increase in the short-term investment expenditure in lieu of consumption expenditure, resulting in suppressed demand of an average of 52€ per capita for the affected population, representing 5.7 million people of the lower half of the population (income groups R1-R4 of R1-R6 because R5 and the 16.2% of the R6 income group do not experience suppressed demand). For these households, the budget remains restricted despite the additional cash flow, and the cost-optimal solution is to continue to suppress demand. The higher income groups see no changes to their investment and consumption patterns with the addition of the climate bonus. With the alternative distribution of 200€ per capita to the lower 50% of the population (CBLI scenario), the suppressed demand is reduced to the equivalent of about 118€ per capita for approximately 131,000 people affected, so the severity and the extent of suppressed demand is reduced significantly and focussed to specific households. A table summarising the outcome of the suppressed demand in this comparison is provided in Table D-3 Appendix D.

To help understand the suppressed demand, the trends in investment and consumption can be observed in Figure 5-22. Investment and consumption are higher in the CBLI scenario than in both other scenarios after 2030 with earlier financial emphasis placed on consumption expenditure then shifting towards investment. The average investments in the REF scenario increase steadily to 2040 then exhibit a significant peak to 2050 before decreasing again towards 2060. This can be attributed to the lack of budget in the lower two income groups (R1 and R2), who must accumulate budget in order to make investments. These two income groups are no longer present after 2055 whereupon the investments decrease again. The suppression of demand in the CB scenario is lower than in the REF scenario although investments are the most moderate among the three scenarios, also peaking in 2050. However, the investments in the CB scenario are more evenly distributed across the four income groups because the additional cash flow support higher investments in the lowest income groups. The investment patterns in the R3 and R4 income groups are only moderately higher than in the reference scenario thereby resulting in a lower average investment than the REF scenario overall. In the CBLI scenario, investments also increase but due to the additional cash flow, so does the consumption expenditure, which translates into lower suppressed demand.

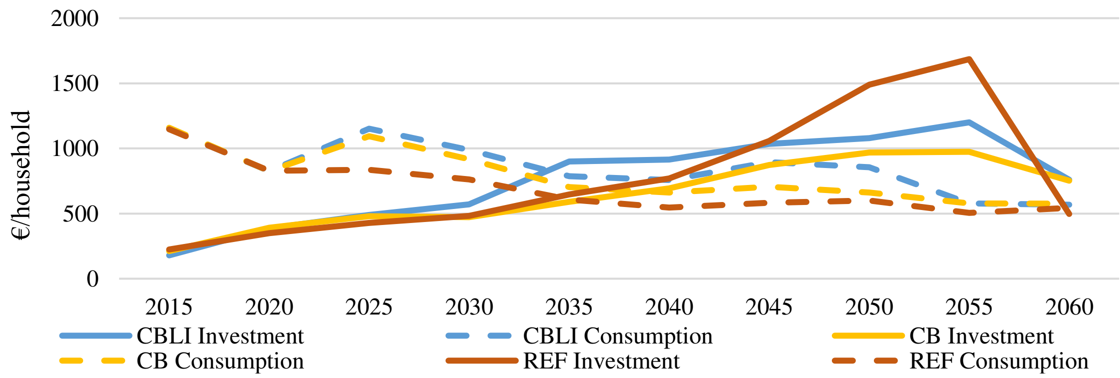

Figure 5-22: Investment and consumption trends in the average R1-R4 household by scenario, 2020-2060

5.4.4 Insights

The debate about the types of policies that could or should be implemented to support a just transition is ongoing. In order to consider the energy welfare of households according to scenarios defined through the energy transition, it is also necessary to understand the implications, or the distributional impacts, of policies on the areas that define the energy welfare of households, namely as outlined in Chapter 2, access and affordability of energy services as well as the opportunity to participate in the energy transition process. The TAM-Households model was specifically designed to evaluate the overall energy and emissions, and investment and consumption patterns of different profiles through key methodological improvements incorporated in the model including disaggregation and budget constraints. Several scenarios evaluated the implications of the methodological improvements on the results, and included the evaluation of the suppressed demand. One scenario assessed the impact of the carbon tax, while another looked at the redistribution schemes of a climate bonus.

The carbon tax plays a role as a price signal to shift investment towards renewable technologies and energy efficiency, however this can also result in negative consequences for lower income households and tenants, who lack either the capital or decision-making power to make structural changes to avert the effect of the carbon tax. The relationship between carbon taxes and electricity levy reliefs could be assessed with this model. The carbon tax, as currently implemented, results in households consuming carbon-emitting fuels to pay a levy on the emissions produced. To further encourage a shift towards electricity and electricity-renewable hybrid technologies, such as heat pumps, a levy reduction is enacted on the consumption of electricity. However, lower income households and tenants consume more carbon-emitting fuels and less electricity and are, thus, penalised twice as they do not gain as much benefit from the electricity levy reduction as they are paying in carbon taxes. Therefore, a disaggregated assessment can provide insights towards finding a path towards the fair distribution of a carbon fund for deliberation on the national government level. The methodology implemented in the model allowed insights into the implications for different users, including owners, tenants, different income groups, building types, locations, all of which are parameters that can assist with the targeting of policies.

To address the concerns of tenants, who lack decision-making power, one means to redistribute the impact of the carbon tax was to allocate the burden equally between landlords and tenants was considered. This type of analysis is possible, because the disaggregation built into the model accounted for the different carbon-consumption patterns by income group and tenure. This allowed a bottom-up calculation of the distribution of the actual tenant emissions rather than a statistical top-down calculation. This could show that while this burden allocation resulted in significant reductions in the tax burden on tenants and across most income groups, owners and commercial and government owner associations were not disproportionately burdened with additional costs. These results then also suggested that this cost distribution does not result in a faster exit from fossil fuel reliance compared to the reference case.

However, an assessment of energy use and emissions, investment and consumption alone do not provide a holistic view on the energy welfare of households. Lower income households already have negative savings and suppress energy demands and so the methodology developed in this thesis also allows the comparison of the expected suppressed demand experienced by households across the various scenarios. Therefore, the impact of a policy option that allocates a fund either with 100€ per capita to all households with a policy option that provides 200€ per capita and directed to the lower half of the population was compared. Due to the existing suppressed demands, lower income households are in a place where they must decide between investments that will improve the long-term energy consumption patterns, or expenditure to meet current unmet needs. The more a lower income household can put towards their budgets, the more they are able to do both of these as was shown with the CBLI policy approach. The methodology supports further assessments to find the right redistribution scheme.

5.5 Evaluation of scenario indicators

In order to evaluate whether a policy achieves its desired effects and how this relates to the energy welfare of households, indicators can be applied to show the potential implications according to specific markers due to the integration of the methodological improvements in the energy system optimisation model. As discussed in Chapter 5.1.3, certain indicators were selected and applied to the base year, 2013, for the reference scenario, and subsequently across all scenarios for the year 2030. The indicators show the carbon and energy intensity, share of renewables for heating, share of access to self-generation, as well as correlate the potential energy poverty status. Since the energy poverty indicators are actually usually only survey-based and based on subjective responses, the interpretation of this indicator should be put into perspective. The potential development of this indicator is calculated for 2030 in comparison to the developments in income and expenditure patterns. Although these indicators do not conclusively reflect the pathway towards alleviating energy poverty, the individual indicators do provide insights to parameters that influence the expected investment and consumption, affordability and energy welfare of households in the long-term as they relate to different actors in the household sector. The indicators applied show the possible trends as they compare the ratio of investment and consumption expenditure to income in the base year and extrapolated to 2030 based on the same parameters. A summary of the indicators is compared in Table 5-15 to Table 5-18 grouped by parameters (income, location, building type and tenure), while more detailed information on the outcome of the indicators across more socio-economic parameters can be found in Appendix D, Table D-4-Table D-9. The analysis is divided into two sections representing an analysis by parameters and by scenarios.

Income influences the affordability of investment and consumption expenditure. Comparing the implications income has on different income groups, the indicators are presented for the lowest income group, the average and higher income households by scenario in Table 5-15 for the situation in the year 2030. Overall, the reference scenario has the best performance for the lowest income group across most indicators, but this should be interpreted in the context of the energy welfare of households. Suppressed demand affects 99.7% of the population in this group, which explains why the affordability indicators are low (households are not spending money on investments or consumption, so the share of income will remain low) and this parameter in turn influences the other energy poverty markers which are all based on income and expenditure. The lowest income group has the best outcomes for carbon intensity, affordability of investments, and the second best outcome for suppressed demand in the CO2TO scenario. The key variable of influence here is that the majority of lower income households are tenants, so measures that benefit tenants support lower income households in general. However, because budget is a dynamic parameter and in any given year households may be in a position to afford investments or consumption, reflecting on the significance of an indicator at only one point in time can be misleading. For example, when comparing the share of population spending more than twice the median (hidden energy poverty), and the share of population spending less than half the median for the lowest income group in the EP and VC scenarios. While both scenarios suggest energy poverty will worsen compared to the reference scenario, the EP scenario suggests that energy poverty would become even worse than the VC scenario. However, it is also key to put these indicators into perspective: in the long-term, energy prices increase (including the addition of the carbon tax) while income does not increase proportionately. This means that any expenditure on investments or on consumption (especially on meeting suppressed demands) that is enabled through additional budget might show that in relation to expenditure patterns in the reference scenario deteriorates the situation for households. But the indicators do not consider the reduction in suppressed demand, which taken together would rather suggest an improvement in the energy welfare. The EP scenario subsidises investment, so the share of budget spent on indirect energy-related expenditure is reduced significantly compared to the VC scenario, while the opposite trend is visible regarding direct energy expenditure (which is subsidised in the VC scenario). Whereas the EP scenario affects 80.4% of the population in the lowest income group, each person needs only 0.02€ to enable the full consumption compared to 7.4% of the population in need of 2€ each (despite the consumption subsidisation). This effect is also observed in the BUDGET0 scenario, where the hidden energy poverty also increases to 57% in comparison, but here all required consumption and investment expenditure is undertaken unlike in the reference case where budget constraints limit the amount of investments and energy consumed. As such, indicators must be interpreted within the right context. However, this can also provide deeper insights into the financial burden that households will face in order to participate in the energy transition and at the same time improve their own energy welfare. The average and higher income households experience little disadvantages across the various indicators. However, within the scenarios where investment support is not provided to them, in comparison to other scenarios, the performance of the indicators is worse, such as in the VC scenario, and these households are not affected by suppressed demand.

Urbanisation influences the accessibility households have to particular resources, such as renewables or network solutions as seen in the comparison in Table 5-16. The energy poverty scenario supports higher shares of investments for renewables in heating in general and higher shares of self-generation in rural households, which reflects greater access to resources. However, due to greater reliance on more flexible energy sources, such as oil, the carbon intensity is higher than in urban households, who can switch to decarbonised grid options such as district heating. Rural households are also more likely to subjectively indicate an inability to keep warm and exhibit arrears in utility bills due to the higher shares of expenditure on fuel costs.

The building type will influence not only the amount of energy consumed (e.g. SFH have greater ratio of living space to floor area) but also the lack of decision-making power in MFH is greater especially as the share of tenants in this building type is highest, compared in Table 5-17. For this reason, the CO2TO scenario provides the greatest carbon intensity reduction in MFH buildings as well as the reducing consumption expenditure. The EP scenario provides the greatest investments in renewables in heating because the shares of lower income tenants receiving invest subsidisation is highest in this building type. Whereas SFH, due to the larger share of higher income owners, profit most in the CO2TO, CB and CBLI scenarios which provide a greater platform for investment into renewables and self-generation. The higher investment expenditure results in lower consumption expenditure for the average household living in a SFH.

Tenure is a key parameter influencing the decision-making power related to the investment and consumption patterns, given in Table 5-18. Overall tenants profit the most towards structural changes in the EP scenario, because subsidisation targets investments which enable the greatest shares of renewables for heating, but also have acceptable influence on the carbon intensity and the other affordability indicators. The VC scenario, on the other hand, only reduces the consumption expenditure without significant improvements in any of the other indicators. Owners, similar to the average SFH, benefit most from the CO2TO, CB and CBLI scenarios, because they provide additional cash or incentives to undertake structural investments. Conversely, owners perform worst in the VC scenario due to the lack of incentives to make investments to decrease consumption overall. However, the range of differences between the scenarios for this actor group is very low.

Overall, with the comparisons made between scenarios, the CO2TO scenario appears to result in the most favourable markers for carbon intensity and renewables for heating, as well as improving the overall energy welfare of households across various parameters including affordability for consumption (since the carbon tax burden is halved). Whereas investment affordability is improved the most through the EP scenarios indicating that investment support can greatly influence the overall structural system. This assessment showed that the methodology provides insights to the impacts of different variables on different actors within the household sector. They enable the measurement of the potential impacts on, for example, energy welfare or affordability that would otherwise not be visible in a common modelling exercise. The application of the indicators on the different scenarios also shows the impact of specific variables, such as investment or consumption subsidisation, and so allow a comparison of the interactions between measures and the energy system for specific household types.

Table 5-15: Summary evaluation of indicators across scenarios by income, 2030

Indicator		Greenhouse gas emissions	Energy efficiency:	Renewables for heating	Access: self-generation of	Affordability: income spent on	Affordability: income spent on	Inability to keep	Arrears in utility bills	Hidden energy poverty: 2M	Hidden energy	Suppressed demand	Budget deficit
Unit		*CO2-eq/ capita*	*Ratio*	*% RE*	*% PV*	*% income*	*% income*	*%pop*	*%pop*	*%pop*	*%pop*	*%pop*	*€/capita*
	REF	0.85	0.84	0.9%	11.2%	2.4%	5.6%	8.1%	4.4%	25.2%	12.0%	99.7%	89 €
	BUDGET0	1.04	1.20	2.5%	0.0%	3.1%	12.7%	18.5%	10.0%	57.5%	27.4%	0.0%	0 €
	EP	1.00	1.26	9.4%	0.1%	3.0%	12.1%	17.5%	9.5%	54.6%	32.1%	80.4%	0.02 €
<900	**VC**	0.82	0.95	4.4%	0.0%	11.9%	5.3%	11.2%	6.1%	34.9%	16.6%	7.4%	2 €
	CO2TO	0.61	1.32	0.9%	0.0%	1.0%	10.0%	19.5%	10.6%	60.7%	28.9%	2.0%	1 €
	CB	0.92	1.10	0.9%	0.1%	3.2%	9.9%	14.3%	7.8%	44.6%	21.2%	80.6%	40 €
	CBLI	0.87	1.09	0.9%	0.1%	4.6%	11.6%	16.9%	9.2%	52.6%	25.0%	5.4%	27 €
	REF	0.65	0.75	24.0%	6.6%	1.3%	2.5%	2.8%	1.9%	9.1%	9.1%	N/A	N/A
	BUDGET0	0.64	1.06	23.2%	8.5%	1.2%	2.6%	3.0%	2.0%	9.7%	9.7%	N/A	N/A
	EP	0.65	1.00	23.2%	5.7%	1.2%	2.4%	2.9%	2.0%	16.2%	16.2%	N/A	N/A
Avg.	**VC**	0.73	1.09	23.1%	4.6%	2.2%	1.5%	3.2%	2.1%	10.4%	10.4%	N/A	N/A
	CO2TO	0.53	0.98	24.0%	7.8%	0.3%	2.2%	2.7%	1.9%	9.0%	9.0%	N/A	N/A
	CB	0.63	1.06	24.0%	8.0%	1.4%	2.5%	2.8%	1.9%	9.3%	9.3%	N/A	N/A
	CBLI	0.65	1.08	24.0%	7.8%	1.5%	2.6%	2.9%	2.0%	9.6%	9.6%	N/A	N/A
	REF	0.46	1.04	46.8%	0.2%	1.0%	1.8%	0.2%	0.2%	2.8%	7.0%	N/A	N/A
	BUDGET0	0.47	0.61	46.9%	19.6%	1.0%	1.8%	0.3%	0.3%	2.9%	7.2%	N/A	N/A
	EP	0.52	0.47	44.7%	0.2%	1.0%	1.4%	0.2%	0.2%	4.3%	10.7%	N/A	N/A
5000-18000	**VC**	0.77	0.71	34.2%	0.1%	1.1%	1.0%	0.3%	0.3%	3.3%	8.3%	N/A	N/A
	CO2TO	0.67	0.51	46.8%	6.7%	0.2%	1.6%	0.3%	0.3%	2.9%	7.3%	N/A	N/A
	CB	0.40	0.58	46.8%	0.2%	1.1%	1.7%	0.2%	0.2%	2.7%	6.8%	N/A	N/A
	CBLI	0.46	0.64	46.8%	0.2%	1.1%	1.8%	0.2%	0.2%	2.8%	7.1%	N/A	N/A

Table 5-16: Summary evaluation of indicators across scenarios by location, 2030

Indicator		Greenhouse gas emissions: CO_2 intensity	Energy efficiency: energy use intensity	Renewable energy: renewables for heating	Access: self-generation of total electricity consumption	Affordability: income spent on energy-related investments	Affordability: income spent on energy consumption	Inability to keep comfortably warm	Arrears in utility bills
Unit		*CO2-eq/ capita*	*Ratio*	*% RE*	*% PV*	*% income*	*% income*	*%pop*	*%pop*
Urban	**REF**	0.60	0.76	21.9%	6.9%	1.4%	2.8%	1.2%	1.0%
	BUDGET0	0.60	1.06	20.9%	6.5%	1.3%	2.9%	1.3%	1.0%
	EP	0.61	1.01	19.9%	6.4%	1.3%	2.7%	1.2%	1.0%
	VC	0.65	1.11	20.8%	5.0%	2.5%	1.7%	1.3%	1.1%
	CO2TO	0.48	0.97	21.9%	8.1%	0.3%	2.5%	1.2%	1.0%
	CB	0.58	1.07	21.9%	9.8%	1.5%	2.8%	1.2%	1.0%
	CBLI	0.59	1.08	21.9%	9.6%	1.6%	2.9%	1.2%	1.0%
Rural	**REF**	0.83	0.73	31.1%	5.7%	1.1%	2.2%	4.2%	2.4%
	BUDGET0	0.76	1.03	31.0%	7.0%	1.1%	2.3%	4.4%	2.6%
	EP	0.79	0.98	34.5%	4.8%	1.1%	2.3%	4.3%	2.6%
	VC	1.02	1.03	30.8%	4.6%	1.9%	1.4%	4.7%	2.8%
	CO2TO	0.70	0.99	31.1%	8.2%	0.3%	1.9%	4.0%	2.4%
	CB	0.80	1.01	31.1%	5.4%	1.4%	2.3%	4.2%	2.5%
	CBLI	0.87	1.00	31.1%	5.3%	1.4%	2.3%	4.3%	2.5%

Table 5-17: Summary evaluation of indicators across scenarios by building type, 2030

Indicator		Greenhouse gas emissions: CO_2 intensity	Energy efficiency: energy use intensity	Renewable energy: renewables for heating	Access: self-generation of total electricity consumption	Affordability: income spent on energy-related investments	Affordability: income spent on energy consumption	Inability to keep comfortably warm	Arrears in utility bills	Hidden energy poverty: 2M	Hidden energy poverty: M/2
Unit		*CO2-eq/ capita*	*Ratio*	*% RE*	*% PV*	*% income*	*% income*	*%pop*	*%pop*	*%pop*	
SFH	**REF**	0.60	0.76	21.9%	6.9%	1.4%	2.8%	1.2%	1.0%	7.6%	8.2%
	BUDGET0	0.60	1.06	20.9%	6.5%	1.3%	2.9%	1.3%	1.0%	7.9%	8.6%
	EP	0.61	1.01	19.9%	6.4%	1.3%	2.7%	1.2%	1.0%	14.3%	15.4%
	VC	0.65	1.11	20.8%	5.0%	2.5%	1.7%	1.3%	1.1%	8.1%	8.7%
	CO2TO	0.48	0.97	21.9%	8.1%	0.3%	2.5%	1.2%	1.0%	7.5%	8.1%
	CB	0.58	1.07	21.9%	9.8%	1.5%	2.8%	1.2%	1.0%	7.4%	8.0%
	CBLI	0.59	1.08	21.9%	9.6%	1.6%	2.9%	1.2%	1.0%	7.6%	8.2%
MFH	**REF**	0.83	0.73	31.1%	5.7%	1.1%	2.2%	4.2%	2.4%	10.7%	9.6%
	BUDGET0	0.76	1.03	31.0%	7.0%	1.1%	2.3%	4.4%	2.6%	11.5%	10.3%
	EP	0.79	0.98	34.5%	4.8%	1.1%	2.3%	4.3%	2.6%	19.1%	17.1%
	VC	1.02	1.03	30.8%	4.6%	1.9%	1.4%	4.7%	2.8%	12.8%	11.5%
	CO2TO	0.70	0.99	31.1%	8.2%	0.3%	1.9%	4.0%	2.4%	10.5%	9.4%
	CB	0.80	1.01	31.1%	5.4%	1.4%	2.3%	4.2%	2.5%	11.2%	10.0%
	CBLI	0.87	1.00	31.1%	5.3%	1.4%	2.3%	4.3%	2.5%	11.4%	10.2%

Table 5-18: Summary evaluation of indicators across scenarios by tenure, 2030

Indicator		Greenhouse gas emissions: CO_2 intensity	Energy efficiency: energy use intensity	Renewable energy: renewables for heating	Access: self-generation of total electricity consumption	Affordability: income spent on energy-related investments	Affordability: income spent on energy consumption	Inability to keep comfortably warm	Arrears in utility bills
Unit		*CO2-eq/ capita*	*Ratio*	*% RE*	*% PV*	*% income*	*% income*	*%pop*	*%pop*
Owner	**REF**	0.76	0.71	34.9%	12.4%	1.3%	2.4%	1.6%	1.3%
	BUDGET0	0.75	1.01	34.7%	11.4%	1.3%	2.5%	1.7%	1.4%
	EP	0.79	1.00	32.8%	10.1%	1.3%	2.4%	1.6%	1.4%
	VC	0.86	0.98	34.3%	9.1%	1.4%	1.5%	1.7%	1.4%
	CO2TO	0.73	0.86	34.9%	14.9%	0.3%	2.1%	1.5%	1.3%
	CB	0.66	0.97	34.9%	15.1%	1.3%	2.4%	1.6%	1.3%
	CBLI	0.69	0.96	34.9%	14.8%	1.3%	2.4%	1.6%	1.3%
Tenant	**REF**	0.55	0.91	7.8%	0.0%	1.3%	2.5%	2.5%	1.9%
	BUDGET0	0.54	1.01	7.1%	0.0%	1.1%	2.7%	2.7%	2.1%
	EP	0.52	0.90	9.8%	0.0%	1.1%	2.4%	2.6%	2.0%
	VC	0.63	1.09	7.5%	0.0%	3.1%	1.6%	3.0%	2.3%
	CO2TO	0.36	1.00	7.8%	0.0%	0.3%	2.4%	2.5%	1.9%
	CB	0.60	1.03	7.8%	0.0%	1.5%	2.6%	2.6%	2.0%
	CBLI	0.61	1.04	7.8%	0.0%	1.6%	2.7%	2.7%	2.0%

5.6 Conclusion: Summary of key insights

The various scenarios considered through the application of the TAM-Households model showed that in order to reflect on the impact changes in the energy system have on lower income households and on energy poverty, the methodology in the energy system analysis needed to be expanded. Common modelling exercises do not allow a differentiated assessment of lower income households or in combination with other specific parameters. Key elements were outlined in Chapter 2-4, such as the influence of access and affordability on differentiated investment and consumption patterns across the household sector and the resulting concepts related to energy poverty and vulnerable consumers. To enable this, TAM-Households combined disaggregation with budget constraints into an energy system optimisation model to represent the diversity of the household sector as well as the limited financial capacities. Disaggregation was useful to assess the differentiated energy service needs of different households based on their income, location, building type and tenure. This method alone already enabled a better assessment of the access to resources, technologies and services, and the investment and consumption patterns of different actors in the household sector.

However, this alone proved to be insufficient to evaluate the lack of financial capacity of specific households. The methodology developed in TAM-Households include a budget constraint, which makes it possible to evaluate the financial limitations of particular households with regard to the ability to afford the high upfront costs of investments. Without the inclusion of the budget constraint the model operates on a single objective to minimise the overall system costs, which does not allow insights into the investment and consumption behaviour of specific households. The addition of the budget constraint requires the model to aim for the dual objectives of maximising the benefit to the household (or actor group) in addition to minimising the system costs.

Increasing the resolution on the types of demand profiles in the household sector resulted in a divergence in the future pathways when compared with the common approach using an aggregated household sector model, which does not incorporate disaggregation or a budget constraint. This highlights that the cost-optimal choices to achieve decarbonisation in 2050 for different profiles means potentially unexpected energy carrier patterns, such as biofuels and hydrogen, which emerge as alternatives for households to maintain the existing infrastructure over new infrastructure investments. In this way, the cost-optimal solution from the household perspective is to replace the fuel mix with lower operating costs rather than the technology until such budget is available to undertake the high upfront costs of new investments. This insight is made visible through the budget constraint and highlights the trend of delayed investments due to insufficient budget indicating that the transformation of the energy system may be prolonged, particularly for some segments of the household sector. This twofold method highlighted the true limitations of households to afford the high upfront costs of new investments and revealed that the expected regression of fossil fuels would likely be slower than expected.

The impact on the energy vulnerability of households since lower income households will likely continue to use less efficient appliances for longer and are not in a position to save money for larger, meaningful investments, thereby perpetuating the energy poverty cycle. Therefore, the model was developed to assess access and affordability as well as the impact of policies on the energy use and emissions of households in Germany as well as assess investment and consumption patterns in addition to the energy welfare of households. This methodology provides a platform to assess the impacts of different policies on the energy use and emissions of specific household types and, as such, also a method to assess the significance of energy poverty.

From the outset, it should be noted that the majority of lower income households do not have sufficient budget to meet the expected investment and consumption patterns. This is made evident through the disconnection rates for electricity and gas and the level of suppressed demand estimated in the reference scenario to affect 11 million people in 2020. As such, households will often employ coping mechanisms to deal with the investment costs of a replacement appliance often turning to the second-hand market, or using technologies beyond their technical lifetime. To assess the significance and potential implications for the expected projection of the overall household energy use and emissions, a case study was included in the model looking at the impact of second-hand appliances using the example of freezers and refrigerators. The case study outlined that second-hand appliances and extending the lifetime of technologies can result in lower investment costs per household compared to the reference scenario, but also in higher energy consumption. This methodology could be applied to include several other appliances with high annual energy consumption, such as clothes dryers, washing machines and dishwashers, which could also contribute to unexpectedly higher energy demands from particular households.

Households qualifying for social welfare will often profit from financial assistance for electricity and heating bills. This is the approach taken in Germany and is in line with the perspective of providing bill support and disconnection protection as given for vulnerable consumers. Energy poverty, a concept broader than just electricity and gas and not recognised in Germany, aims to address the underlying causes of energy poverty by targeting renewable and efficient technologies and building refurbishments. The modelling methodology was applied to evaluate a comparison of the impact of the two approaches to providing financial support. The assessment showed that reduction of the investment cost burden results in higher shares of renewables and less fossil fuel consumption compared to the reference scenario. However, reduction of the consumption cost burden (for electricity and assuming the costs of the carbon tax) showed that households maintained fossil fuel consumption, shifting little in the underlying energy system. This analysis enabled a comparison of different policy designs and the impact this may have for specific households, technologies or fuel types.

The debate about a socially just energy transition includes a discourse on the best way to redistribute the taxes levied on emissions produced through fossil fuel consumption. This thesis evaluated first the impact of the carbon tax together with the levy reduction on electricity prices, then followed with an assessment of three alternative redistribution schemes for a climate bonus. Financial support in the means of a climate bonus showed to have positive effects on the household and on the overall energy system. Lower income households currently consume more carbon-emitting fuels and less electricity and are not in a financial position to react to the price signal from the carbon tax, nor is the financial burden reconciled through the electricity levy reduction. Through the addition of household disaggregation, the results showed the impact on different profiles within the household sector. Significantly, that the majority of lower income households suppress demand and the provision of any additional funding will go towards meeting this demand, or could be invested into new technologies but in lieu of using them to their full potential. The newly developed model always chooses the cost-optimal path and sheds consumption where this can be done most economically overall, and it is through this methodology that the suppressed demand can be estimated. The lowest income households have competing household budget and the current taxation and redistribution schemes do provide some, but inadequate support. Several indicators, while not definitive in their conclusion, were applied and can suggest how policy approaches may differ from each other and in which aspects, thereby enabling the improvement of understanding the potential impacts of policies on different profiles within the household sector. Overall, the methodology of the disaggregation and the budget constraints allowed an analysis of the impacts by different parameters, such as income groups, building type, location and tenure. Through the application of the indicators, it becomes possible to assess the influence of these variables on the access and affordability by different parameters and so enable an analysis of the interactions between different policies as well as the implications of measures on specific groups.

Crucially, the key outcome of the methodology developed in this thesis supported the systematic analysis to evaluate the concept that lower income households are not in a financial position to improve their energy welfare and are only able to take action once sufficient budget is accumulated. Through this analysis the perpetuation of energy poverty can be better understood through the dynamic changes in the energy supply sector with the influence of policies such as carbon taxes or subsidisation. The methodology enables a comparison of subsidisation schemes, be they for investments, consumption or additional income. Through this scenario analysis comparisons can be made between shifting the investment focus towards access to renewable and more efficient technologies, the influence and implications of limited budgets as well as the broader questions about how to achieve the decarbonisation targets given this heterogeneous household sector and the financial limitations.

"We have been trying to shape the people around the energy system when what we should be doing is shaping the energy system around the people."

Dr. Paul Deane, University College Cork

6 Conclusion and outlook

Households have a prominent role to play in ensuring the energy transition targets can be met as these are responsible for a third of the final energy consumption and about 10% of the direct greenhouse gas emissions. However, the participation of households has not been adequate in increasing the levels of renewable energy and energy efficiency to meet the energy transition targets. The energy transition boasts endeavours to ensure affordability of energy consumption despite key measures, such as carbon taxes, to act as a financial incentive for households to invest in alternative technologies and refurbish their homes. This inaction can be attributed to two circumstances: lack of income and lack of decision-making ability. With increasing energy bills, low energy efficiency in appliances and buildings, and the effects of low income, energy poverty is on the rise with an estimated 11-21% of the German population affected. Despite these trends, the concept of energy poverty is not recognised in the German context. The significance of addressing energy poverty within the energy transition is becoming increasingly important. The limitations facing households are discounted in common modelling approaches, where averaged households are typically represented. The absence of recognition for the issue leads to unrealistic expectations from the household sector regarding the achievement of renewable energy and energy efficiency targets. This thesis focussed on 1) providing a pathway towards recognising and addressing energy poverty in Germany, and 2) developing a method to support evidence-based policy assessment considering the diverse attributes describing a heterogeneous household sector through an energy system analysis to assess the impact on households and the energy system.

Germany is not alone in declining to explicitly recognise and address energy poverty nationally through policy. Only a handful of countries in the EU have legislated a definition of energy poverty to date. Research conducted within this context of this thesis contributed to the European understanding of energy poverty by recognising that the common approach to addressing vulnerabilities in the energy sector is typically restricted to so-called vulnerable consumers within the liberalised energy markets. This limiting stance led to vulnerabilities associated with general poverty and so measures to support vulnerable consumers are classically addressed through the social welfare system whereby little is undertaken to address the underlying causes of these vulnerabilities. This erroneous approach means little is done to ensure lower income households can participate in and benefit from the energy transition beyond bill support and disconnection protection. As a result of challenging the fundamental assumptions about how to position vulnerabilities within the energy transition and the liberalised markets, the differences between energy poverty and vulnerable consumers led to incorporation of two distinct articles for each concept in the revision of the electricity Directive of the European Parliament and the Council. This legitimises the extension of viewing vulnerabilities in the energy sector beyond electricity and gas and gives credence to the importance of addressing the underlying issues leading to energy poverty. Energy poverty and vulnerable consumers are experienced within the current energy system and efforts to mobilise investment from the private sector into renewables and energy efficiency are hindered by households that cannot participate due to insufficient capital or decision-making power. Likewise, without considering these circumstances, progress on the energy transition could also lead to further inequalities.

This thesis took the interdisciplinary approach to combine energy poverty research typically based in the social sciences with an economic-engineering method developed for technology assessment and energy system analysis, thus bridging the gap towards an integrated energy transition study. New empirical evidence highlighting the limited investment potential of households by income groups was uncovered. Understanding energy poverty and its role in the broader energy transition debate led to the development of an energy system optimisation model incorporating specific features, such as disaggregated profiles accounting for the lack of financial capacity or decision-making power. This novel modelling approach takes an interdisciplinary approach to combining energy poverty research with a techno-economic energy system assessment based on achieving the dual objectives of minimising costs and maximising welfare. Parameters that are significant for understanding and integrating consideration for energy poverty in the energy planning process, such as budget restrictions for investment and consumption, second-hand appliance markets and extended life-time of technologies (e.g. to show the potential influence of policies) are included in the newly developed energy system optimisation model, named TAM-Households.

The key methodological improvements include the household disaggregation and the budget constraints. Comparison of the results from TAM-Households including these parameters and an aggregated model (without the extended methodology) revealed that unexpected fuel types enter the future mix when accounting for the full costs to the household for various heating technologies and not only taking a system view of costs. This highlights that the future energy landscape would then need alternative network extensions and a more in-depth view of these results within the overall energy system. The inclusion of both disaggregation and the budget constraints are the cornerstones that enabled an evaluation of the energy welfare of households. Disaggregation without the budget constraint forces the model to only solve for the cost-optimal system costs, while the addition of the budget constraint adds the additional model objective to also maximise the benefit to the household. This methodology enabled an analysis of the overall energy use and emissions and distributional impacts of different policies, as well as the impact on the energy welfare of households.

The method developed in this thesis provides a platform from which to conduct a review of the impact of various policies and measures, whether they are targeted towards lower income households or the general population. The TAM-Households model is capable of assessing the impact on lower income households as well as other household segments and can help to support future policy analyses. Understanding the causes and effects of energy poverty can help to target support appropriately. The model was applied in several example scenarios, which demonstrated that the methodology developed is well-suited to effectively analyse the implications of various policy options on different household segments, as well as the interactions between various parameters on the energy use and emissions in the household sector. As a result of this scenario analysis, a comparison can be drawn between shifting investment focus to access to renewables and more efficient technologies, the impact of budget constraints, as well as the broader question of how to support effective decarbonisation without compromising on the energy welfare of households.

Crucially, the inclusion of the budget constraint highlighted the financial deficit of households to meet their energy needs and enabled an estimation of the number of people affected by suppressed demand as well as the financial shortfall across various scenarios. This type of result adds another layer towards the holistic analysis of the energy welfare of households beyond only the energy use and emissions. The inclusion of the budget constraint underscores that because lower income households are not in the financial position to improve their energy welfare nor participate in the energy transition with costly investments, and are only able to make these investments once sufficient budget is accumulated, these households will be slower in shifting to climate-friendly technologies, and the realisation of the energy transition targets will be delayed. Without sufficient capital, lower income households will turn to the second-hand market for household appliances, which are often less efficient than a new one. This has implications not only for the household energy consumption budget but also for the overall household energy consumption, particularly when considering the potential impact additional household appliances could have on the overall system and how this phenomenon is discounted in modelling forecasts. Given these financial limitations, the model facilitates the exploration of different types of financial support. Insights could be gained about the interactions between the provision of subsidies – either for investment or consumption expenditure, or as additional income – and the implications for the energy use and emissions for different household segments. The comparison between subsidising investment and subsidising consumption illuminated that subsidising investment led to a final energy consumption in lower income household fulfilled with a greater degree of renewable energy. In contrast, and as can be expected, subsidising the consumption of electricity and assuming the responsibility for the carbon tax maintains the current energy system for the lower income households, which sees little meaningful investments and a perpetuation of the status quo. With various policies aiming to financially encourage households to switch away from fossil fuel consumption, there is also the debate about how to redistribute the funds in a just way in recognition of the lack of financial capacity and decision-making power some households lack. These aspects can also be considered with this modelling methodology and allowed an analysis of impacts on not only different income groups, but also investigate the impacts on tenants and owners. The modelling results demonstrated different ways to implement a carbon tax redistribution scheme – from an equal distribution between tenants and landlords to per capita distribution of 100€ to all or 200€ to only the lower half of the population. The results suggest redistribution schemes are useful to empower lower income households to make positive changes to the energy system that also benefit them. Overall, these results provide a perspective to view the energy transition and household energy investment and consumption patterns through an energy poverty lens. The results highlighted the significance of common practices including coping mechanisms that impact the individual household but are negligible for the bigger picture. However, a just transition should ensure that all households are able to participate in and profit from the future energy system, and the interactions between energy system and households can be assessed through this methodology

This research is, however, not without its limitations. While the disaggregation incorporated a more detailed representation of the building stock, limited information about the building stock as it relates to the socio-economic profiles defined in this thesis means the insights regarding the costs and impacts of energy efficiency could be vastly improved. These technical gaps, however, also provide scope for further research where future data collection efforts systematise the triangulation of these parameters. While this research has provided an interesting overview of the inequality within the energy system based on the perspective of household income, this can be taken further to include perspectives from other socio-economic characteristics, such as household composition (e.g. elderly, single-parent households) or other factors such as education level, migrant status. These further insights will assist in fine-tuning the targeting of policies to tailor the response even further. Similarly, the interdependency with the transport sector should be assessed, particularly with regard to the carbon tax redistribution.

This disaggregation methodology already illustrated the impact of assessing the budget constraints of households in terms of investing in appliances that will reduce expenditure on energy and highlighted the limit to the participation of certain households from contributing to and benefiting from the energy transition. This finer representation of the actor groups in this model allows for better targeting of policy measures towards specific actor groups and a more realistic expectation of the energy and emissions as well as the overall costs to achieve the energy transition while including the participation of lower income households. The application of this methodology can be useful where the aim is to target specific subsidy schemes to particular income groups. The model currently has a single temporal resolution which could limit the insights to the impact of the refrigeration on the overall electricity peak load demand as well as energy efficiency behaviour in appliance use, but this should not discount the insights to the general different solutions required for different economic subsectors of the residential sector. The disaggregation is based on defining profile-specific, plausible data derived through publically available data sources and triangulated with literature. These were corroborated with expert input and various other data sources, but still assume that all households within one profile (despite the fine resolution) have similar investment and consumption behaviours. Future research can build on this database and improve the resolution to include additional socio-economic parameters, such as household size, single-parents, or age of occupants, or finer building descriptions to better support policy debates around the Renovation Wave and National Renovation Strategies.

As such, this thesis lays out the groundwork for further research, model development and applications. The incorporation of considerations for the consumer into energy system modelling better enables a path forward for a consumer-driven energy transition pathway analysis and opens the door for further applications. There is considerable scope to apply this platform towards more assessing inclusiveness in the energy transition process through the integration of further aspects of the different profiles elaborated in this thesis, e.g. to consider the impact and significance of gender, household composition (e.g. household size, single-parent households, elderly, students). This will further highlight the needs and capabilities of different sectors of society and entrench the need for a differentiated approach to developing policies tailored towards not only the impact of energy poverty on different consumer groups but in general as well.

Feasibly the TAM-Households model can be applied to study various other political mechanisms as single policies or as combinations of several policies. Of interest might be to combine subsidisation support for lower income households that provides acute bill support in addition to investment support. Other examples might include a comparison of various other redistribution models for the climate bonus, which can also be explored to include differentiated taxation, collection and redistribution as subsidies for, for example, specific technologies. One example could be to explore the effect of a refrigerator rebate programme as a means to redistribute funds that are invested into the energy system directly. Or by targeting a specific building type which is prone to sustained fossil fuel consumption. Multifamily houses are the most occupied building type and inevitably have difficulties with investment decisions owing to the diverse ownership structure. A holistic approach integrating social and psychological research can support understanding of how best to diffuse this sector. In terms of lower income households, a sensitivity analysis could be undertaken to find the value of the financial aid to trigger the desired investments. An additional feature is built into the model to provide profile-specific energy carrier prices, which offers an opportunity to further investigate the influence of consumption prices and would add value to the results given that some (especially lower income households) are locked into higher energy tariffs. While TAM-Households applied a differentiated tax structure, this feature would be especially useful to explore the opportunity and impacts of a differentiated tariff structure for different consumer groups. Other conceivable applications of TAM-Households include investigating impacts on suppressed demand and rebound in households, which could be significant in terms of better integrating behaviour of consumers into a cost-optimisation energy system model. This has implications for exploring minimum consumption standards as outlined in the Right to Energy discourse. The method in TAM-Households can be applied to investigate various minimum standards and evaluate the impact on the welfare of households within the overall household energy sector by applying the indicators operationalised in this thesis.

Crucially, the outcomes of this thesis can be applied to shape the analysis of the energy transition around consumer needs, particularly to support a just transition. When the consideration for energy poverty is incorporated into the National Energy and Climate Plans and long-term strategies developed which specifically target households experiencing energy poverty, this data disaggregation and model could form the basis for further development to address how these strategies could be designed and implemented. TAM-Households can be implemented to support this process to integrate energy poverty into policy by providing a reflection of the impact of different policies on the various profiles by their characteristics.

Solutions to addressing energy poverty do not conflict with the objectives of the energy transition. Recognition of the issue will drive forward not only the energy transition but will benefit all households through targeted policies and measures designed to achieve the future vision and ensure no one is left behind.

"Overcoming poverty is not a gesture of charity. It is the protection of a fundamental human right, the right to dignity and a decent life…Do not look the other way; do not hesitate. Recognize that the world is hungry for action, not words. Act with courage and vision."

Nelson Mandela (1918– 2013)

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"If you don’t have a strategy, you’re part of someone else’s strategy."

Alvin Toffler (1928– 2016)

Appendix

A. Additional energy poverty information

A.1 Energy poverty indicators

Table A-1: Overview of relevant energy poverty indicators

Income and expenditure
Income is a vital indicator when looking at energy poverty, as it is also the key indicator to assess the share of the population at risk of poverty and has implications for the ability to afford energy needs
Energy consumption based on fuel types
Higher consumption (and therefore expenditure) may increase household vulnerability to price increases. However, the drivers of consumption are complex, and may be due to climatic factors, income drivers (affordability (due to higher incomes or lower energy prices) and standard of living) and energy efficiency of buildings and appliances. The type of energy used is also important as it can be indicative of heating systems, and applicability of measures for protecting vulnerable consumers, and tackling energy poverty.
Energy prices
The price of energy influences affordability of energy and vulnerability to energy poverty. Many factors influence price of energy, including whether prices are regulated / competitive, levels of taxation, and costs of supply. For vulnerability, a key issue is how these prices change over time, particularly in dynamic markets, and the impacts on different groups in society. It is the change in price of energy combined with consumption needs that can indicate vulnerability to energy poverty. This is useful information in understanding the leverage Governments have in reducing or increasing prices.
Tenure status and other housing characteristics
Tackling the challenges of energy poverty also require an understanding of tenure status. Tenure status can impact the implementation of measures; renting can pose problems for tenants in investing in measures, particularly in the private sector. Conversely, tenants living in social housing could benefit from larger scale building retrofit efforts. Keeping track of this type of indicator highlights the importance of implementing measures to address these issues (or combination of issues). In addition to climate, the type of dwelling will also influence the energy demand of the building, where detached housing will have a greater energy demand than semi-detached houses or flats. It can also have an impact on the implementation of retrofit programmes and other measures associated with addressing energy use.
Energy services (e.g. space heating) and building types
A further factor influencing overall household energy demand is the type of heating system employed. This information is fundamental for addressing especially space heating demands and ensuring efficient use of energy in this arena through appropriate measures. The importance of the above indicators for understanding the challenge across different building type, heating system, fuel use and tenure type is critical. Even if correlation does not equate to causation, improved understanding will enable more effective targeting of measures. It is also important to be aware of seasonal heating needs, and the adequacy of household systems. From the Winter of 2002/2003 to the Winter of 2010/2011, Malta, Portugal, Spain, Cyprus and Belgium had the highest seasonal variation in mortality (Excess Winter Deaths Index) in Europe (Fowler et al. 2015), thus highlighting the need to further investigate the correlation between heating system (indoor temperature) and energy poverty (mortality rate in the cold season), even in Member States with milder winter temperature (and with inadequate heating systems).
Energy poverty proxy indicators
These include living in dwellings with leakages and damp walls, having arrears in accounts, ability to keep the home comfortably cool, and the ability to keep the home adequately warm, which are qualitative statistics

collected through the Eurostat Survey on Income and Living Conditions (SILC). These energy poverty proxy indicators are currently the only indicators available to use and compare the status of energy poverty across the EU, and therefore despite their weaknesses (see (Thomson and Snell 2013), provide an important basis. While attempts to develop a composite index to estimate the state of energy poverty across Member States is undertaken (Thomson and Snell 2013), the usefulness of a single indicator is disputed (Tirado Herrero 2017; Simcock et al. 2016). Categorised into primary and secondary indicators, the primary ones include arrears on utility bills and inability to keep comfortably warm, while secondary indicators include dwellings with leakages and damp walls. Dwellings with leakages and damp walls provide some indication of building quality, although this can of course not be directly translated to energy efficiency.
Arrears on utility bills
The indicator for share of population with arrears in accounts provides some insights into energy affordability.
Inability to keep comfortably warm
Arguably, the most relevant indicator is households unable to keep the home adequately warm. The recently (2012) added cooling related indicator provided by EU-SILC is increasingly becoming relevant as this relates to the use of energy for cooling, as opposed to heating, and is relevant to the issue of energy poverty. Southern European Countries have been experiencing frequent heat wave events in the summer time which seem to be responsible for mortality rate growth among low income households and vulnerable people. It was estimated that 80,000 people died in the 2003 summer in Europe, one fourth in Italy, highlighting that a more comprehensive vision of the issue should drive the design of future measures towards an effective reduction of fuel poverty related issues.
Low absolute energy expenditure (M/2)
This measures the share of households whose absolute energy expenditure is below half the national median, which could indicate suppressed demand, but could also result from high energy efficiency standards. This type of indicator is based on microdata showing the distribution of expenditure by income deciles with an interpretation of the results best assessed in conjunction with consensual indicators. (Thema and Vondung 2020).
2M: Share of energy expenditure
This indicator captures the share of households spending over twice the median expenditure on energy relative to the disposable income and the annual (changing) threshold. This indicator alone can also misrepresent the actual burden experienced in households when, for example, lower income households under consume (underspend), or when energy costs are include, e.g. in rent prices.
Low Income High Cost (LIHC)
Households are considered to be energy poor if they have required fuel costs that are above the median level (high cost); and were they to spend that amount they would be left with a residual income below the official poverty line (low income). Required fuel costs are those calculated as the amount of fuel required to maintain an adequate level of warmth. The energy poverty gap is the amount by which the assessed energy needs of the energy poor households exceed the threshold for reasonable costs (Hills 2012).

Table A-2: Energy poverty indicators and their application to the German context
Source: (Heindl 2014)

Indicator	**Description**	**Share of fuel poor (weighted)**	**Average equivalised income of fuel poor (BHC)**	**Share of fuel poor below poverty line (952€)**	**Average expenditure on energy services of fuel poor (equiv. Income)**
10% NE BHC	expenditure on energy services greater or equal to 10% of income (or any other share)	29.8%	1,054	45.7%	20.3%
2 x median expenditure	expenditure on energy services greater or equal to 2 x median expenditure (or any other factor)	4.1%	2,549	8.1%	21.5%
2x median share of expenditure	share of energy expenditures relative to income greater or equal to 2x median share of expenditures in the sample	12.0%	933	58.2%	28.2%
2x mean expenditure	expenditure on energy services greater or equal to 2x average expenditure (or any other factor)	2.4%	2,648	7.9%	22.1%
2x mean share of expenditure	share of energy expenditures relative to income greater or equal to 2x mean share of expenditures in the sample	5.4%	779	74.8%	36.5%
MIS (SGBII)	Minimum income	9.9%	721	89.2%	25.0%
HCLI EI BHC	High cost, low income equivalised income before housing costs	11.1%	907	52.2%	26.3%
HCLI EI AHC	High cost, low income equivalised income after housing costs	13.7%	998	43.5%	24.5%

A.2 Practical measures to address energy poverty in Germany

A number of measures have been carried out in Germany, but the measures initiated by national government address the issues arising as a result of the energy transition and are not specifically aimed to address the issue of energy poverty. The consumer advice centre of North-Rhine Westphalia published an analysis of the current status of energy poverty activities in the state of North-Rhine Westphalia in Germany (VZ NRW, 2014). In this report, it is reiterated that without the acknowledgement and definition of energy poverty on the national government level, little tangible protection can be provided for vulnerable consumers. The measures are localised, project-based, dependent on funding and limited in implementation. Nonetheless, some of the projects, namely the "Energy savings check" projects, have shown to have remarkable financial benefits (as well as improving standard of living) not only to lower income households, but to the regional and national governments. Measures to reduce the effects of energy poverty either increase income (or the ability to afford energy) or reduce the energy consumption. Further protection mechanisms, such as disconnection prevention, could be classified as increasing income as these are mechanisms that extend the payment date (thereby increasing the virtual income at least in the short-term).

A.2.1 Energy efficiency interventions

These interventions include building retrofits as well as installations of energy saving equipment and appliances. The "Energy savings check" project initiated by Caritas in 2005 has been instituted in 170 locations across German cities, municipalities and regions. This project trained 4,200 long-term unemployed people to become energy consultants who provide other lower income households with free energy consultation with advice about energy saving behaviour and some simple energy efficiency interventions[3], such as energy efficient light bulbs and low-flow showerheads to a value of 70€ per household. In the first project phase, each household saved about 130€ annually in electricity, water and heating costs. Not only households benefited financially from the interventions, but the federal government saved about 1,316,660€ for their share of the water and heating costs, while local government saved 5,789,656€ in total over the lifespan of the products (Caritas 2014b).

By 2015, the Energy Savings Check has reached 164,395 households. Before the consultations and interventions (on average costing about 68€ per household (or 218€ including the refrigerator exchange), the status of the energy and water consumption in each of the households (95% of which lived in apartments) was documented (Caritas 2015). The average consumption values for each household before interventions as well as the average savings her household are shown in Table A-3 (Pye et al. 2015b).

Table A-3: Energy and water consumption before interventions
Source: (Caritas 2014b)

	Unit	Average annual consumption	Average annual savings Incl. fridge	Average annual savings Excl. fridge
Electricity	*kWh/ household * a*	2,915	789	393
Water	*m^3/ household * a*	96	12	12
Warm water	*kWh/ household * a*	2,689	222	222
Annual savings	*€/ household * a*	-	245	149

On average, one household is able to save about 149€ annually in electricity and water costs where this figure increases to about 245€ when a refrigerator exchange is included. Over the lifetime of the installations, total savings of 1,070€ per household can be achieved, while for all households this figure is around 136 million Euros. National governments are able to save about 18 million Euros and regional governments save about 22 million Euros. Per "Energy Savings Check", the regional government saved about 135€ and the federal government saves 113€. Overall the public sector saves 248€ per household. These are substantial savings given that a qualifying household at the time only received 28.12€ per month to cover electricity needs, which is an amount that has not been increased due to inflation and is therefore almost 14€ too little to cover the electricity needs of a household. Allocations have since been increased to cover the costs of inflation. Similar initiatives were undertaken in other parts of Germany using a similar model, such as the "Energy savings initiative Bonn" and implementation of energy efficient measures in social beneficiary households in Freiburg and Berlin showing similarly impressive results as well as through the sister project,

[3] Energy savings installations: energy efficient bulbs, multiple socket outlets with switch, standby switches, time switches, water-saving showerheads and low-flow water regulators, fridge thermometers, thermohygrometer, thermostop; Appliance exchanges: refrigerator; Information and awareness: Tips for using energy wisely (washing/drying, cooking/baking, refrigerating/freezing, lighting, standby, heating and ventilation, warm water and washing) and energy audit

ACHIEVE, which attained similar results in other European countries attesting to the effectiveness of the project (SWB 2010; BMUB 2008; ACHIEVE 2014).

A.2.2 Financial support

Financial interventions are made first and foremost in the form of social transfers to cover the costs of energy bills to households qualifying to draw on social benefits (SA 2014; BJZ 2021). A lump sum is provided in the form of a basic income grant where a portion is allocated for energy bills (usually around 8% of total monthly allocation depending on the family constellation) (Bundesministerium für Arbeit und Soziales 2022).

The Federal Ministry for Economic Affairs and Energy provides subsidies and low or no interest loans for energy efficient renovations and upgrades in residences through its service provider, KfW and updated through legislative revision (KfW 2014; BWA 2021). Some utilities have made a provision for a social tariff in their portfolio in order to assist lower income households with their energy bills. These tariffs are open to households whose income falls below the national poverty line. Households pay on average 30% less for energy and save on average 80€ per month (Care 2014).

A.2.3 Information and awareness

Although the “Energy savings check” project also qualifies as information and awareness, the majority of savings could be associated with the technical interventions. These measures also encompassed debt counselling, tariff switching as well as energy audits giving the opportunity for households to make behavioural or technical changes to save energy and, therefore, money (Caritas 2014a; Hinterleuthner et al. 2012; Fahl and Oertel 2014; VZ 2015).

A.2.4 Consumer protection

Regarding consumer protection, the major mechanism is protection from disconnection. A pilot project in Cologne saw the installation of 660 smart meters into social housing. Households unable to pay would then have their demand reduced to 1000W instead of being completely disconnected from electricity thereby allowing households to continue to use electricity, particularly for basic needs such as cooking, lighting and heating (BEV 2013). Energy disconnections are tightly controlled through regulations (BNetzA 2015). Electricity and gas customers are provided for through the basic legislation for electricity (StromGVV) and gas (GasGVV), which, in each instance, ensures that the connection, delivery and payment terms are specifically regulated (VZ RLP 2012). There is a precise process that must be followed in order for the electricity or gas utility to disconnect a customer, for example, for non-payment. Since there is a contract between the energy supplier and the customer, this process includes the customer accumulating arrears to the total of 100-150 Euros and the supplier giving adequate notice of the defaulted payment and of the impending disconnection and 4 weeks for the customer to react. Reconnection incurs at least an additional 100€.

Additional protection is in place for particular circumstances. The disconnection is considered to be unreasonable if the disconnection causes hazards disproportionate to the debts incurred, these would include households with small children, the elderly, chronically ill, or even those dependent on the connection in order to carry out a livelihood. An appeal must, however, be made in a timely manner outlining these details. The disconnection can also be avoided if the customer engages the energy utility and works out a payment plan within the financial means of the customer, yet includes the prospect that all debts are recovered before the next financial year (VZ RLP 2012; Hinterleuthner et al. 2012).

Table A-4: Government departments and areas of jurisdiction related to energy poverty

Government Department	Responsibilities related to energy poverty
Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railway (*Bundesnetzagentur*)	The national regulatory authority authorised through the national Energy Act and tasked to ensure fair and effective competition in the supply of electricity and gas. They are also tasked with monitoring the Energy Transition process. As such, they are responsible for ensuring consumer rights in the electricity and gas markets.
Ministry of Economic Affairs and Energy (*Bundesministerium für Wirtschaft und Energie – BMWi)*	Energy policy, energy transition and monitoring, electricity and gas regulator – responsible for consumer market participation, ensuring consumer protection. is tasked with promoting investments, invigorating innovation in the industrial sector, ensuring a dependable infrastructure, fostering cooperation, strengthening skilled labour and promoting energy reforms, which includes ensuring affordable energy prices. They are the section of government accountable for addressing concerns about energy poverty. Furthermore, they support the Consumer Advice Centres financially in their Energy-Savings-Check programme.
Ministry of Education & Research (*Bundesministerium für Bildung und Forschung – BMBF*)	Energy poverty, social distributional effects of energy transition resulting from increased energy prices. supports broader research, for example, on developing cities which take into account aspects including energy poverty, including the SOKO project
Ministry of Environment, Nature Conservation, Buildings and Nuclear Safety (*Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit)*	Environment, CO_2 targets, building energy efficiency. Financing of energy poverty projects, such as the “Energy savings check” carried out by Caritas through their National Climate Initiative.
Ministry of Health	Health care system; health insurance through social welfare system
Ministry of Justice and Consumer Protection	Consumer protection, incl. electricity and gas markets -> fair prices, dispute settlements, disconnection protection
Ministry of Labour and social affairs	Dispensing social transfers, unemployment benefits

B. Distribution and validation of population and households

The objective is to disaggregate and validate the population and household distribution into the profiles used in this thesis as described in Chapter 3. Key parameters were used to define the framework, then using other related statistics, a holistic picture was formed about the distribution of households by location, tenure and building type, and income group.

B.1 Households and population

The base year values for 2013 for households and population need to be established. Statistics relating to the household sector refer to numbers of households and/or population. To differentiate between statistics correlating to number of households and those to population, it is necessary to establish the relationship between the two in relation to the various other parameters introduced (e.g. location, building type) through the household size. Values differ by dataset depending on the definitions and methods used to calculate the data. The EVS 2013 was used as the main reference due to the additional data available in this dataset, which is used to support the analysis undertaken in this thesis. All other data sources are adjusted to these values. In 2013, there were 39,326 thousand households and 78,851 people with an average household size of 2 people per household (Destatis 2013b).

B.2 Location

The urbanisation rate was taken from (EUROSTAT 2020), which uses the same definitions applied to German national statistics, where the population is classified as urban, semi-urban and rural and finally condensed to urban and rural categories (Destatis 2011). The urban population encompasses 76.9% of the population (60,636) with the remaining 23.1% (18,215) of the population living in rural areas. To translate the population into the number of households, the average household sizes of 1.9 and 2.3 for urban and rural, respectively, was applied resulting in 80.2% of households in urban areas and 19.8% in rural areas. The final distribution for population and households by location is given in Table B-1.

Table B-1: Final population and households by location, 2013
Source: (EUROSTAT 2020; Destatis 2011)

	Population		**Households**		**Average Household size**
2013	*%*	*m*	*%*	*m*	*pp/HH*
Urban	76.9%	60.64	80.2%	31.55	1.9
Rural	23.1%	18.22	19.8%	7.77	2.3
Total	100%	78.85	100%	39.33	2.0

B.3 Tenure and building type

The distribution of households and population by tenure and building type was established through statistics. The distribution begins with the overall splits of households and population, population by building type and location, and tenure by building type as given in Tables Table B-2 - Table B-4 (Destatis 2013d).

Table B-2: Ownership by households and population, 2013
Source: (Destatis 2013d)

	Households	Population
Owner	44.5%	54.3%
Tenant	55.5%	45.7%
Total	100%	100%

Table B-3: Population by building type and location, 2013
Source: (Destatis 2013d)

	SFH	MFH	Total
Urban	15%	61%	75.9%
Rural	13%	12%	24.1%
Total	27.9%	72.1%	100.0%

Table B-4: Tenure by building type
Source: (Destatis 2013d)

	Owner	Tenant
MFH	17%	52%
SFH	27%	4%
Total	45%	56%

B.4 Final distribution by building type, ownership, location and income group

The final distribution by building type and location was validated by using ownership by building type on the state level with the shares of urbanisation by building type applied as shown in Table B-5. By including the distribution of the average disposable income per capita in these urban and rural areas, building type and ownership, the distribution of income groups was determined and summarised into the final distribution of households given as shares in Table B-6 and in absolute numbers in Table B-7, and the distribution of population as shares in Table B-8 and in absolute numbers in Table B-9.

Table B-5: Households by tenure, building type and state, 2013
Source: (Destatis 2017a)

State	SFH	MFH	owner	tenant	SFH owner	MFH owner	SFH tenant	MFH tenant	total HHs	HH size
Baden-Württemberg	29.9%	70.1%	52.4%	47.6%	12.7%	39.7%	17.2%	30.4%	5,309	1.97
Bayern	34.7%	65.3%	48.8%	51.2%	14.1%	34.7%	20.6%	30.6%	6,339	1.94
Berlin	12.9%	87.1%	18.7%	81.3%	4.4%	14.3%	8.5%	72.9%	1,581	2.14
Brandenburg	40.8%	59.2%	39.9%	60.1%	22.4%	17.5%	18.4%	41.7%	1,080	2.21
Bremen	31.7%	68.3%	38.6%	61.4%	12.7%	25.9%	19.0%	42.4%	340	1.89
Hamburg	22.8%	77.2%	25.1%	74.9%	7.6%	17.6%	15.3%	59.6%	846	2.03
Hessen	31.5%	68.5%	46.9%	53.1%	13.5%	33.4%	18.0%	35.1%	2,952	2.01
Mecklenburg-Vorpommern	34.2%	65.8%	35.4%	64.6%	17.8%	17.6%	16.3%	48.3%	731	2.12
Niedersachsen	45.0%	55.0%	46.5%	53.5%	19.5%	27.0%	25.5%	28.0%	3,904	1.95
Nordrhein-Westfalen	30.6%	69.4%	43.4%	56.6%	13.2%	30.2%	17.5%	39.2%	8,509	2.01
Rheinland-Pfalz	42.6%	57.4%	50.8%	49.2%	20.5%	30.3%	22.0%	27.2%	1,941	2.00
Saarland	37.9%	62.1%	58.6%	41.4%	20.8%	37.7%	17.0%	24.4%	496	1.93
Sachsen	20.7%	79.3%	37.9%	62.1%	12.8%	25.1%	7.9%	54.2%	1,835	2.14
Sachsen-Anhalt	33.6%	66.4%	39.9%	60.1%	18.4%	21.6%	15.2%	44.9%	1,047	2.06
Schleswig-Holstein	49.5%	50.5%	40.6%	59.4%	20.6%	20.0%	29.0%	30.5%	1,442	1.90
Thüringen	29.0%	71.0%	44.2%	55.8%	17.3%	26.9%	11.7%	44.0%	974	2.14
Deutschland	33.1%	66.9%	44.5%	55.5%	14.7%	29.8%	18.4%	37.1%	39,326	2.01

Table B-6: Characterisation and distribution of households in Germany as share of total, 2013
Source: own calculations based on (Destatis 2011, 2013b, 2017a, 2013c; EUROSTAT 2020)

Monthly income per household (€)			<900	900-1500	1500-2000	2000-2600	2600-3600	3600-5000	5000-18000	Total	Urban / Rural
Urban	**SFH**	**Owner**	0.3%	1.1%	1.6%	3.5%	5.8%	6.4%	8.1%	26.9%	**76.7%**
		Tenant	0.3%	0.7%	0.7%	0.6%	0.7%	0.7%	0.7%	4.4%	
	MFH	**Owner**	0.4%	1.4%	1.7%	2.5%	3.6%	3.6%	4.0%	17.3%	
		Tenant	6.6%	12.5%	9.4%	7.6%	7.4%	4.6%	3.3%	51.5%	
Rural	**SFH**	**Owner**	0.3%	1.1%	1.6%	3.5%	5.8%	6.7%	8.4%	27.3%	**23.3%**
		Tenant	0.2%	0.7%	0.7%	0.6%	0.7%	0.7%	0.7%	4.4%	
	MFH	**Owner**	0.3%	1.4%	1.7%	2.5%	3.7%	3.8%	4.1%	17.5%	
		Tenant	6.3%	12.1%	9.2%	7.6%	7.5%	4.8%	3.4%	50.9%	
Total			7.5%	15.7%	13.4%	14.2%	17.6%	15.5%	16.2%	100%	
SFH			1.8%	5.9%	7.3%	13.0%	20.8%	22.9%	28.4%	100%	
MFH			10.0 %	20.2%	16.2%	14.7%	16.2%	12.1%	10.6%	100%	
Owner			1.5%	5.8%	7.5%	13.5%	21.3%	23.0%	27.5%	100%	
Tenant			12.2 %	23.6%	18.1%	14.7%	14.7%	9.5%	7.2%	100%	

Table B-7: Characterisation and distribution of households in Germany (million), 2013

Source: own calculations based on (Destatis 2011, 2013b, 2017a, 2013c; EUROSTAT 2020)

Monthly income per household (€)			<900	900-1500	1500-2000	2000-2600	2600-3600	3600-5000	5000-18000	Total	Urban / Rural
Urban	SFH	Owner	0.10	0.36	0.51	1.09	1.82	2.03	2.57	8.47	**31.55**
		Tenant	0.08	0.23	0.21	0.19	0.23	0.21	0.22	1.37	
	MFH	Owner	0.11	0.45	0.55	0.79	1.15	1.15	1.25	5.45	
		Tenant	2.09	3.95	2.98	2.40	2.35	1.45	1.04	16.26	
Rural	SFH	Owner	0.02	0.09	0.12	0.27	0.45	0.52	0.65	2.12	**7.77**
		Tenant	0.02	0.05	0.05	0.05	0.06	0.05	0.06	0.34	
	MFH	Owner	0.03	0.11	0.13	0.19	0.29	0.29	0.32	1.36	
		Tenant	0.49	0.94	0.72	0.59	0.59	0.37	0.26	3.96	
Total			2.94	6.17	5.27	5.58	6.93	6.08	6.37	39.33	
SFH			0.22	0.73	0.89	1.60	2.56	2.81	3.49	12.31	
MFH			2.71	5.45	4.38	3.97	4.37	3.27	2.87	27.02	
Owner			0.26	1.00	1.31	2.34	3.71	4.00	4.78	17.40	
Tenant			2.68	5.17	3.96	3.23	3.22	2.09	1.58	21.93	

Table B-8 Characterisation and distribution of population in Germany as share of total, 2013

Source: own calculations based on (Destatis 2011, 2013b, 2017a, 2013c; EUROSTAT 2020)

Monthly income per household (€)			<900	900-1500	1500-2000	2000-2600	2600-3600	3600-5000	5000-18000	Total	Urban / Rural
Urban	SFH	Owner	0.3%	1.1%	1.6%	3.5%	5.8%	6.4%	8.1%	26.9%	**80.2%**
		Tenant	0.3%	0.7%	0.7%	0.6%	0.7%	0.7%	0.7%	4.4%	
	MFH	Owner	0.4%	1.4%	1.7%	2.5%	3.6%	3.6%	4.0%	17.3%	
		Tenant	6.6%	12.5%	9.4%	7.6%	7.4%	4.6%	3.3%	51.5%	
Rural	SFH	Owner	0.3%	1.1%	1.6%	3.5%	5.8%	6.7%	8.4%	27.3%	**19.8%**
		Tenant	0.2%	0.7%	0.7%	0.6%	0.7%	0.7%	0.7%	4.4%	
	MFH	Owner	0.3%	1.4%	1.7%	2.5%	3.7%	3.8%	4.1%	17.5%	
		Tenant	6.3%	12.1%	9.2%	7.6%	7.5%	4.8%	3.4%	50.9%	
Total			7.5%	15.7%	13.4%	14.2%	17.6%	15.5%	16.2%	100%	
SFH			1.8%	5.9%	7.3%	13.0%	20.8%	22.9%	28.4%	100%	
MFH			10.0%	20.2%	16.2%	14.7%	16.2%	12.1%	10.6%	100%	
Owner			1.5%	5.8%	7.5%	13.5%	21.3%	23.0%	27.5%	100%	
Tenant			12.2%	23.6%	18.1%	14.7%	14.7%	9.5%	7.2%	100%	

Table B-9: Characterisation and distribution of population in Germany (million), 2013

Source: own calculations based on (Destatis 2011, 2013b, 2017a, 2013c; EUROSTAT 2020)

Monthly income per household (€)			<900	900-1500	1500-2000	2000-2600	2600-3600	3600-5000	5000-18000	Total	Urban / Rural
Urban	**SFH**	**Owner**	0.14	0.70	1.00	1.94	3.25	4.80	4.22	16.05	**60.51**
		Tenant	0.05	0.14	0.17	0.27	0.43	0.51	0.48	2.05	
	MFH	**Owner**	0.23	0.97	1.23	1.86	2.90	3.27	2.90	13.36	
		Tenant	2.00	4.59	4.04	4.08	5.76	4.14	4.46	29.06	
Rural	**SFH**	**Owner**	0.03	0.16	0.23	0.45	0.77	1.16	2.46	5.25	**18.34**
		Tenant	0.01	0.03	0.04	0.06	0.10	0.12	0.28	0.65	
	MFH	**Owner**	0.05	0.22	0.28	0.43	0.68	0.79	1.69	4.15	
		Tenant	0.44	1.03	0.92	0.95	1.36	1.00	2.60	8.30	
Total			2.94	7.83	7.91	10.04	15.24	15.81	19.10	78.85	
SFH			0.22	1.03	1.44	2.72	4.54	6.60	7.45	23.99	
MFH			2.71	6.80	6.47	7.32	10.69	9.21	11.65	54.86	
Owner			0.44	2.04	2.74	4.68	7.60	10.03	11.28	38.81	
Tenant			2.49	5.79	5.17	5.36	7.64	5.78	7.81	40.04	

C. Development of the disaggregated energy balance

An energy balance for the defined profiles is lacking and needs to be developed. While there is some disaggregation in existing modelling studies to represent building types and location of households, these are limited to 6 profiles including urban single-family homes (existing and one new alternative), multi-family homes (existing and one new alternative) and one rural building type represented by a single-family home (existing and one new alternative), resulting in 6 profiles (Haasz 2017; Fais 2015). The energy balance needs to be further disaggregated to account for income groups, tenure status and the representation of multi-family homes in rural areas.

C.1 Energy consumption by fuel type and end-use

The disaggregated energy balances was compiled with energy carriers consumed by end-use described on an aggregate level for all households on an annual basis (BMWi 2021) and also by building types (single-family/two-family buildings and multifamily buildings) (Frondel et al. 2015a). The main input data for the overall distribution of the final energy consumption by energy carrier and end-use was based on (BMWi 2021). The categories for the energy carriers and end-uses are given in Table C-1.

Table C-1: Categories and abbreviations of energy carriers and end-uses

End-uses		**Energy carriers**	
Abbreviation	**Description**	**Abbreviation**	**Description**
CDR	clothes drying	**AHT**	ambient heat
COK	cooking	**BIO**	biomass
COL	cooling	**COA**	coal
CWA	clothes washing	**ELC**	electricity
DWA	dishwashing	**GAS**	natural gas
FREEZ	freezer	**GEO**	geothermal energy
H	heating	**LPG**	Liquid Petroleum Gas
LIG	lighting	**LTH**	district heating
OEL	other electric appliances	**OIL**	oil
REFRI	refrigeration	**SOL**	solar thermal
REFRZ	refrigeration/freezer		
WH	water heating		

The household sector consumed 2,552.3 PJ in 2013 and the initial distribution for the main energy carriers and end-uses is aligned with the overall energy balance for the household sector as given in Table C-2 (BMWi 2021). The energy carriers could be aligned with only the exclusion of "other mineral oil products", which is small and likely used for household appliances such as lawnmowers, etc. It is neglected in further analysis and therefore will not be integrated in the energy system model. Additionally, the further disaggregation of the broad category "renewable energy" needed to be disaggregated into ambient heat (AHT), biomass (BIO), geothermal (GEO) and solar thermal (SOL). The disaggregation of this data is based on the AGEB satellite energy balance for renewable energy in 2013 (see Table C-3) (AGEB 2015).

Table C-2: Final energy consumption of household sector by energy type and end-use, 2013 (PJ)
Source: (BMWi 2021)

Energy carriers	Total energy (PJ)	End-uses	Total energy (PJ)
Bituminous coal	8.3	space heating	1813.3
Lignite coal	20.2	- thereof oil	492.6
Renewables	305.1	- thereof gas	788.1
Heating oil	553.3	- thereof LPG*	22.4
other mineral oil products**	3.7	- thereof electricity	33.7
Liquid petroleum gas*	25.3	- thereof district heating	170.6
Gas	991.3	- thereof coal	28.5
-thereof natural gas	966.0	- thereof renewables	277.3
Electricity	489.6	water heating	345.0
District heating	184.5	- thereof oil	60.7
Total	2556.0	- thereof gas	173.7
		- thereof LPG*	2.8
		- thereof electricity	66.2
		- thereof district heating	13.9
		- thereof coal	0.0
		- thereof renewables	27.7
		other process heat	142.8
		- thereof gas	4.2
		- thereof LPG*	0.1
		- thereof electricity	138.4
		air conditioning	4.3
		other process cooling (electricity)	107.5
		mechanical energy	17.1
		- thereof other oil products**	3.7
		- thereof electricity	17.1
		ICT (electricity)	82.0
		Lighting (electricity)	40.3
		Total (PJ)	2552.3

**additional assumptions, including reallocating LPG from gas to an oil product to harmonise the data from both tables*
*** not included, likely used for lawnmowers, etc.*

Table C-3: Renewable energy consumption of household sector by energy carrier, 2013

Source: (AGEB 2015)

Renewable energy	PJ/a
Hydro and wind power and PV	
Hydropower	-
Wind power	-
Photovoltaic	-
Biomass and renewable landfill gas	
solid biomass	251.0
liquid biofuels	0.7
Biogas	-
bio landfill gas	-
Other renewable	
Geothermal	0.9
Solar thermal	22.8
Ambient heat	29.7
Total	**305.1**

The total renewable energy in the household sector in 2013 totalled 305.1 PJ. The distribution of this total is allocated to the end-uses according to the shares given in Table C-2 as follows: space heating (277.3 PJ) and water heating (27.7 PJ) (BMWi 2021). These shares are further distributed according to the type of renewable energy. Geothermal and ambient heat are used exclusively in heat pumps with shares of 95% and 5% for space heating and water heating, respectively, and, in contrast, solar thermal energy is mainly used for water heating (95%) (Frondel et al. 2015a). The final distribution across the end-uses for space heating and water heating by renewable energy carriers is presented in Table C-4.

Table C-4: Distribution of renewable energy in the household sector by type of renewable energy carrier, 2013

Source: own calculations based on (AGEB 2015; Frondel et al. 2015b)

Energy carrier	**Space heating Shares (%)**	**Water heating Shares (%)**	**Space heating PJ/a**	**Water heating PJ/a**	**Total PJ/a**
BIO	80.4%	2.1%	245.4	6.3	251.7
GEO	0.3%	0.0%	0.9	0.0	0.9
SOL	0.7%	6.7%	2.2	20.6	22.8
AHT	9.5%	0.3%	28.9	0.8	29.7
Total	90.9%	9.1%	277.3	27.7	305.1

In terms of the end-uses, some overarching categories needed to be discerned to common household end-uses: other process heat, other process cooling (electricity) and mechanical energy. The category "other process heat" is distributed using assumptions from TIMES-D (Haasz 2017) for the shares allocated to clothes drying (CDR), cooking (COK), clothes washing (CWA) and dishwashing (DWA) and allocated to the total energy (142.8 PJ) and energy carriers (electricity (ELC) (138.4 PJ), gas (4.2 PJ) and liquid petroleum gas (LPG) (0.1 PJ)) allocated in 2013 according to the statistical fuel split by end-use designated in Table C-2, as shown in Table C-5 (BMWi 2021).

Table C-5: Distribution of "other process heat" by end-use and energy carrier
Source: own calculations based on (Haasz 2017)

	TIMES-D (2010)		ELC	Gas	LPG	Total
End-uses	**Shares (%)**	**PJ/a**	**PJ/a**	**PJ/a**	**PJ/a**	**PJ/a**
CDR	5.2%	7.5	7.5	0.0	0.0	7.5
COK	49.3%	70.4	66.1	4.2	0.1	70.4
CWA	26.7%	38.1	38.1	0.0	0.0	38.1
DWA	18.7%	26.8	26.8	0.0	0.0	26.8
Total	100.0%	0.0	138.4	4.2	0.1	142.8

The category “other process cooling” (107.5 PJ) from Table C-2 is distributed in a bottom-up calculation by first using the shares of appliance ownership for freezers (61.9% of households) and refrigerators/refrigerator-freezer combinations (Destatis 2014a) to find the average calculated total consumption for freezers (FREEZ) (21.9 PJ). Without data describing the total appliance ownership by size and energy consumption class, an average annual consumption of 250kWh/a per appliance is allocated for the bottom-up calculation of the freezer consumption, where the total ranges from 76 kWh/a for a 60 litre and A+++ class freezer and 435 kWh/ for a 150 litre D class freezer (UBA 2011). The remaining expected total consumption (85.6 PJ) is applied evenly between refrigerators (REFRI) and refrigerator-freezer combinations (REFRZ) as shown in Table C-6.

Table C-6: Distribution of "other process cooling" by end-use
Source: own calculations based on (UBA 2011; Destatis 2014a, 2014b)

Total households, 2014	m	*39.3*
Share of households with freezers	%	*61.9%*
Average annual electricity consumption	kWh/a	*250*
Total FREEZ annual energy	PJ/a	*21.9*
Total REFRI annual energy	PJ/a	*42.8*
Total REFRZ annual energy	PJ/a	*42.8*
Total	PJ/a	*107.5*

The category “mechanical energy” (17.1 PJ) from Table C-2 is largely used for the operation of motors in household appliances, such as clothes dryers (CDR), washing machines (CWA) and dishwashers (DWA) (Frondel et al. 2015a). The distribution of the 17.1 PJ of electrical mechanical energy (Table C-2) is distributed using assumptions in TIMES-D (Haasz 2017), which allocates 61.2% towards clothes drying (CDR) resulting in an assumed 10.6 PJ, and the remaining amount is shared evenly across washing machines (CWA) and dishwashers (DWA) as shown in Table C-7.

Table C-7: Distribution of mechanical energy by end-use
Source: own calculations based on (Haasz 2017; Frondel et al. 2015a)

End-use	Share	PJ/a
CDR	61.8%	10.6
CWA	19.1%	3.3
DWA	19.1%	3.3
Total	100.0%	17.1

In summary, the end-uses were distributed into the energy consumption categories defined in Table C-1 as shown in Table C-8.

Table C-8: Final energy consumption by end-use and energy carrier for households in Germany, 2013 (PJ)
Source: own calculations described in previous steps

	AHT	BIO	COA	ELC	GAS	GEO	LPG	LTH	OIL	SOL	Total
CDR				18.0							18.0
COK				66.1	4.2		0.1				70.4
COL				4.3							4.3
CWA				41.4							41.4
DWA				30.0							30.0
FREEZ				21.9							21.9
H	28.9	245.4	28.5	33.7	788.1	0.9	22.4	170.6	492.6	2.2	1,813.3
LIG				40.3							40.3
OEL				82.0							82.0
REFRI				42.8							42.8
REFRZ				42.8							42.8
WH	0.8	6.3		66.2	173.7	0.0	2.8	13.9	60.7	20.6	345.0
Total	29.7	251.7	28.5	489.6	966.0	0.9	25.3	184.5	553.3	22.8	2,552.3

C.2 Energy consumption by building type

The buildings are distributed according to socio-economic characteristics (location, income group, and building type (number of units per building, i.e. single-family home, multi-family home) as described in Chapter 3.2. Given this distribution of households by income groups and the availability of other building-related data parameters, this analysis was constrained to two types of buildings: single-family homes (SFH), representing in 2013 (the base year for the analysis) 31.3% of all households, and multi-family homes (MFH) accounting for the remaining 68.7%. This constraint is in line with the establishment of reference buildings for energy performance standards in Europe and Germany (Diefenbach and Clausnitzer 2010; European Parliament 2012).

The profiles are further distinguished with statistical data as owners (44.2%) or tenants (55.8%) resulting in an overall distribution of 26.9% of households as owners in SFH, 4.4% as tenants in SFH, 17.3% as owners in MFH and the majority of 51.4% as tenants in MFH (Destatis 2011, 2013c). The final statistically based distribution of households, population and building type in 2013 are summarised for the parameters by building type in Table C-9.

Table C-9: Households, population and living space by building type, 2013
Source: (Cischinsky and Diefenbach 2018; dena 2016; Destatis 2013a)

	Unit	SFH	MFH	Total
Number of households	*m*	12.3	27.0	39.3
Share of households	%	31.3%	68.7%	100%
Population	*m*	24.0	54.9	78.9
Share of population	%	30.4%	69.6%	100%
Living area	*m* m_2	1.68	2.319	3.99
Share of living area	%	42.1%	57.9%	100%

The energy characteristics of each existing building type for the respective profiles is aggregated based on the distribution of the age of the building, floor area, and the heating system structure within each profile. The statistical distribution of the building age by income group is shown in Figure C-1 (Cischinsky and Diefenbach 2018; dena 2016; Destatis 2013a). The oldest building age category is spread fairly evenly across the income groups, but distinctly as income increases the trend towards newer, more energy efficient buildings increases.

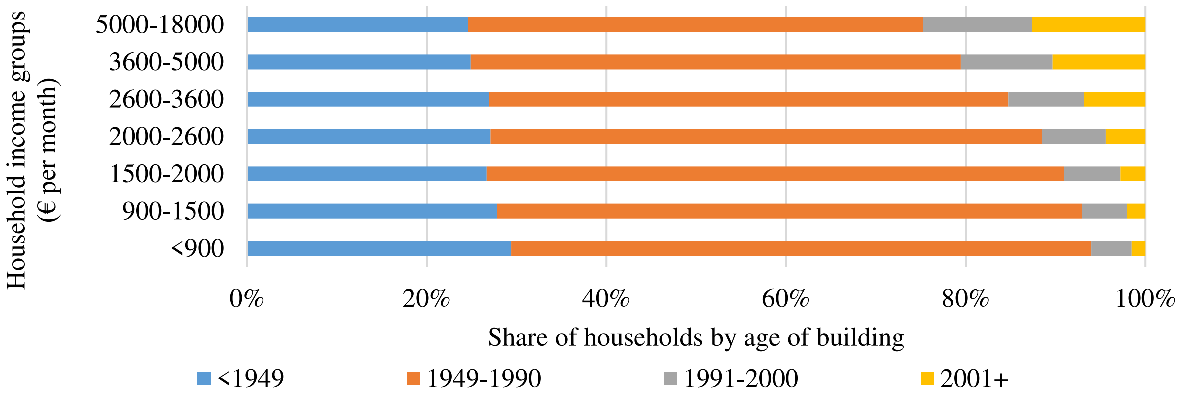

Figure C-1: Distribution of building age by income group

Source: (Cischinsky and Diefenbach 2018; dena 2016; Destatis 2013a)

The floor area per building type is distinguished by the age of the building and the income group. The average statistical floor area across all building ages per income group is shown in Figure C-2 (Cischinsky and Diefenbach 2018; dena 2016; Destatis 2013a). As income increases and the newer the building, the greater the living space.

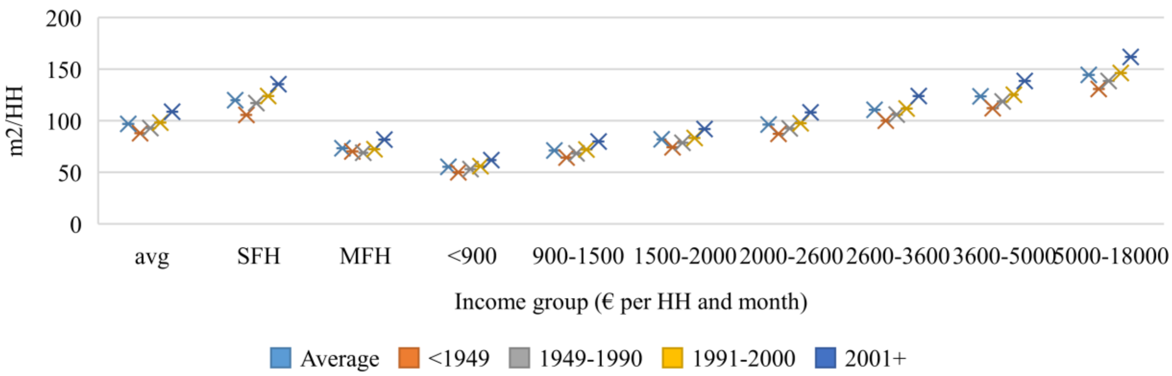

Figure C-2: Average floor area per dwelling by building age and income group

Source: (Cischinsky and Diefenbach 2018; dena 2016; Destatis 2013a)

The energy consumption by energy carrier and end-use is further disaggregated to these building types and validated through indicators from literature. A detailed disaggregation of the energy balance is provided by building type (single-family homes (SFH), two-family homes (TFH) and multi-family homes (MFH)) for the years 2012 and 2014, and on a regular basis by the Rhineland Westphalia Institute (RWI) (Frondel and Ritter 2013a; Frondel et al. 2016a). This data for the RWI study is based on panel data collected through surveys and scaled up to match other national energy balances, such as those generated by AGEB and BMWi, noting explicitly that differences are due to systematic differences in the estimation of use of some energy carriers, e.g. gas, district heating, coal and oil (Frondel et al. 2015b; AGEB 2018). For this thesis, the TFH and MFH building types were merged and then the total energy and the total energy by end-use per building type (SFH and MFH) was harmonised to the BMWi data set according to the categories applied by RWI, the energy balance for 2013 was generated based on averages from 2012 and 2014 and aligned to overall energy consumption and end-uses given in BMWi for 2013 (BMWi 2021; Frondel et al. 2016b; Frondel et al. 2015b). These are then balanced against the end-use and energy carrier categories defined for this study according to the distribution described in Table C-1.

The consumption by building type will also be determined by specific technologies, such as heat pumps and PV. Heat pumps are used exclusively in SFH (Frondel et al. 2015b). The distribution of the potential and existing installations of PV, solar thermal and heat pump technologies is outlined in Chapter 5.1.2.2. This results in the distribution of energy consumed by end-use and energy carrier for the two building types, SFH and MFH, as shown in Table C-10.

Table C-10: Final energy consumption of households by end-use, energy carrier and building type, 2013 (PJ)
Source: own calculations described in previous steps

	CDR	COK	COL	CWA	DWA	FREEZ	H	LIG	OEL	REFRI	REFRZ	WH	Total
Single-family homes (SFH)													
AHT	-	-	-	-	-	-	28.9	-	-	-	-	0.8	29.7
BIO	-	-	-	-	-	-	75.9	-	-	-	-	4.8	80.8
COA	-	-	-	-	-	-	9.3	-	-	-	-	-	9.3
ELC	3.3	22.6	1.3	14.1	9.9	8.2	15.3	11.9	27.3	14.9	14.5	19.7	163.1
GAS	-	0.9	-	-	-	-	259.2	-	-	-	-	61.8	321.9
GEO	-	-	-	-	-	-	0.9	-	-	-	-	0.0	0.9
LPG	-	0.0	-	-	-	-	7.4	-	-	-	-	1.0	8.4
LTH	-	-	-	-	-	-	57.4	-	-	-	-	4.2	61.6
OIL	-	-	-	-	-	-	163.9	-	-	-	-	20.5	184.4
SOL	-	-	-	-	-	-	1.0	-	-	-	-	8.1	9.1
Total, SFH	3.3	23.5	1.3	14.1	9.9	8.2	619.2	11.9	27.3	14.9	14.5	120.9	869.0
Multi-family homes (MFH)													
AHT	-	-	-	-	-	-	-	-	-	-	-	-	0.0
BIO	-	-	-	-	-	-	169.4	-	-	-	-	1.5	171.0
COA	-	-	-	-	-	-	19.2	-	-	-	-	0.0	19.2
ELC	6.4	43.5	3.0	27.6	19.5	17.0	18.4	28.4	54.7	31.2	30.4	46.5	326.5
GAS	-	3.3	-	-	-	-	528.9	-	-	-	-	111.9	644.1
GEO	-	-	-	-	-	-	0.0	-	-	-	-	0.0	0.0
LPG	-	0.1	-	-	-	-	15.0	-	-	-	-	1.8	16.9
LTH	-	-	-	-	-	-	113.2	-	-	-	-	9.7	122.9
OIL	-	-	-	-	-	-	328.7	-	-	-	-	40.2	369.0
SOL	-	-	-	-	-	-	1.3	-	-	-	-	12.4	13.7
Total, MFH	6.4	46.9	3.0	27.6	19.5	17.0	1194.1	28.4	54.7	31.2	30.4	224.1	1683.2
Total	9.8	70.4	4.3	41.7	29.4	25.2	1813.3	40.3	82.0	46.1	44.9	345.0	2552.3

The total energy carriers and end-uses align to those given in Table C-8 and validated against indicators for consumption by building type in Table C-11 derived from literature (Frondel et al. 2015b; Döring et al. 2020). Due to the aggregation of the building typologies and the similarities in the heating structure of SFH and TFH, and the need to further disaggregate biomass to tenure, location and income groups, the statistics for biomass are supplemented with assumptions from (Döring et al. 2020). Discrepancies in the validation indicators can be attributed to the differences in the average household sizes for SFH and MFH between the RWI study (2.7 and 1.9 ppl/HH) and the Destatis statistics (2.3 and 1.8 ppl/HH) used in this thesis. As a result, the MWh/capita comparisons vary between the studies, but the extensive distribution of the population and households by building type and income group conducted in this thesis are based on statistical values combining income, population and households.

Table C-11: Validation of final energy consumption distribution by building type, 2013
Source: own calculations described in previous steps based on (Frondel and Ritter 2013b; Frondel et al. 2016b; BMWi 2021)

		Statistical values			This study		
		SFH	**MFH**	**Average/ Total**	**SFH**	**MF H**	**Average/ Total**
Total energy	*MWh/cap*	12.2	7.6	9.0	12.3	7.5	9.0
	PJ/a	1,054	1,498	2,552	1,06 5	1,487	2,552
Electricity	*MWh/cap*	2.0	1.6	1.7	1.9	1.6	1.7
	PJ/a	169	320	490	167	322	490
Gas & LPG	*MWh/cap*	4.5	3.1	3.5	4.5	3.1	3.5
	PJ/a	387	605	991	386	605	991
Oil	*MWh/cap*	2.4	1.8	1.9	2.4	1.8	1.9
	PJ/a	205	348	553	204	349	553
Biomass	*MWh/cap*	2.5	0.2	0.9	2.5	0.2	0.9
	PJ/a	218	33	252	216	36	252
Clothes washing/ drying	*MWh/cap*	0.2	0.2	0.2	0.2	0.2	0.2
	PJ/a	18	33	51	18	33	51
Freezer/ Refrigerator/ Cooking/ Dishwashing	*MWh/cap*	0.9	0.7	0.8	0.9	0.7	0.8
	PJ/a	74	142	216	75	141	216
Heating	*MWh/cap*	9.1	5.2	6.4	9.2	5.2	6.4
	PJ/a	784	1,030	1,813	793	1,020	1,813
Water heating	*MWh/cap*	1.6	1.0	1.2	1.6	1.0	1.2
	PJ/a	141	204	345	139	206	345

C.3 Energy consumption by tenure

Tenure in the home is a significant determinant of energy consumption and the next step in the disaggregation in this study. To distribute the energy by tenure, each building type is divided according to the statistically distributed shares of households within each of these profiles. The distribution of the appliance and fuel shares for space and water heating are distributed by building type and tenure according to the shares of households using particular fuels as given in Table C-12 and Table C-13 (Destatis 2014a, 2014b, 2013d). Assumptions for biomass consumption by tenure are taken from (Döring et al. 2020).

Table C-12: Distribution of appliance shares for space heating by building type and tenure
Source: (Destatis 2014a, 2014b, 2013d) (Döring et al. 2020).

	SFH				**MFH**			
	Share of all households		**Share of fuel type**		**Share of all households**		**Share of fuel type**	
	owner	**tenant**	**owner**	**tenant**	**owner**	**tenant**	**owner**	**tenant**
AHT	1.2%	0.5%	91.8%	8.2%	0.0%	0.0%	0.0%	0.0%
BIO	20.5%	13.8%	96.4%	3.6%	14.0%	2.3%	79.2%	20.8%
COA	1.6%	1.7%	83.1%	16.9%	0.9%	0.5%	36.3%	63.7%
ELC	3.9%	4.7%	80.9%	19.1%	4.2%	4.4%	22.5%	77.5%
GAS	42.2%	48.6%	81.5%	18.5%	44.3%	50.2%	21.0%	79.0%
GEO	1.2%	0.5%	91.8%	8.2%	0.0%	0.0%	0.0%	0.0%
LPG	0.0%	0.1%	49.5%	50.5%	0.0%	0.2%	5.4%	94.6%
LTH	2.0%	4.8%	68.5%	31.5%	6.6%	23.2%	7.9%	92.1%
OIL	25.8%	24.7%	84.2%	15.8%	28.6%	18.8%	31.5%	68.5%
SOL	1.6%	0.7%	92.2%	7.8%	1.3%	0.3%	52.9%	47.1%

Table C-13: Distribution of appliance shares for water heating by building type and tenure
Source: (Destatis 2014a, 2014b, 2013d) (Döring et al. 2020).

	SFH				**MFH**			
	Share of all households		**Share of fuel type**		**Share of all households**		**Share of fuel type**	
	owner	**tenant**	**owner**	**tenant**	**owner**	**tenant**	**owner**	**tenant**
AHT	1.4%	0.6%	94.7%	5.3%	0.0%	0.0%	0.0%	0.0%
BIO	4.5%	3.0%	92.2%	7.8%	4.5%	0.8%	73.3%	26.7%
COA	14.1%	20.7%	84.4%	15.6%	17.6%	22.1%	27.2%	72.8%
ELC	44.4%	45.1%	88.6%	11.4%	40.9%	41.5%	31.6%	68.4%
GAS	1.4%	0.6%	94.7%	5.3%	0.0%	0.0%	0.0%	0.0%
GEO	0.2%	0.8%	71.6%	28.4%	0.1%	0.1%	28.5%	71.5%
LPG	2.0%	4.2%	79.0%	21.0%	5.8%	20.5%	11.7%	88.3%
LTH	27.0%	23.2%	90.2%	9.8%	26.9%	14.0%	47.5%	52.5%
OIL	5.0%	1.9%	95.5%	4.5%	4.1%	1.0%	65.6%	34.4%
SOL	1.4%	0.6%	94.7%	5.3%	0.0%	0.0%	0.0%	0.0%

The number of households determines the distribution of appliances, such as freezers, refrigerators and refrigerator-freezer combinations (Frondel et al. 2015a). The amount of energy consumed by other household appliances and end-uses, such cooking, clothes dryers, washing machines dishwashers, water heaters and other electric appliances (e.g. ICT) depend on the occupancy rate within the household (Frondel et al. 2015a). Lighting, like heating, depends rather on the size of the home and are therefore distributed using the share of living area (Rehdanz 2007). Appliance ownership statistics for the other end-uses are applied according to statistics for owner and tenants (Destatis 2014a) distributed across SFH and MFH according to consumption parameters per end-use, as described in (share of households with appliances x share of households) (BJZ 2020), shown in Table C-18.

Table C-14: Appliance distribution by end-use, building type and tenure
Source: (Frondel et al. 2015a) (Rehdanz 2007) Destatis 2014b

Distribution of total share of appliances by end-use and tenure										
End-use		**CDR**	**COK**	**COL**	**CWA**	**DWA**	**FREEZ**	**OEL**	**REFRI**	**REFRZ**
owner		77.6%	48.1%	80.0%	49.0%	66.8%	78.5%	55.7%	50.8%	50.8%
tenant		22.4%	51.9%	20.0%	51.0%	33.2%	21.5%	44.3%	49.2%	49.2%
Shares of parameters by building type, tenure and end-use based on shares of population or household										
Parameter		*per HH*	*per cap*	*per HH*	*per HH*	*per HH*	*per HH*	*per cap*	*per HH*	*per HH*
SFH	**owner**	86.1%	88.1%	86.1%	86.1%	86.1%	86.1%	88.1%	86.1%	86.1%
	tenant	13.9%	11.9%	13.9%	13.9%	13.9%	13.9%	11.9%	13.9%	13.9%
MFH	**owner**	25.2%	30.5%	25.2%	25.2%	25.2%	25.2%	30.5%	25.2%	25.2%
	tenant	74.8%	69.5%	74.8%	74.8%	74.8%	74.8%	69.5%	74.8%	74.8%
Shares of appliances distributed according to appliances and population of households										
End-use		**CDR**	**COK**	**COL**	**CWA**	**DWA**	**FREEZ**	**OEL**	**REFRI**	**REFRZ**
SFH	**owner**	69.4%	45.2%	77.5%	45.4%	60.7%	69.1%	45.5%	42.5%	42.5%
	tenant	2.7%	5.8%	1.4%	6.6%	4.1%	2.7%	5.8%	7.0%	7.0%
MFH	**owner**	20.3%	15.7%	22.7%	13.3%	17.7%	20.2%	15.8%	12.4%	12.4%
	tenant	14.5%	33.8%	7.5%	35.3%	22.1%	14.8%	33.6%	37.8%	37.8%
Distribution of appliances within each building type by tenure										
SFH	**owner**	96.3%	88.6%	98.2%	87.4%	93.7%	96.2%	88.8%	85.8%	85.8%
	tenant	3.7%	11.4%	1.8%	12.6%	6.3%	3.8%	11.2%	14.2%	14.2%
MFH	**owner**	58.4%	31.6%	75.2%	27.3%	44.5%	57.8%	31.9%	24.7%	24.7%
	tenant	41.6%	68.4%	24.8%	72.7%	55.5%	42.2%	68.1%	75.3%	75.3%

The share of appliances according to the share of owners and tenants by building type is further distributed corresponding to share of population, households or living space. The parameters for this data are given in Table C-15.

Table C-15: Households, population and living space by building type, 2013
Source: own calculations as described in Appendix A based on (Destatis 2011, 2013b; EUROSTAT 2020)

	SFH			**MFH**			
	total	**owner**	**tenant**	**total**	**owner**	**tenant**	**Total**
Households (m)	12.3	10.6	1.7	27.0	6.8	20.2	39.3
share of HHs	100.0%	86.1%	13.9%	100.0%	25.2%	74.8%	
share of total	31.3%	26.9%	4.4%	68.7%	17.3%	51.4%	100.0%
Population (m)	28.9	25.5	3.4	49.96	15.2	34.7	78.9
share of pop	100.0%	88.1%	11.9%	100.0%	30.5%	69.5%	
share of total	36.6%	32.3%	4.4%	63.4%	19.3%	44.0%	100.0%
Living space (m m^2)	1.6	1.402	0.183	2.309	0.750	1.558	3.990
share of m^2	94.9%	89.1%	5.8%	100.0%	32.5%	67.5%	194.9%
share of total	42.1%	37.5%	4.6%	57.9%	18.8%	39.1%	100.0%

The energy distribution is in line with the given guidelines for expenditure in (Destatis 2014b) and validated according to overall expenditure by fuel type (BMWi 2021). Household energy prices for different fuel types are taken from statistics and those used in this analysis are presented in Table C-16 (BMWi 2021).

Table C-16: Household energy prices by fuel type, 2013
Source: own calculations as described in Chapter 5.1.2.1 based on (BMWi 2021; BDEW 2020; Harthan et al. 2020; Ahanchian et al. 2020)

Fuel type	Biomass	Coal	District heating	Electricity	Gas	LPG	Oil
€/GJ (2015)	13.8	18.1	26.0	81.3	23.0	24.3	24.2

The distribution of the energy is validated according to statistics and literature as well as various parameters such as expenditure or energy consumption per person by fuel type. The validation of the calculations are presented in the following steps. Table C-17 presents the average costs per end-use (€/GJ) in this study compared to the statistical values. Households spend an average of 1,791€ annually in 2013 (BMWi 2021).

Table C-17: Average household energy expenditure by end-use, 2013
Source:(BMWi 2021)

End-use	€/GJ	This study
Electricity-based demands (Clothes washing/drying, dishwashing, lighting, appliances, freezer/refrigeration)	81.8	81.8
Cooking	78.2	79.0
Space heating	22.5	22.6
Water heating	32.8	31.9

Validation of the energy balance is done through expenditure on energy consumption by owners compared to tenants. As described in Chapter 3.2.3, owners spent 1.71 more on energy than tenants. In the bottom-up calculation of consumption done in this thesis according to the previous steps described, the expenditure of owners is only 1.46 more than tenants, where the average expenditure of each building type by tenure on direct energy expenditure (i.e. excluding heating and water heating as these are often included in rental prices) as shown in Table C-18, which aligns with the overall average and by end-use. This discrepancy can be attributed to the assumption that the expenditure on energy is based on the average of total expenditure without regard to income, which may result in a higher number. Also, other payment schemes may not be considered, such as those included in heating bills paid to the landlord directly or any repayments or debts calculated by the energy company annually. Therefore, the calculated estimate is within an acceptable range of deviation (Destatis 2017b).

Table C-18: Average monthly direct expenditure on energy per household by building type and tenure, 2013
Source: (Destatis 2017b)

	Total	SFH		MFH		Average	
		Owner	Tenant	Owner	Tenant	Owner	Tenant
€/household and month	160	192	154	198	131	194	133
Expenditure ratio (owner: tenant)	-	1.24		1.52		1.46	

Another parameter of validation is the consumption per capita by ownership, which is provided in Table C-19 for SFH and in Table C-20 for MFH in 2013. The average consumption per capita is compared to the statistics for total energy, electricity, gas and heating and are shown to be within expected ranges compared to the average (see Table C-11).

Table C-19: Energy consumption per capita by end-use and energy carrier, tenure and building type (SFH), 2013

Source: energy balance calculated in this thesis as described in previous steps

MWh per capita	**Owner**	**Tenant**	**SFH average**	**O/T ratio**	**SFH average Cf. Table C-11**
Electricity	2.0	1.7	1.9	1.2	2.0
Gas	4.3	5.2	4.4	0.8	4.5
Oil	2.3	2.5	2.4	0.9	2.4
Bio	2.7	0.8	2.5	3.3	2.5
CWA/CDR	0.2	0.2	0.2	1.1	0.2
FREEZ/REFRI/REFRZ/COK/DWA	0.9	0.8	0.9	1.1	0.9
Heating	9.3	8.5	9.2	1.1	9.1
ICT	0.3	0.2	0.3	1.2	N/A
Lighting	0.2	0.1	0.2	2.0	N/A
Water heating	1.5	2.1	1.6	0.7	1.6
Total	12.4	11.9	12.3	1.0	12.2

Table C-20: Energy consumption per capita by end-use and energy carrier, tenure and building type (MFH), 2013

Source: energy balance calculated in this thesis as described in previous steps

MWh per capita	**Owner**	**Tenant**	**MFH average**	**O/T ratio**	**MFH average Cf. Table C-11**
Electricity	1.8	1.6	1.6	1.2	1.6
Gas	2.8	3.1	3.0	0.9	3.1
Oil	2.3	1.5	1.8	1.6	1.8
Bio	0.4	0.1	0.2	8.1	0.2
CWA/CDR	0.2	0.2	0.2	1.1	0.2
FREEZ/REFRI/REFRZ/COK/DWA	0.8	0.7	0.7	1.2	0.8
Heating	5.3	5.1	5.2	1.0	2.5
ICT	0.3	0.3	0.3	1.1	N/A
Lighting	0.2	0.1	0.1	1.9	N/A
Water heating	1.1	1.0	1.0	1.1	1.0
Total	7.9	7.4	7.5	1.1	7.6

After validating the separate calculations according to the parameters described above, the final energy distribution across building type and tenure is given in Table C-21 for SFH tenants and owners and Table C-22 for MFH tenants and owners.

Table C-21: Final energy consumption distribution by building type and tenure, 2013 (PJ)

Source: energy balance calculated in this thesis

End-use	CDR	COK	COL	CWA	DWA	FREEZ	H	LIG	OEL	REFRI	REFRZ	WH	Total
SFH owner													
AHT	-	-	-	-	-	-	27.3	-	-	-	-	0.8	**28.0**
BIO	-	-	-	-	-	-	202.2	-	-	-	-	5.8	**208.0**
COA	-	-	-	-	-	-	9.9	-	-	-	-	-	**9.9**
ELC	3.3	20.1	1.0	13.1	9.6	8.5	13.7	12.8	22.6	14.2	13.8	18.5	**151.3**
GAS	-	1.3	-	-	-	-	261.6	-	-	-	-	63.6	**326.5**
GEO	-	-	-	-	-	-	0.8	-	-	-	-	0.0	**0.9**
LPG	-	0.0	-	-	-	-	5.1	-	-	-	-	1.1	**6.3**
LTH	-	-	-	-	-	-	29.0	-	-	-	-	0.8	**29.8**
OIL	-	-	-	-	-	-	160.8	-	-	-	-	19.0	**179.8**
SOL	-	-	-	-	-	-	0.9	-	-	-	-	8.6	**9.5**
Total, SFH owner	**3.3**	**21.5**	**1.0**	**13.1**	**9.6**	**8.5**	**711.4**	**12.8**	**22.6**	**14.2**	**13.8**	**118.3**	**950.1**
SFH tenant													
AHT	-	-	-	-	-	-	1.6	-	-	-	-	0.0	**1.6**
BIO	-	-	-	-	-	-	7.5	-	-	-	-	0.5	**8.0**
COA	-	-	-	-	-	-	1.3	-	-	-	-	-	**1.3**
ELC	0.1	2.8	0.3	1.8	0.6	0.3	2.1	0.8	2.3	1.8	1.7	1.6	**16.2**
GAS	-	0.2	-	-	-	-	38.1	-	-	-	-	11.8	**50.0**
GEO	-	-	-	-	-	-	0.0	-	-	-	-	0.0	**0.1**
LPG	-	0.0	-	-	-	-	3.4	-	-	-	-	0.1	**3.4**
LTH	-	-	-	-	-	-	8.6	-	-	-	-	0.3	**8.9**
OIL	-	-	-	-	-	-	19.4	-	-	-	-	5.1	**24.5**
SOL	-	-	-	-	-	-	0.0	-	-	-	-	0.9	**1.0**
Total, SFH tenant	**0.1**	**3.0**	**0.3**	**1.8**	**0.6**	**0.3**	**82.0**	**0.8**	**2.3**	**1.8**	**1.7**	**20.3**	**115.0**

Table C-22: Final energy consumption distribution by building type and tenure, 2013 (PJ)
Source: energy balance calculated in this thesis

End-use	CDR	COK	COL	CWA	DWA	FREEZ	H	LIG	OEL	REFRI	REFRZ	WH	Total
MFH owner													
AHT	-	-	-	-	-	-	-	-	-	-	-	-	**-**
BIO	-	-	-	-	-	-	28.3	-	-	-	-	-	**28.3**
COA	-	-	-	-	-	-	8.1	-	-	-	-	-	**8.1**
ELC	3.7	12.1	2.4	7.7	8.8	10.0	5.6	12.7	19.7	9.1	8.8	12.5	**113.2**
GAS	-	0.9	-	-	-	-	142.9	-	-	-	-	31.1	**174.9**
GEO	-	-	-	-	-	-	-	-	-	-	-	-	**-**
LPG	-	-	-	-	-	-	1.1	-	-	-	-	0.4	**1.6**
LTH	-	-	-	-	-	-	15.7	-	-	-	-	1.5	**17.2**
OIL	-	-	-	-	-	-	130.1	-	-	-	-	17.4	**147.5**
SOL	-	-	-	-	-	-	0.8	-	-	-	-	7.2	**8.0**
Total, MFH owner	**3.7**	**13.0**	**2.4**	**7.7**	**8.8**	**1-**	**332.6**	**12.7**	**19.7**	**9.1**	**8.8**	**70.2**	**498.7**
MFH tenant													
AHT	-	-	-	-	-	-	-	-	-	-	-	-	**-**
BIO	-	-	-	-	-	-	7.4	-	-	-	-	-	**7.4**
COA	-	-	-	-	-	-	9.1	-	-	-	-	-	**9.1**
ELC	2.6	31.0	0.6	19.1	10.4	6.5	12.3	14.0	37.3	21.0	20.4	33.6	**209.0**
GAS	-	1.9	-	-	-	-	345.5	-	-	-	-	67.2	**414.6**
GEO	-	-	-	-	-	-	-	-	-	-	-	-	**-**
LPG	-	0.1	-	-	-	-	12.8	-	-	-	-	1.1	**13.9**
LTH	-	-	-	-	-	-	117.4	-	-	-	-	11.3	**128.7**
OIL	-	-	-	-	-	-	182.3	-	-	-	-	19.2	**201.5**
SOL	-	-	-	-	-	-	0.5	-	-	-	-	3.8	**4.3**
Total, MFH tenant	**2.6**	**33.0**	**0.6**	**19.1**	**10.4**	**6.5**	**687.3**	**14.0**	**37.3**	**21.0**	**20.4**	**136.2**	**988.5**
Total	9.8	70.4	4.3	41.7	29.4	25.2	1813.3	40.3	82.0	46.1	44.9	345.0	2552.3

C.4 Energy consumption by location

The location of households in 2013 was determined by applying statistically appropriate definitions to the population and determining the households in urban (corresponding to 76.9% of the population and 80.2% of households) and rural (corresponding to 23.1% of the population and 19.8% of households) areas (Destatis 2011; EUROSTAT 2020; United Nations 2018). The next step of the distribution is to disaggregate the energy consumption by end-use, energy carrier, building type and location. To further distribute the energy consumption by urban and rural locations, the starting point is an allocation for end-use by certain parameters, such as share of households, population, living area, appliances and fuel types (BJZ 2020). These parameters are based on statistical analysis and presented in Table C-23.

Table C-23: Households, population and living area by location, 2013
Source: (Destatis 2011; EUROSTAT 2020; United Nations 2018)

	Unit	Urban	Rural	Total
Number of households	*m*	31.6	7.8	39.3
Share of households	%	80.2%	19.8%	100.0%
Population	*m*	60.5	18.3	78.9
Share of population	%	76.7%	23.3%	100.0%
Living area	*m* m^2	3.1	0.79	3.9
Share of living area	%	79.9%	20.1%	100.0%

Broadly, this distribution of parameters to the end-uses results in 77% of the total energy consumed in urban areas and 23% in rural areas according to typical assumptions for the distribution of energy consumption per capita, per household or per m^2 (BJZ 2020), as shown in Table C-24.

Table C-24: Distribution of energy by end-use and location
Source: own calculations based on assumptions (BJZ 2020);

End-use	Parameter	Urban shares (%)	Rural (shares %)	urban (PJ/a)	rural (PJ/a)	Total (PJ/a)
CDR	*per capita*	78.0%	22.0%	7.6	2.1	9.8
COK	*per capita*	77.8%	22.2%	54.8	15.6	70.4
COL	*urban only*	100.0%	0.0%	4.3	-	4.3
CWA	*per capita*	78.0%	22.0%	32.5	9.2	41.7
DWA	*per capita*	77.8%	22.2%	22.8	6.5	29.4
FREEZ	*per HH*	77.8%	22.2%	19.6	5.6	25.2
H	*per m2*	78.1%	21.9%	1,409.5	403.7	1,813.3
LIG	*per m2*	77.4%	22.6%	31.2	9.1	40.3
OEL	*per capita*	72.0%	28.0%	59.1	23.0	82.0
REFRI	*per HH*	77.8%	22.2%	35.9	10.2	46.1
REFRZ	*per HH*	77.8%	22.2%	34.9	10.0	44.9
WH	*per capita*	76.7%	23.3%	253.6	91.4	345.0
Total		77.0%	23.0%	1,965.8	586.4	2,552.3

The overall distribution of the final energy consumption for each of the already disaggregated data steps is disaggregated into urban and rural based on the values given in Table C-24 is validated according to various studies, which have characterised energy consumption per capita for different energy carriers (Kramer 2010) and end-uses (Kleinhückelkotten et al. 2016) based on location. Assumptions for biomass consumption by location are taken from (Döring et al. 2020). Consumption patterns for various energy carriers (total energy, electricity, gas, and oil) are derived for the differences of urbanisation in the state of Rhineland-Palatinate in Germany as shown in Table C-25 (Kramer 2010).

Table C-25: Energy consumption per capita by energy carrier and location in Rhineland-Palatinate, 2010

Source: own calculations based on (Kramer 2010; AGEB 2018)

MWh per capita	Urban	Rural	Average	U/R Ratio
Electricity	1.72	1.73	1.72	1.00
Gas	3.56	2.90	3.40	1.23
Oil	1.74	2.63	1.95	0.66
Total	7.02	7.26	7.08	0.97

Similarly, consumption values per capita for various end-uses and rate of urbanisation are presented in Table C-26 (Kleinhückelkotten et al. 2016). Comparing these data shows that in both studies electricity (or electricity-based end-uses) are distributed fairly evenly per capita and, as can be expected, gas dominates in urban areas while oil is more dominant in rural areas. However, the total consumption per capita are reversed between the two studies.

Table C-26: Energy consumption per capita by end-use and location, 2014

Source: own calculations based on (Kramer 2010; Kleinhückelkotten et al. 2016; BMWi 2021; AGEB 2018)

MWh per capita	Urban	Rural	Average	U/R Ratio
CWA/CDR	0.18	0.17	0.18	1.08
FREEZ/REFRI/REFRZ/COK/DWA	0.76	0.71	0.75	1.06
Heating	6.50	6.01	6.39	1.08
ICT	0.27	0.35	0.29	0.78
Lighting	0.14	0.14	0.14	1.04
Water heating	1.22	1.18	1.22	1.03
Total	9.39	7.69	8.99	1.22

A comparison of these per capita consumption values with those calculated through the generation of the final energy consumption in this thesis is the next step. The distribution assumptions per end-use and energy carrier in Table C-24 result in the per capita consumption for the same categories in the studies described above and presented in Table C-27.

Table C-27: Energy consumption per capita by end-use, energy carrier and location, 2013
Source: own calculations based on (Kramer 2010; Kleinhückelkotten et al. 2016)

MWh per capita	This thesis			This thesis	Kramer 2010	Kleinhückelkotten et al. 2016
	Urban	Rural	Average	U/R Ratio	U/R Ratio	U/R Ratio
Electricity	1.76	1.61	1.72	1.09	1.00	
Gas	3.65	2.97	3.49	1.23	1.23	
Oil	1.74	2.63	1.95	0.66	0.66	
Bio	0.73	1.40	0.89	0.52		
CWA/CDR	0.19	0.16	0.18	1.20		1.08
FREEZ/ REFRI/ REFRZ/ COK/DWA	0.78	0.69	0.76	1.13		1.06
Heating	6.47	6.11	6.39	1.06		1.08
ICT	0.29	0.29	0.29	1.00		1.08
Lighting	0.15	0.13	0.14	1.14		0.95
Water heating	1.16	1.38	1.22	0.84		1.04
Total	9.06	8.77	8.99	1.03	0.95	1.03

There is little to no deviation between the distribution in this thesis shown in Table C-27 and those derived from (Kleinhückelkotten et al. 2016) presented in Table C-26. These per capita values and the ratios between urban and rural confirm the distribution of end-uses assuming consumptions per capita indicate urban households consume around the same as rural households for clothes washing, drying, freezing, refrigeration, refrigerator-freezer combinations, cooking, dishwashing, heating, lighting and overall energy, but less for water heating and ICT. The greatest deviation occurs for the respective magnitude of oil and gas consumption per capita which is less in this thesis and likely due to the fact that the comparison study (Kramer 2010) is based only on a small, region-specific survey and therefore not representative of a national picture for urban and rural energy consumption patterns, and because this thesis also considers the consumption of biomass for heating. However, the average urban to rural ration is comparable. The ratio for heating is similar with more heating consumed in urban areas, varying only by the magnitude in use. The final distribution of energy by end-use by urban and rural is given in Table C-28.

These parameters were applied to the energy carrier distribution using the distribution steps described above according to the shares given in Table C-28 based on the steps described across the end-uses and urbanisation. These are then validated by comparing the calculations derived with the indicators for consumption per capita by various energy carriers as given in the literature review. The validation of the distribution is shown in Table C-29. These shares are also used for the further distribution of the energy consumption in each additional step of the disaggregation.

A distribution of the shares of fuel types consumed in urban and rural areas is further compared with (Groenenberg et al. 2011) in Figure C-3. Variations occur due to the wider inclusion of energy types, assumptions taken, e.g. district heating not available and less gas less available in rural areas, and biomass assumptions (Döring et al. 2020). The final distribution of energy carriers by location is given in Figure C-3. The distributions of the bottom-up calculation is deemed acceptable given that the validation parameters are precisely the same (or within a reasonable range of deviation) as the studies to which they are compared in the steps leading up to this point. Due to the fact that there are few studies delineating the consumption by location, a comparison is made with the only existing studies available. However, since these other studies do not base their assumptions on a bottom-up calculation according to precise population distribution, the figures given in these comparative studies can be viewed as estimates.

Table C-28: Final energy consumption by end-use and location, 2013
Source: own calculations based on (Kleinhückelkotten et al. 2016; Kramer 2010; Döring et al. 2020)

End-use	Urban shares (%)	Rural shares (%)	urban (PJ/a)	rural (PJ/a)	Total (PJ/a)
CDR	77.4%	22.6%	7.6	2.2	9.8
COK	77.2%	22.8%	54.4	16.0	70.4
COL	100.0%	0.0%	4.3	-	4.3
CWA	77.4%	22.6%	32.3	9.4	41.7
DWA	77.2%	22.8%	22.7	6.7	29.4
FREEZ	77.2%	22.8%	19.5	5.7	25.2
H	77.7%	22.3%	1,409.55	403.7	1,813.3
LIG	76.8%	23.2%	31.0	9.4	40.3
OEL	75.2%	24.8%	61.7	20.3	82.0
REFRI	77.2%	22.8%	35.6	10.5	46.1
REFRZ	77.2%	22.8%	34.6	10.2	44.9
WH	73.5%	26.5%	253.6	91.4	345.0
Total	77.1%	22.9%	1,966.60	585.65	2,552.3

Table C-29: Validation of distribution by key indicators
Source: own calculations based on (Kleinhückelkotten et al. 2016; Kramer 2010; Döring et al. 2020)

	Unit	Urban	Rural	Average/Total	**Average cf.** Table C-25-Table C-26
Total energy	*MWh/cap*	9.06	8.77	8.99	8.99
	PJ/a	1,73.6	578.7	2,552.3	-
Electricity	*MWh/cap*	1.76	1.61	1.72	1.72
	PJ/a	376.3	113.3	489.6	-
Gas	*MWh/cap*	3.65	2. 979	3.40	3.40
	PJ/a	794.7	171.3	966.0	-
Oil	*MWh/cap*	1.74	2.63	1.95	0.66
	PJ/a	379.5	173.9	553.3	-

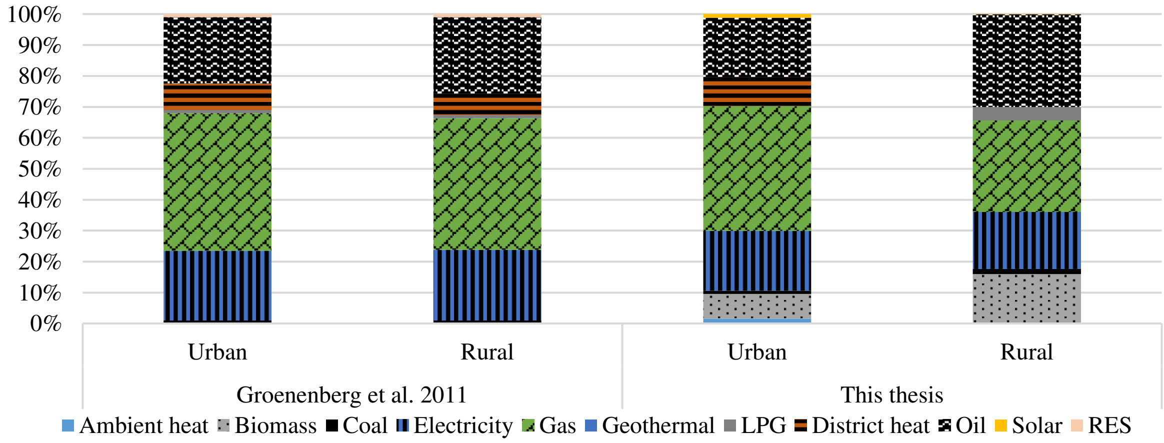

Figure C-3: Comparison between shares of energy carriers by location (Groenenberg et al. 2011) (left) and this thesis (right)

Table C-30: Final energy consumption by fuel type and location, 2013

Source: own calculations based on steps described in previous steps

Energy carrier	Urban shares (%)	Rural (shares %)	urban (PJ/a)	rural (PJ/a)	Total (PJ/a)
AHT	99.0%	1.0%	29.4	0.3	29.7
BIO	63.3%	36.7%	159.4	92.3	251.7
COA	66.9%	33.1%	19.0	9.4	28.5
ELC	78.3%	21.7%	383.1	106.5	489.6
GAS	82.3%	17.7%	794.7	171.3	966.0
GEO	99.0%	1.0%	0.9	0.0	0.9
LPG	1.4%	98.6%	0.35	25.0	25.3
LTH	100.0%	0.0%	184.5	-	184.5
OIL	68.6%	31.4%	379.5	173.9	553.3
SOL	99.0%	1.0%	22.5	0.2	22.8
Total	77.3%	22.7%	1,973.39	578.86	2,552.25

C.5 Energy consumption by income group

The disaggregation of the residential sector by income groups for the purposes of modelling is not often undertaken, but has been recognised as a key driver of energy consumption as well as a limit for households to achieve a certain level of energy services in the home (Cayla et al. 2011). For this study, the income groups are aligned to the income group categories given in Destatis in the Income and Expenditure household budget survey (Destatis 2013b) as per household and month follows:

- R1 = <900€
- R2 = 900-1500€
- R3 = 1500-2000€
- R4 = 2000-2600€
- R5 = 2600-3600€
- R6 = 3600-5000€
- R7 = 5000+

In order to distribute the energy plausibly, the same distribution method is undertaken whereby the appliance shares are applied to the end-uses via the application of consumption parameters for each end-use according to typical assumptions for the distribution of energy consumption per capita, per household or per m^2 (BJZ 2020). As these parameters (population, household and floor area) vary for each finalised profile, the distribution of the energy carriers per end-use vary within each income group, which also indicates adjustments according to the building type, ownership and location. Therefore, the distribution for fuels across the income groups is summarised per end-use in Table C-31 and per energy carrier in Table C-32.

Table C-31: Final energy consumption per income group by end-use, 2013 (PJ)
Source: own calculations based on (BJZ 2020)

	R1	R2	R3	R4	R5	R6	R7	Total
CDR	0.0	0.3	0.4	1.0	2.2	2.4	3.4	**9.8**
COK	1.0	6.2	5.6	7.9	15.6	14.8	19.2	**70.4**
COL	0.0	0.2	0.3	0.4	0.9	1.0	1.5	**4.3**
CWA	1.1	6.0	4.7	5.6	9.0	7.2	8.2	**41.7**
DWA	0.1	1.8	2.2	3.6	7.2	6.6	7.9	**29.4**
FREEZ	0.2	1.6	1.8	3.4	3.7	6.3	8.2	**25.2**
H	82.2	206.0	195.0	245.7	338.3	335.1	410.9	**1813.3**
LIG	0.1	0.9	0.7	2.9	7.4	12.2	16.0	**40.3**
OEL	0.5	3.5	4.0	7.1	17.8	19.4	29.7	**82.0**
REFRI	1.3	6.2	4.8	5.9	9.7	8.2	9.9	**46.1**
REFRZ	1.3	6.0	4.7	5.7	9.4	8.0	9.6	**44.9**
WH	13.4	33.5	34.7	40.7	64.7	71.6	86.4	**345.0**
Total	**101.3**	**272.4**	**259.0**	**329.9**	**485.9**	**492.8**	**610.9**	**2552.3**

Table C-32: Final energy consumption per income group by energy carrier, 2013 (PJ)
Source: own calculations based on (BJZ 2020)

	R1	R2	R3	R4	R5	R6	R7	Total
AHT	0.1	0.5	0.7	5.0	4.4	7.6	11.4	**29.7**
BIO	2.4	8.7	10.2	27.1	55.2	62.6	85.5	**251.7**
COA	0.5	1.3	1.4	5.7	4.0	5.7	9.9	**28.5**
ELC	12.7	46.2	43.4	49.9	102.0	103.8	131.5	**489.6**
GAS	42.5	111.0	108.7	128.8	180.0	182.0	213.1	**966.0**
GEO	0.0	0.0	0.0	0.2	0.1	0.2	0.3	**0.9**
LPG	1.2	3.1	2.9	3.0	3.8	3.6	7.6	**25.3**
LTH	20.1	41.7	31.7	27.3	27.0	20.8	15.9	**184.5**
OIL	21.5	59.3	59.0	78.5	106.0	100.6	128.5	**553.3**
SOL	0.2	0.7	0.9	4.4	3.4	5.9	7.2	**22.8**
Total	**101.3**	**272.4**	**259.0**	**329.9**	**485.9**	**492.8**	**610.9**	**2552.3**

While a detailed energy balance is not available for direct comparison, three studies based on statistics from the Research Data Centre (FDZ) of the Federal Statistical Office provide insights into the average consumption of different energy carriers for electricity-based consumption and heating per decile for 2013 can be compared for validation (Cludius et al. 2018; Bleckmann et al. 2016; Held 2019a). We can compare the consumption and expenditure between these studies and this thesis. (Bleckmann et al. 2016) applied the analysis in terms of quantifying the share of households in expenditure categories for electricity and heating without reference to the specific income groups, therefore, is not considered further.

For comparison purposes, the data from the studies was applied to the redistributed population according to the income groups in this thesis. Table C-33 and Table C-34 demonstrate the shares of the total final energy consumption by income group for heating and electricity-based uses for the two studies and compares the averages in Table C-35 with the differences in this study. Variations are due to the analysis methodologies applied in each of the two studies, where it should be noted that the analysis in the comparison studies only cover heating energy and electricity, so energy use for water heating is excluded entirely and only electric cooking is included in the electricity total consumption, and the study by (Cludius et al. 2018) excludes renewable energy. The results in this study are also adjusted to accommodate a direct comparison with the reference studies by excluding water heating, alternative energy for cooking and merging some fuels for the category “other”. Comparing the differences in the total fuels, these are all within ±3%.

Table C-33: Share of energy consumption by income groups, 2013 (Held 2019a)
Source: own calculations based on (Held 2019a)

	R1	R2	R3	R4	R5	R6	R7	Total
Heating	2.2%	6.2%	6.9%	9.5%	15.6%	17.5%	25.0%	83.0%
Gas	0.9%	2.5%	2.8%	3.9%	6.5%	7.0%	11.2%	34.8%
Oil	0.4%	1.3%	1.8%	2.9%	5.1%	6.1%	8.7%	26.4%
Coal, biomass	0.2%	0.5%	0.6%	1.0%	1.6%	2.1%	2.7%	8.7%
Electricity	0.1%	0.2%	0.2%	0.2%	0.3%	0.4%	0.4%	1.8%
District heating	0.6%	1.7%	1.5%	1.5%	2.0%	1.8%	2.0%	11.1%
Other (RE, LPG)	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.3%
Electricity	0.5%	1.5%	1.5%	2.0%	3.2%	3.5%	4.8%	17.0%
Total	2.8%	7.7%	8.4%	11.5%	18.8%	21.0%	29.8%	100.0%
This thesis (total share)	2.2%	6.2%	6.9%	9.5%	15.6%	17.5%	25.0%	100.0%

Table C-34: Share of energy consumption by income groups, 2013 (Cludius et al. 2018)
Source: own calculations based on (Cludius et al. 2018)

	R1	R2	R3	R4	R5	R6	R7	Total
Heating	2.9%	7.7%	9.2%	11.0%	14.4%	15.2%	19.5%	80.0%
Gas	1.6%	4.0%	4.7%	5.8%	8.2%	8.2%	10.7%	43.2%
Oil	0.4%	1.5%	2.5%	3.4%	3.7%	4.7%	6.5%	22.7%
Coal, biomass	0.1%	0.4%	0.5%	0.6%	0.9%	0.9%	1.0%	4.4%
Electricity	0.1%	0.1%	0.2%	0.2%	0.3%	0.4%	0.4%	1.7%
District heating	0.8%	1.6%	1.3%	1.0%	1.3%	1.0%	1.0%	8.1%
Other (RE, LPG)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Electricity	1.0%	2.4%	2.4%	2.8%	3.8%	3.5%	4.0%	20.0%
Total	4.0%	10.1%	11.7%	13.9%	18.2%	18.7%	23.4%	100.0%
This thesis (total share)	2.9%	7.7%	9.2%	11.0%	14.4%	15.2%	19.5%	80.0%

Table C-35: Final share of energy consumption by energy carrier and income group, 2013

Source: own calculations based on previous steps described

	R1	R2	R3	R4	R5	R6	R7	Total
Heating	3.6%	9.1%	8.6%	10.8%	14.9%	14.8%	18.1%	79.9%
Gas	1.6%	4.2%	4.0%	4.7%	6.4%	6.3%	7.5%	34.7%
Oil	0.9%	2.4%	2.4%	3.1%	4.2%	3.9%	4.8%	21.7%
Coal, biomass	0.1%	0.4%	0.5%	1.4%	2.6%	2.9%	4.1%	12.1%
Electricity	0.1%	0.2%	0.2%	0.1%	0.3%	0.3%	0.2%	1.5%
District heating	0.8%	1.7%	1.3%	1.1%	1.1%	0.8%	0.6%	7.5%
Other (RE, LPG)	0.1%	0.2%	0.2%	0.4%	0.4%	0.5%	0.8%	2.4%
Electricity	0.5%	1.8%	1.7%	2.1%	4.2%	4.3%	5.6%	20.1%
Total	4.1%	10.9%	10.3%	12.9%	19.1%	19.1%	23.7%	100.0%

However, while the shares across the income groups are comparable, there are larger discrepancies across the studies regarding the magnitude of energy and fuel types consumed within the income groups. For example, looking at the share of gas consumed, (Held 2019b) assumes shares of 6.5% for R5, 7% for R6 and 11.2% for R7, while (Cludius et al. 2018) assume shares of 8.2%, 8.2% and 10.7% for R5, R6, and R7, respectively. While (Cludius et al. 2018) present their analysis as energy per household, (Held 2019b) presents his analysis on a per capita basis and this can result in disparities due to methodology and distribution of households and population across the deciles depending on the absolute value taken. Since these studies are also based on national statistics, it is assumed that the same population and household values for 2013 are taken according to (Destatis 2013b). Furthermore, the distribution of the consumption per capita by fuel type in (Held 2019a) is distributed fairly evenly per fuel type across all profiles thereby discounting the regional, technological, access and building type factors, with exceptions for gas and oil (increasing with income) and district heating (decreasing with income). Additionally, the grouping of the population into deciles loses the heterogeneity of disaggregation since households from different income groups (with different energy consumption and financial capacities) will again be merged). The average energy consumption for heating and electricity per capita for the two reference studies and this thesis are presented in Figure C-4. Deviations within each income group in this thesis can be attributed to the bottom-up methodology applied, which accounts for the differences in building type, location, tenure and appliance ownership all of which influence consumption. The overall consumption is also higher in this thesis – especially in the lower income population - because this thesis considered all energy types consumed and aligned the detailed breakdown according to national statistics by end-use as described in the previous sections, particularly regarding biomass consumption (which is often underestimated) and the distribution of gas and district heating by income groups. Renewable energy is excluded from the representation, but make up greater shares of consumption as income increases.

To make comparisons on absolute expenditure between the studies, certain assumptions need to be made: 1) the same energy prices are used, and 2) since both of the reference studies use the same dataset, it is assumed that the same population distribution is used[4]. The expenditure is calculated based on energy prices given by BMWi and the same median income of each income group is assumed across the studies. The ranges of expenditure across the two studies and this thesis are presented in Figure C-5. The expenditure results from (Held 2019b) distributes the energy to

[4] However, the population dataset is only explicitly given in Held 2019b and the actual total number of households are not given in either study but are assumed to align with Destatis 2013b.

increase uniformly per capita and as such does not provide insights into energy expenditure variations by income groups. The ranges within the income groups varies greatly as the types of fuels consumed for each income group diverge. Since this thesis considers the efficiencies and types of technologies used, the consumption of oil and gas decreases with income in line with (Cludius et al. 2018). Variations also occur for electricity demand for other applications, which are difficult to compare between the study and this thesis because it is not clear which appliances and end-uses are included. Since this thesis adapts the consumption by specific appliances, building type and location, when broken down to the per capita level, these values can vary. However, comparing the overall average, these vary only by ±3%.

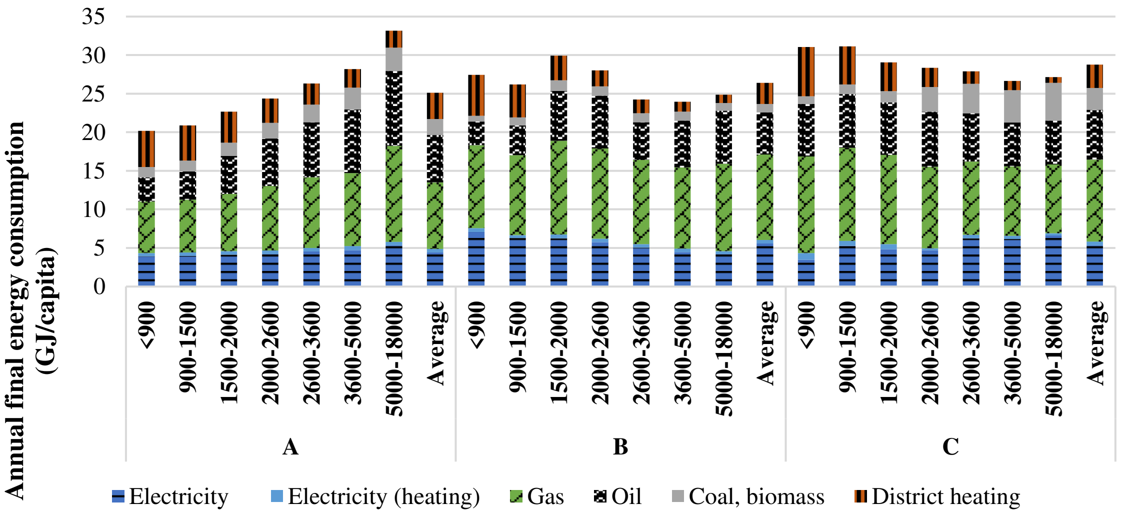

Figure C-4: Comparison of energy consumption per capita by study
Source: A = (Held 2019a); B = (Cludius et al. 2018); C = this thesis

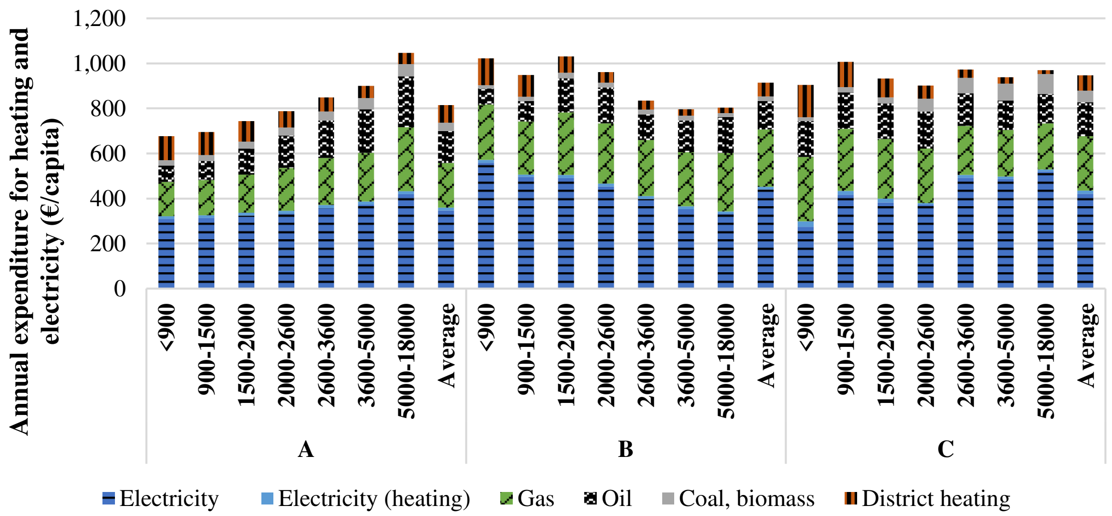

Figure C-5: Comparison of annual expenditure for heating and electricity by income group, 2013
Source: A = (Held 2019a); B = (Cludius et al. 2018); C = this thesis

This analysis has converted the assessment to income groups to preserve the heterogeneity of the consumption patterns. In an energy analysis the distribution of the population evenly across deciles can lead to amalgamation of consumption patterns within deciles that dilute the magnitude and shares of energy consumed thereby reducing the significance of the magnitude of energy consumed. as shown in Table C-36 (cf. Table 3-2 and Table 3-3). The lowest income group (R1) represents the 7.5% of households and 2.8% of the final energy consumption whereas the highest income group (R7) represents 16.2% of households and 29.8% of the final energy consumption. Compared to deciles where the lowest and highest deciles, which represents 9% and 11.5% of households and 7.5% and 13.7% of the final energy consumption, respectively.

Table C-36: Share of energy consumption by income groups, 2013
Source: own calculations based on previous steps described and (Held 2019a)

Income group	Share of final energy consumption
R1 = <900€	2.8%
R2 = 900-1500€	7.7%
R3 = 1500-2000€	8.4%
R4 = 2000-2600€	11.5%
R5 = 2600-3600€	18.8%
R6 = 3600-5000€	21.0%
R7 = 5000-18000€	29.8%
Decile 1	7.5%
Decile 2	8.2%
Decile 3	8.8%
Decile 4	9.2%
Decile 5	9.5%
Decile 6	10.5%
Decile 7	10.2%
Decile 8	11.0%
Decile 9	11.4%
Decile 10	13.7%

Each step of the calculations for the development of the energy balance were compared with various studies to compare with existing studies whether the data was sound. According to the best available data, comparisons were made to validate the data along each calculation step. The validation at each step ensured that the next step in the calculation could be taken, because the values are distributed to ensure a fit, therefore, the values taken in this study can be considered robust and applicable for this thesis.

D. Additional scenario assumptions and results

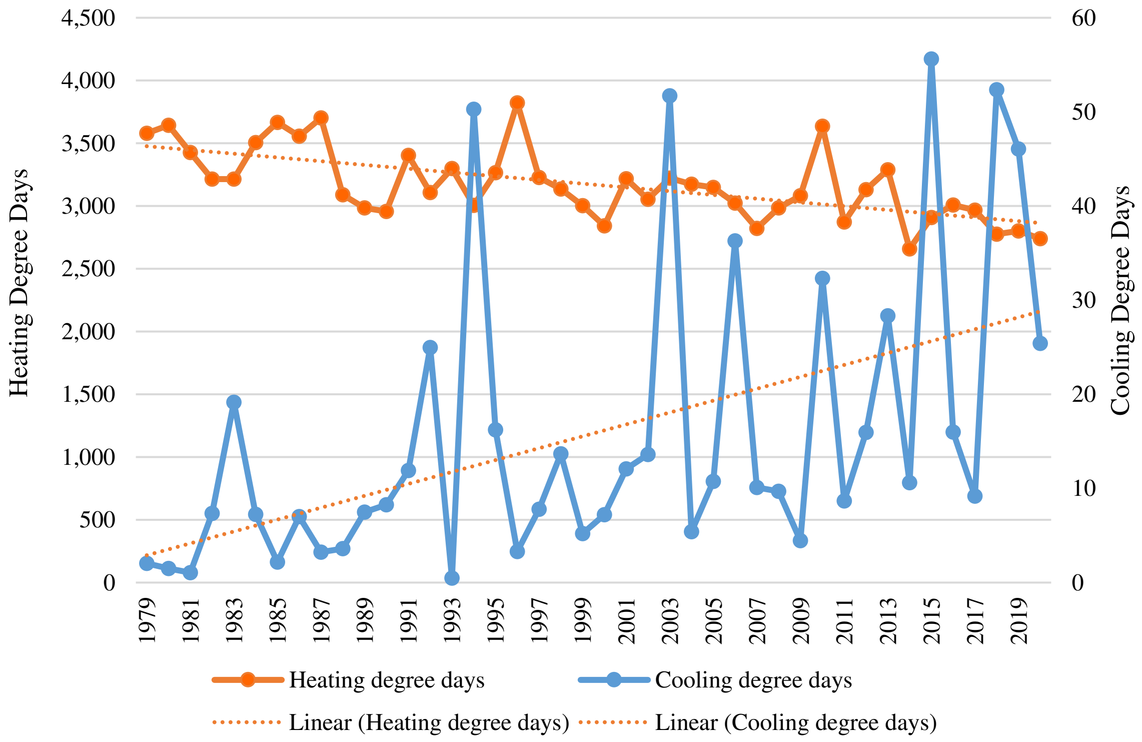

Figure D-1: Heating and cooling degree days in Germany, 1979-2019

Source: own graph based on (EUROSTAT 2021d)

Table D-1: Share of population within each income group benefiting from higher climate bonus

Source: own calculations for the distribution of the population by income level. This table represents the share of each income group that is a part of the lower half of the population. Population assumptions by income group and their development is described in Chapter 5.1.1

Total population	**2025**	**2030**	**2035**	**2040**	**2045**	**2055**	**2060**
<900€	100%	100%	100%	100%	100%		
900-1500€	100%	100%	100%	100%	100%	100%	100%
1500-2000€	100%	100%	100%	100%	100%	100%	100%
2000-2600€	100%	100%	100%	100%	100%	100%	100%
2600-3600€	77%	97%	100%	100%	100%	100%	100%
3600-5000€	0%	0%	16%	34%	50%	64%	77%
5000-18000€	0%	0%	0%	0%	0%	0%	0%

Table D-2: Summary of suppressed demand by scenario, 2035

	Reference (REF)	**Energy poverty (EP)**	**Vulnerable consumers (VC)**
Population affected	6,100,581	951,695	6,113,583
Share of R1-R3 population[1]	59.8%	9.33%	59.9%
Suppressed demand/ Additional capital required per capita for each affected person	151.07€	61.78€	74.01€

[1] *R1-R3 = lowest four income groups, <2000€ per month*

Table D-3: Summary of suppressed demand by scenario, 2030

	Reference (REF)	CB	CBLI
Population affected	11,371,772	881,214	58,549
Share of R1-R3 population affected[1]	51.36%	25.98%	0.59%
Suppressed demand/ Additional capital required per capita for each affected person	83.99€	51.80€	118.27€

[1]*R1-R3 = lowest four income groups, <2000€ per month*

Table D-4: Indicators for evaluation of scenario 1: disaggregated TAM-HHs, 2030

Indicator	Greenhouse gas emissions	Energy use intensity	Renewables for heating	Share of self-generation of total electricity	Affordability: investments	Affordability: consumption	Inability to keep comfortably warm	Arrears in utility bills	Hidden energy poverty: overspending	Hidden energy poverty: underspending
Abbreviation	GHG-I	EU-I	%RE	%PV	%INV	%EXP	%Warm	%Debt	2M	M/2
Unit	*CO_2-eq/ capita*	*Ratio*	*% RE*	*% PV*	*% income*	*% income*	*%pop*	*%pop*	*%pop*	*%pop*
<900	0.85	0.84	0.9%	11.2%	2.4%	5.6%	8.1%	4.4%	25.2%	12.0%
900-1500	0.64	1.12	3.6%	16.9%	6.0%	4.7%	7.1%	4.3%	23.9%	11.7%
1500-2000	0.85	0.81	5.7%	20.0%	2.6%	3.7%	4.2%	3.2%	15.4%	10.1%
2000-2600	0.80	0.72	0.9%	11.5%	2.2%	6.2%	4.6%	3.1%	19.5%	18.6%
2600-3600	0.71	0.70	24.9%	8.5%	2.2%	5.3%	2.0%	1.7%	12.0%	17.6%
3600-5000	0.72	0.78	12.9%	7.5%	1.8%	4.0%	1.0%	1.0%	7.6%	13.0%
5000-18000	0.46	1.04	46.8%	0.2%	1.0%	1.8%	0.2%	0.2%	2.8%	7.0%
Urban	0.60	0.76	21.9%	6.9%	1.4%	2.8%	1.2%	1.0%	-	-
Rural	0.83	0.73	31.1%	5.7%	1.1%	2.2%	4.2%	2.4%	-	-
SFH	1.00	0.66	35.4%	18.6%	1.3%	2.3%	2.7%	1.8%	7.6%	8.2%
MFH	0.54	0.82	17.5%	1.6%	1.3%	2.6%	2.8%	1.9%	10.7%	9.6%
Owner	0.76	0.71	34.9%	12.4%	1.3%	2.4%	1.6%	1.3%	-	-
Tenant	0.55	0.91	7.8%	0.0%	1.3%	2.5%	2.5%	1.9%	-	-
Total	0.65	0.75	24.0%	6.6%	1.3%	2.5%	2.8%	1.9%	9.1%	9.1%

Table D-5: Indicators for evaluation of scenario 1: no budget constraint BUDGET0, 2030

Indicator	Greenhouse gas emissions	Energy use intensity	Renewables for heating	Share of self-generation of total electricity	Affordability: investments	Affordability: consumption	Inability to keep comfortably warm	Arrears in utility bills	Hidden energy poverty: overspending	Hidden energy poverty: underspending
Abbreviation	GHG-I	EU-I	%RE	%PV	%INV	%EXP	%Warm	%Debt	2M	M/2
Unit	*CO_2-eq/ capita*	*Ratio*	*% RE*	*% PV*	*% income*	*% income*	*%pop*	*%pop*	*%pop*	*%pop*
<900	1.04	1.20	2.5%	0.0%	3.1%	12.7%	18.5%	10.0%	57.5%	27.4%
900-1500	0.81	1.20	0.9%	0.0%	3.4%	8.9%	13.5%	8.2%	45.3%	22.3%
1500-2000	0.54	1.19	4.8%	0.0%	2.0%	4.6%	5.3%	4.0%	19.3%	12.7%
2000-2600	0.86	1.32	0.5%	10.0%	2.3%	5.9%	4.4%	2.9%	18.4%	17.6%
2600-3600	0.69	1.14	27.4%	8.1%	2.2%	5.2%	2.0%	1.7%	11.9%	17.4%
3600-5000	0.69	1.28	10.9%	6.1%	1.8%	4.1%	1.0%	1.0%	7.7%	13.2%
5000-18000	0.47	0.61	46.9%	19.6%	1.0%	1.8%	0.3%	0.3%	2.9%	7.2%
Urban	0.60	1.06	20.9%	6.5%	1.3%	2.9%	1.3%	1.0%	-	-
Rural	0.76	1.03	31.0%	7.0%	1.1%	2.3%	4.4%	2.6%	-	-
SFH	0.94	1.04	33.4%	16.7%	1.3%	2.4%	2.8%	1.9%	7.9%	8.6%
MFH	0.54	1.07	17.6%	0.9%	1.2%	2.8%	3.0%	2.0%	11.5%	10.3%
Owner	0.75	1.01	34.7%	11.4%	1.3%	2.5%	1.7%	1.4%	-	-
Tenant	0.54	1.01	7.1%	0.0%	1.1%	2.7%	2.7%	2.1%	-	-
Total	0.64	1.06	23.2%	8.5%	1.2%	2.6%	3.0%	2.0%	9.7%	9.7%

Table D-6: Indicators for evaluation of scenario 2: EP, 2030

Indicator	Greenhouse gas emissions	Energy use intensity	Renewables for heating	Share of self-generation of total electricity	Affordability: investments	Affordability: consumption	Inability to keep comfortably warm	Arrears in utility bills	Hidden energy poverty: overspending	Hidden energy poverty: underspending
Abbreviation	GHG-I	EU-I	%RE	%PV	%INV	%EXP	%Warm	%Debt	2M	M/2
Unit	*CO_2-eq/ capita*	*Ratio*	*% RE*	*% PV*	*% income*	*% income*	*%pop*	*%pop*	*%pop*	*%pop*
<900	1.00	1.26	9.4%	0.1%	3.0%	12.1%	17.5%	9.5%	54.6%	32.1%
900-1500	0.62	1.16	6.9%	7.9%	2.9%	7.9%	12.0%	7.3%	48.8%	24.0%
1500-2000	0.56	1.08	20.2%	14.9%	2.0%	4.7%	5.4%	4.1%	22.4%	14.7%
2000-2600	0.74	1.22	1.0%	10.4%	2.4%	6.0%	4.5%	3.0%	23.1%	22.1%
2600-3600	0.69	1.17	22.7%	7.8%	2.2%	5.4%	2.1%	1.7%	15.2%	22.2%
3600-5000	0.77	1.28	9.4%	6.3%	1.8%	4.0%	1.0%	1.0%	8.8%	15.2%
5000-18000	0.52	0.47	44.7%	0.2%	1.0%	1.4%	0.2%	0.2%	4.3%	10.7%
Urban	0.61	1.01	19.9%	6.4%	1.3%	2.7%	1.2%	1.0%	-	-
Rural	0.79	0.98	34.5%	4.8%	1.1%	2.3%	4.3%	2.6%	-	-
SFH	1.04	1.07	20.9%	14.2%	1.2%	2.3%	2.7%	1.8%	14.3%	15.4%
MFH	0.52	0.96	24.4%	1.6%	1.2%	2.6%	2.9%	2.0%	19.1%	17.1%
Owner	0.79	1.00	32.8%	10.1%	1.3%	2.4%	1.6%	1.4%	-	-
Tenant	0.52	0.90	9.8%	0.0%	1.1%	2.4%	2.6%	2.0%	-	-
Total	0.65	1.00	23.2%	5.7%	1.2%	2.4%	2.9%	2.0%	16.2%	16.2%

Table D-7: Indicators for evaluation of scenario 2: VC, 2030

Indicator	Greenhouse gas emissions	Energy use intensity	Renewables for heating	Share of self-generation of total electricity	Affordability: investments	Affordability: consumption	Inability to keep comfortably warm	Arrears in utility bills	Hidden energy poverty: overspending	Hidden energy poverty: underspending
Abbreviation	GHG-I	EU-I	%RE	%PV	%INV	%EXP	%Warm	%Debt	2M	M/2
Unit	*CO_2-eq/ capita*	*Ratio*	*% RE*	*% PV*	*% income*	*% income*	*%pop*	*%pop*	*%pop*	*%pop*
<900	0.82	0.95	4.4%	0.0%	11.9%	5.3%	11.2%	6.1%	34.9%	16.6%
900-1500	0.59	0.99	27.8%	3.3%	39.7%	3.7%	9.3%	5.7%	31.3%	15.4%
1500-2000	0.88	1.24	20.4%	10.6%	3.5%	3.1%	6.1%	4.6%	22.0%	14.4%
2000-2600	0.74	1.21	8.4%	9.0%	3.2%	4.0%	5.1%	3.4%	21.2%	20.2%
2600-3600	0.62	1.05	28.4%	7.5%	2.7%	3.3%	2.4%	2.0%	14.3%	20.8%
3600-5000	0.76	1.24	10.7%	6.2%	2.1%	2.2%	1.0%	1.0%	8.0%	13.8%
5000-18000	0.77	0.71	34.2%	0.1%	1.1%	1.0%	0.3%	0.3%	3.3%	8.3%
Urban	0.65	1.11	20.8%	5.0%	2.5%	1.7%	1.3%	1.1%	-	-
Rural	1.02	1.03	30.8%	4.6%	1.9%	1.4%	4.7%	2.8%	-	-
SFH	1.18	1.06	33.8%	12.3%	1.4%	1.5%	2.9%	1.9%	8.1%	8.7%
MFH	0.59	1.10	17.3%	1.3%	2.6%	1.6%	3.3%	2.2%	12.8%	11.5%
Owner	0.86	0.98	34.3%	9.1%	1.4%	1.5%	1.7%	1.4%	-	-
Tenant	0.63	1.09	7.5%	0.0%	3.1%	1.6%	3.0%	2.3%	-	-
Total	0.73	1.09	23.1%	4.6%	2.2%	1.5%	3.2%	2.1%	10.4%	10.4%

Table D-8: Indicators for evaluation of scenario 3: CO2TO, 2030

Indicator	Greenhouse gas emissions	Energy use intensity	Renewables for heating	Share of self-generation of total electricity	Affordability: investments	Affordability: consumption	Inability to keep comfortably warm	Arrears in utility bills	Hidden energy poverty: overspending	Hidden energy poverty: underspending
Abbreviation	GHG-I	EU-I	%RE	%PV	%INV	%EXP	%Warm	%Debt	2M	M/2
Unit	*CO_2-eq/ capita*	*Ratio*	*% RE*	*% PV*	*% income*	*% income*	*%pop*	*%pop*	*%pop*	*%pop*
<900	0.61	1.32	0.9%	0.0%	1.0%	10.0%	19.5%	10.6%	60.7%	28.9%
900-1500	0.32	1.10	3.6%	0.0%	1.0%	7.4%	11.6%	7.1%	38.9%	19.1%
1500-2000	0.49	1.17	5.7%	0.0%	0.6%	4.2%	5.3%	4.0%	19.1%	12.5%
2000-2600	0.51	1.27	0.9%	10.1%	0.6%	5.1%	4.0%	2.7%	16.7%	16.0%
2600-3600	0.44	1.17	24.9%	8.2%	0.5%	4.7%	1.9%	1.5%	11.0%	16.1%
3600-5000	0.47	0.93	12.9%	11.6%	0.4%	3.0%	0.8%	0.8%	6.4%	11.1%
5000-18000	0.67	0.51	46.8%	6.7%	0.2%	1.6%	0.3%	0.3%	2.9%	7.3%
Urban	0.48	0.97	21.9%	8.1%	0.3%	2.5%	1.2%	1.0%	-	-
Rural	0.70	0.99	31.1%	8.2%	0.3%	1.9%	4.0%	2.4%	-	-
SFH	0.94	0.93	35.4%	21.5%	0.3%	2.0%	2.7%	1.8%	7.5%	8.1%
MFH	0.40	0.99	17.5%	1.3%	0.3%	2.4%	2.7%	1.8%	10.5%	9.4%
Owner	0.73	0.86	34.9%	14.9%	0.3%	2.1%	1.5%	1.3%	-	-
Tenant	0.36	1.00	7.8%	0.0%	0.3%	2.4%	2.5%	1.9%	-	-
Total	0.53	0.98	24.0%	7.8%	0.3%	2.2%	2.7%	1.9%	9.0%	9.0%

Table D-9: Indicators for evaluation of scenario 3: CB, 2030

Indicator	Greenhouse gas emissions	Energy use intensity	Renewables for heating	Share of self-generation of total electricity	Affordability: investments	Affordability: consumption	Inability to keep comfortably warm	Arrears in utility bills	Hidden energy poverty: overspending	Hidden energy poverty: underspending
Abbreviation	GHG-I	EU-I	%RE	%PV	%INV	%EXP	%Warm	%Debt	2M	M/2
Unit	*CO_2-eq/ capita*	*Ratio*	*% RE*	*% PV*	*% income*	*% income*	*%pop*	*%pop*	*%pop*	*%pop*
<900	0.92	1.10	0.9%	0.1%	3.2%	9.9%	14.3%	7.8%	44.6%	21.2%
900-1500	0.81	0.97	3.6%	11.4%	3.3%	5.9%	9.0%	5.5%	30.1%	14.8%
1500-2000	0.88	1.33	5.7%	14.9%	2.8%	4.7%	5.5%	4.1%	19.8%	13.0%
2000-2600	0.80	1.32	0.9%	14.5%	3.1%	6.0%	4.5%	3.0%	18.8%	17.9%
2600-3600	0.67	1.16	24.9%	14.3%	2.7%	5.2%	2.0%	1.6%	11.8%	17.3%
3600-5000	0.69	1.27	12.9%	10.3%	2.1%	4.1%	1.0%	1.0%	7.7%	13.2%
5000-18000	0.40	0.58	46.8%	0.2%	1.1%	1.7%	0.2%	0.2%	2.7%	6.8%
Urban	0.58	1.07	21.9%	9.8%	1.5%	2.8%	1.2%	1.0%	-	-
Rural	0.80	1.01	31.1%	5.4%	1.4%	2.3%	4.2%	2.5%	-	-
SFH	0.85	1.02	35.4%	22.7%	1.4%	2.2%	2.6%	1.7%	7.4%	8.0%
MFH	0.56	1.07	17.5%	1.5%	1.5%	2.7%	2.9%	1.9%	11.2%	10.0%
Owner	0.66	0.97	34.9%	15.1%	1.3%	2.4%	1.6%	1.3%	-	-
Tenant	0.60	1.03	7.8%	0.0%	1.5%	2.6%	2.6%	2.0%	-	-
Total	0.63	1.06	24.0%	8.0%	1.4%	2.5%	2.8%	1.9%	9.3%	9.3%

Table D-10: Indicators for evaluation of scenario 3: CBLI, 2030

Indicator	Greenhouse gas emissions	Energy use intensity	Renewables for heating	Share of self-generation of total electricity	Affordability: investments	Affordability: consumption	Inability to keep comfortably warm	Arrears in utility bills	Hidden energy poverty: overspending	Hidden energy poverty: underspending
Abbreviation	GHG-I	EU-I	%RE	%PV	%INV	%EXP	%Warm	%Debt	2M	M/2
Unit	*CO_2-eq/ capita*	*Ratio*	*% RE*	*% PV*	*% income*	*% income*	*%pop*	*%pop*	*%pop*	*%pop*
<900	0.87	1.09	0.9%	0.1%	4.6%	11.6%	16.9%	9.2%	52.6%	25.0%
900-1500	0.94	1.09	3.6%	9.2%	5.6%	7.1%	10.7%	6.5%	35.9%	17.6%
1500-2000	0.80	1.30	5.7%	14.1%	3.0%	4.8%	5.6%	4.2%	20.4%	13.4%
2000-2600	0.76	1.29	0.9%	14.2%	3.1%	6.0%	4.5%	3.0%	18.8%	17.9%
2600-3600	0.68	1.17	24.9%	15.0%	2.7%	5.3%	2.0%	1.7%	12.1%	17.7%
3600-5000	0.69	1.25	12.9%	10.0%	2.0%	4.1%	1.0%	1.0%	7.6%	13.2%
5000-18000	0.46	0.64	46.8%	0.2%	1.1%	1.8%	0.2%	0.2%	2.8%	7.1%
Urban	0.59	1.08	21.9%	9.6%	1.6%	2.9%	1.2%	1.0%	-	-
Rural	0.87	1.00	31.1%	5.3%	1.4%	2.3%	4.3%	2.5%	-	-
SFH	0.92	1.02	35.4%	22.6%	1.3%	2.3%	2.7%	1.8%	7.6%	8.2%
MFH	0.56	1.08	17.5%	1.5%	1.6%	2.8%	2.9%	2.0%	11.4%	10.2%
Owner	0.69	0.96	34.9%	14.8%	1.3%	2.4%	1.6%	1.3%	-	-
Tenant	0.61	1.04	7.8%	0.0%	1.6%	2.7%	2.7%	2.0%	-	-
Total	0.65	1.08	24.0%	7.8%	1.5%	2.6%	2.9%	2.0%	9.6%	9.6%

E. Techno-economic assumptions

Table E-1: Sample building characteristics modelled in TAM-Households, 2013

Source. Own calculations based on (Destatis 2013b, 2013d, 2013a; Frondel et al. 2015b; Cischinsky and Diefenbach 2018) as described in more detail in Appendix C

		SFH, existing		MFH, existing	
		Avg. floor area *m²*	**Avg. space heating consumption** *kWh/m²*	**Avg. floor area** *m²*	**Avg. space heating consumption** *kWh/m²*
Income group	**R1**	84.5	128.2	57.6	130.8
	R2	99.9	127.1	68.3	129.2
	R3	109.3	122.6	77.2	124.8
	R4	123.4	132.9	85.5	123.4
	R5	133.4	132.2	94.5	118.4
	R6	141.4	132.1	105.4	117.7
	R7	158.8	131.2	120.5	119.4
Building type	**Average**	116.6	131.1	88.7	122.7
Tenure	**Owner**	133.3	132.0	103.3	123.1
	Tenant	99.9	124.1	74.1	122.5

Illustrative prices given for technology options for an average existing urban SFH - prices vary by building type, income group and location. Reference building for existing: E class with gas heater; calculations for profiles are living area specific according to the installed capacity required; technologies not appropriate for technological or legal reasons are excluded as options. Reference building for new buildings are B class up to modelling time period 2025, thereafter A class with gas heater; calculations for profiles are living area specific according to the installed capacity required; technologies not appropriate for technological or legal reasons are excluded as options. All prices are in 2015 with the starting point investment costs for 2015 calculated based on (Eltrop 2020). The energy efficiency renovation packages are modelled as in competition with another, where each energy efficiency renovation package includes different options (Korkmaz et al., 2019) where costs and savings were calculated for Germany according to (TABULA 2016). Technology descriptions are based on (Haasz 2017) and updated according to (DeVita et al. 2018).

Table E-2: Techno-economic assumptions for space heating technologies for an existing urban SFH

Source: (Eltrop 2020; Korkmaz et al. 2019; DeVita et al. 2018; Haasz 2017)

Technology	**Invest-ment costs** *€2015/GJ*	**Fixed O&M** *€2015/GJ*	**Effi-ciency** *%*	**Technical Life-time** *a*	**Technical Avail-ability Factor (2030)**	**Variable non- fuel costs** *€2015/GJ*
Space heating						
Combined biodiesel boiler (condensing)	20.8	0.6	91.1%	20.0	0.180	2.72E-05
Wood fireplace	35.4	2.1	51.2%	15.0	0.166	6.46E-05
Biomass stove	48.1	2.9	56.7%	22.5	0.166	2.72E-05
Combined biomass boiler	48.1	2.9	75.6%	20.0	0.180	
Combined biodiesel boiler	20.8	0.6	84.6%	20.0	0.180	
Electric resistance	25.7	0.8	93.0%	20.0	0.166	

Technology	Invest-ment costs €2015/GJ	Fixed O&M €2015/GJ	Effi-ciency %	Technical Life-time a	Technical Avail-ability Factor (2030)	Variable non- fuel costs €2015/GJ
Combined electric heat pump	46.8	1.2	76.6%	13.5	0.166	
Combined electric heat pump	46.8	1.2	84.3%	18.0	0.166	
Advanced electric heat pump	46.8	1.2	84.3%	18.0	0.166	
Advanced combined electric heat pump	46.8	1.2	83.7%	18.0	0.166	
Natural gas boiler	20.8	0.6	80.0%	20.0	0.166	
Natural gas boiler (condensing)	20.8	0.6	94.8%	20.0	0.166	
Combined natural gas boiler	20.8	0.6	84.6%	20.0	0.180	
Combined natural gas boiler (condensing)	20.8	0.6	97.5%	20.0	0.180	
Combined natural gas heat pump	34.1	1.5	83.7%	15.0	0.166	
Combined electric ground heat pump	70.2	1.8	77.8%	20.0	0.166	
Combined electric ground heat pump	70.3	1.8	77.8%	20.0	0.166	
LPG Boiler - water system	30.3	0.9	80.0%	20.0	0.158	
Combined LPG Boiler	30.3	0.9	84.6%	15.0	0.171	
LPG Stove	30.3	0.9	78.1%	10.0	0.158	
Combined LPG Heat Pump	43.6	2.0	83.7%	13.5	0.158	
Combined LPG Heat Pump	43.6	2.0	83.7%	13.5	0.158	
Combined Heat Exchanger (District Heat)	32.3	1.0	91.1%	21.7	0.180	6.46E-05
Diesel boiler - water system	34.5	1.0	83.7%	18.3	0.166	
Combined oil boiler (low temperature)	34.5	1.0	84.6%	17.5	0.180	2.72E-05
Combined oil boiler (condensing)	34.5	1.0	91.1%	20.0	0.180	2.72E-05
Oil stove	34.5	1.0	60.5%	15.0	0.166	
Combined solar collector with diesel backup	51.5	1.5	88.4%	20.0	0.180	5.78E-05
Combined solar collector with oil (condensing)	51.5	1.5	69.8%	20.0	0.180	
Combined solar collector with gas backup	51.5	1.5	88.4%	20.0	0.180	2.04E-05
Combined solar collector with gas (condensing)	51.5	1.5	93.0%	20.0	0.180	
Combined solar collector with gas heat pump	64.8	2.9	83.7%	16.0	0.180	
Combined solar collector with electric backup	66.7	2.0	93.0%	20.0	0.180	
Combined solar collector with electric heat pump	80.0	2.0	83.7%	20.0	0.180	
Combined solar collector with biomass boiler	74.9	2.2	85.6%	20.0	0.180	
Energy Efficiency - renovation packages (average savings)						
Level 1 improvements (wall, ceiling, window) 8% savings	157.2	-	-	25	0.183	
Level 2 improvements (wall, ceiling, window) 17% savings	171.9	-	-	25	0.183	

Technology	Investment costs €2015/GJ	Fixed O&M €2015/GJ	Efficiency %	Technical Lifetime a	Technical Availability Factor (2030)	Variable non- fuel costs €2015/GJ
Level 3 improvements (wall, ceiling, window) 29% savings	254.7	-	-	25	0.183	
Level 4 improvements (wall, ceiling, window) 32% savings	341.0	-	-	25	0.183	

Table E-3: Techno-economic assumptions for household appliances

Technology	Investment costs €2015/GJ	Fixed O&M €2015/GJ	Efficiency %	Technical Lifetime a	Technical Availability Factor (2030)	Variable non fuel costs €2015/GJ
Cooking						
Electric stove, higher efficiency	4.1	0.0	0.8	15	0.04	
Gas stove, higher efficiency	1.5	0.0	0.4	15	0.04	
LPG stove, higher efficiency	0.4	0.0	0.3	9	0.04	
Cooling						
Non-reversible heat pump	26.9	0.7	3.3	15		
Room air conditioner, window, portable	302.6	4.6	2.0	10		
Centralised electrical air conditioner	25.0	0.8	2.9	14		
Centralised natural gas air conditioner	58.7	1.4	4.4	15		
Centralised natural gas heat pump	41.8	0.9	1.0	15		
Centralised district heat absorption conditioner	28.4	0.8	1.3	15		
Centralised solar air conditioner	92.7		1.1	14		
Clothes washing/drying						
Clothes dryer, higher efficiency (A,B)	6.7	0.0	1.3	15		
Clothes dryer, medium efficiency	5.3	0.0	1.0	15		
Electric washing machine	5.7	0.0	4.8	11		0.16
Washing machine, higher efficiency (A,B)	6.9	0.0	1.5	15		
Washer/Dryer combination, higher efficiency	8.0	0.0	1.4	13		
Washer/Dryer combination, medium efficiency	6.9	0.0	1.0	10		
Lighting						
Incandescent STAD lighting system	0.9		1.0	5		
Halogen lighting system	1.0		2.8	7		
Fluorescent lighting system	1.7		5.0	9		
Diode lighting system	4.1		12.2	15		
Freezing/Refrigeration						
Freezer B	252.5	1.3		12	0.18	1.18
Freezer A	362.0	1.3		12	0.18	1.18
Refrigerator B	197.1	1.0		12	0.39	1.04
Refrigerator A	283.4	1.0		12	0.39	1.04

Technology	Invest-ment costs $€_{2015}/GJ$	Fixed O&M $€_{2015}/GJ$	Effi-ciency %	Technical Life-time a	Technical Avail-ability Factor (2030)	Variable non fuel costs $€_{2015}/GJ$
Combination Refrigerator/Freezer B	222.4	1.1		12	0.33	0.92
Combination Refrigerator/Freezer A	269.8	1.1		12	0.33	0.92

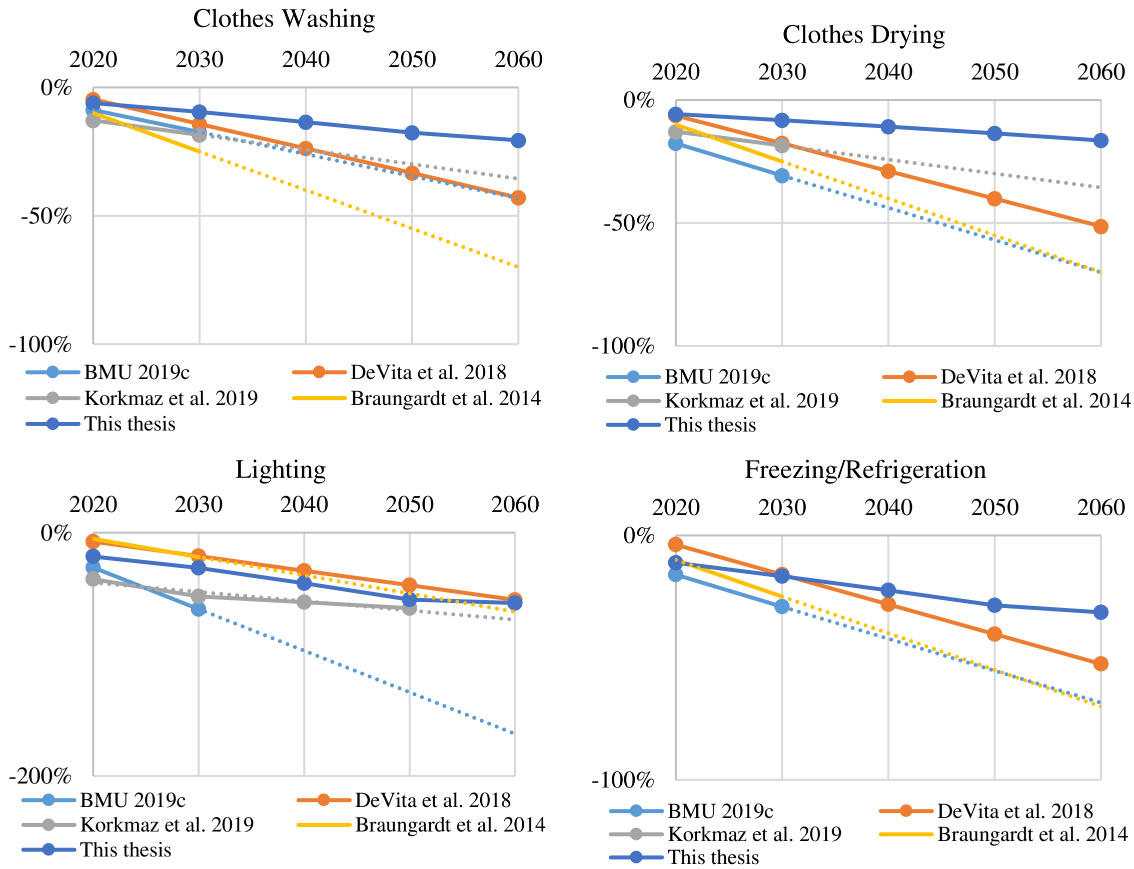

Figure E-1: Energy efficiency trends for electricity-based end-uses

Source: (BMU 2019c; Korkmaz et al. 2019; DeVita et al. 2018; Braungardt et al. 2014)

Table E-4: TAM-Households model description

System boundaries	Households (buildings)
Base year	2013
Base year for cost figures	2015
Time horizon	2060
Time steps	7 years, thereafter 5 year steps
Time resolution	Annual
Spatial resolution	1 region (Germany)
Actors	Households
Sub-sectors	7 income groups, location, building type, tenure
Exogenous drivers	Prices, income (available disposable income for energy expenditures)
Demands	Space heating, water heating, cooking, cooling, clothes drying, clothes washing, appliances (other electricity), lighting, freezing, refrigeration, freezer/refrigeration, dishwashing
Energy carriers	Liquid biofuels, solid biomass, coal, district heat, electricity, natural gas, LPG, geothermal, hydrogen, ambient heat, solar, oil
Policy interventions	Global renewable energy and energy efficiency targets; Household-specific emissions reduction targets
Decision-making behaviour	Income group-specific investment and consumption profiles: restrictions on investment and consumption based on available budget per income group; discount rates; cost minimisation; utility maximisation

F. Case study: energy efficiency, extended technology lifetime and second-hand appliances in freezing and refrigeration demand

F.1 Introduction

Refrigerators are used in 99.9% of all households and consume the largest share of the electricity for appliances in households (Destatis 2018b). Overall the number of refrigerators per household is increasing across all income groups[5] and increase with income as shown in Figure F-1 with an average growth of about 0.5% between 2014 and 2017. This could have a significant impact on the overall residential energy demand where the total electricity consumption for refrigeration in all households increased from 99,7 PJ in 2008 to 104.6 PJ in 2018 despite energy efficiency improvements in refrigeration appliances (BMWi 2019b; ACEEE 2014). Globally, electricity consumption for refrigeration and freezers is expected to increase a further 35% by 2050 while it is acknowledged that the efficiency for these appliances could be doubled through existing technical knowledge (IEA 2019).

The implications of the overall energy policy trends to further the energy transition require the investment into renewable and energy efficient technologies from the household sector and these high upfront costs cannot be borne by lower income households and is therefore lower in lower income households (Schleich 2019). Lower income households thus risk slipping into energy poverty in the face of the energy transition by not being able to reap the benefits of more efficient appliances, which are expected to lower electricity bills.

Another point of consideration is the affordability of the higher upfront costs of household appliances and the policies restricting the uptake of new, more efficient technologies in lower income households dependent on social welfare (HartzIV 2019). Without alternative support programmes for lower income households – such as the “Energy savings check” (Stromsparcheck) project initiated by Caritas - the affordability of the higher upfront costs of more energy efficient appliances may be untenable and means there is a greater reliance on second-hand appliances despite the longer term lower costs of more efficient, but higher priced alternatives (Boardman 2010; Caritas 2015). Especially households depending on social welfare are faced with complicated hurdles when the need to purchase a first appliance or replace a household appliance arises. Households will typically obtain appliances through donations (second-hand) or are often required to make use of payment plans (which lead to higher overall costs) to pay for the investment into a replacement appliance, where they will often then turn to the second-hand market (HartzIV 2019). The benefits of energy efficiency have shown to improve the energy and economic welfare of households (IEA 2015). Energy efficiency directly addresses not only the causes of energy poverty but also services the overarching energy efficiency targets (Dobbins et al. 2019). The perpetuation of the use of second-hand appliances reduces the opportunities for the overall energy system to become more efficient, at the same time there is an environmental impact from the scrapping of appliances that are still operational. There is a need to better assess the trade-off of between newer appliances and the impact on the energy system as well as on the energy welfare of (lower income) households.

The objectives of this case study are to assess the cost-optimal investment and consumption patterns for different profiles by extending the model framework to include additional features (budget constraints, lifetime extension of technologies, second-hand appliance market) using refrigerators and freezers as an example.

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[5] Income groups are disaggregated by monthly income per household R1: <900€, R2: 900-1500€, R3: 1500-2000€, R4: 2000-2600€, R5: 2600-3600€, R6: 3600-5000€, R6: >5000€; See Chapter 3 for further information.

F.2 Household refrigerator and freezer demand patterns and savings opportunities

Efforts to increase energy efficiency for refrigeration has improved over the years, specifically through the technical efficiency of the appliances and the introduction of appliance labelling (consumer awareness). A review of the refrigeration energy demand in Germany reveals a steady increase in the number of refrigerators and share of ownership of refrigeration and freezer appliances with an overall growth of 4% between 2014 and 2018, as shown in Figure F-1 (Destatis 2018b). These figures are shown for specific income groups[6] which highlights that all income groups have more than 1 device per household, but as income increases so does the number of devices per household.

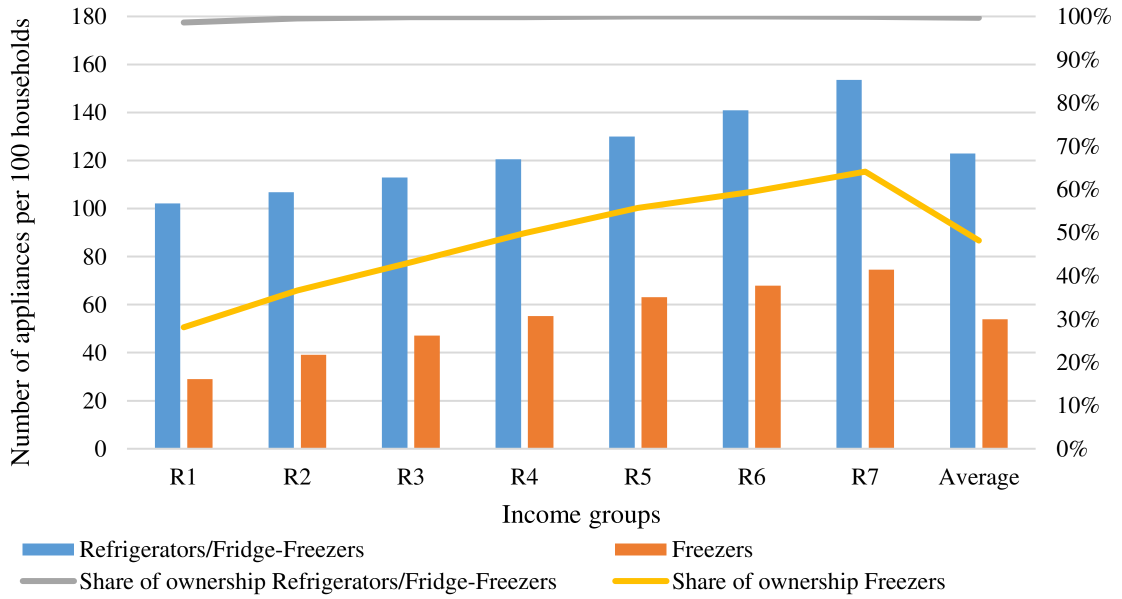

Figure F-1: Growth in the number of refrigerators and total annual energy demand

Source: own graph and calculations based on (Destatis 2018b)

While some households are more likely to purchase new appliances instead of second-hand, the majority of households tend to keep and operate both the old and the replacement appliances[7] (Foulds et al. 2016). Households using older refrigerators as a second device means a higher overall consumption of energy (as the efficiency of the device decreases with age) despite the higher efficiency of the newer appliance. The differentiation in expenditure on electricity on refrigeration and freezer demand by income group is further expanded on in Figure F-2. This shows more clearly see that the average electricity consumption per refrigerator and household decreases with income. Correspondingly, the share of overall electricity consumption for refrigeration decreases with income where R1 households are consuming 35% of their energy consumption for refrigeration while R7 households consume about half that share. Comparing the total electricity consumption and total expenditure across income groups, we see ranges only from about 734kWh and 221€ per household in R1, 868kWh and 262€ per household in R7, and an average of 748kWh and 225€ per household. Despite the lower number of refrigerators per household in R1 compared to R7, the overall electricity consumption per refrigerator and household is higher due to the lower efficiency of the appliances.

[6] Income groups are disaggregated by monthly income per household R1: <900€, R2: 900-1500€, R3: 1500-2000€, R4: 2000-2600€, R5: 2600-3600€, R6: 3600-5000€, R6: >5000€; See section Appendix B for further information.

[7] The study did not distinguish investment and consumption patterns by income group

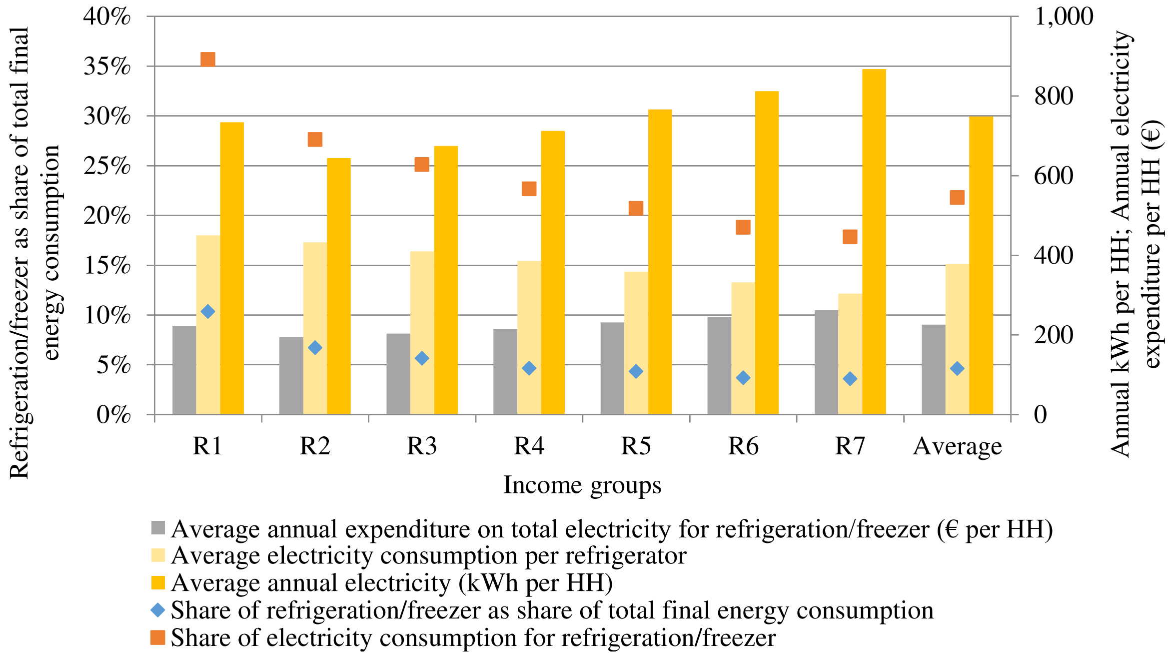

Figure F-2: Overview of electricity consumption and expenditure for refrigeration/freezer demand compared with the share of refrigeration/freezer of the total final energy consumption vs. share of electricity, 2013

Source: own graph and calculations based on (Destatis 2014a, 2013b)

Energy efficiency initiatives aim to save electricity in the household sector and target the replacement of refrigerators after 10-15 years offering a rebate of 100-150 € for the exchange of the refrigerator (Caritas 2019; City of Stuttgart 2020). The exchange of the refrigerator is key because it hinders the option of the consumer to continue to use the old appliance in addition to the newer, more efficient appliance.

The "Energy savings check" (Stromsparcheck) project initiated by Caritas in 2005 provides lower income households with free advice about energy saving behaviour and installs simple energy efficiency interventions, such as energy efficient light bulbs and low-flow showerheads to a value of 70€ per household and/or a refrigerator exchange (218€). In the first project phase, each household saved about 130€ annually in electricity, water and heating costs (Caritas 2014b). The average annual electricity consumption for each household in the programme was around 2915 kWh. The programme enabled average annual electricity savings for the inclusion of energy savings measures to around 789kWh if the refrigerator was exchanged or 393kWh without the exchange of the refrigerator (Caritas 2015). These types of rebate programmes are crucial for lower income households to be in a better position financially to afford more efficient household appliances.

Without these types of support programmes for lower income households, the affordability of the high upfront costs of more energy efficient appliances may be untenable and will use second-hand appliances despite the longer term lower costs of more efficient, but higher priced alternatives (Boardman 2010). Especially households depending on social welfare are faced with complicated hurdles when the need to purchase a first appliance or replace a household appliance arises. Households will typically obtain appliances through donations (second-hand) or are often required to take out loans to pay for the investment into a replacement appliance, where they will often then turn to the second-hand market (HartzIV 2019).

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Inhalt

The energy transition in Germany will increase renewable energy and energy efficiency with the aim to decarbonise the energy system. Households represent a third of the final energy consumption and as such have a crucial role to play by undertaking investments in the household energy infrastructure (building insulation, heating systems, and appliances). However, limited income influences how some households are able to engage with and benefit from the transforming energy system given that the majority of households lack either the sufficient disposable income to afford the high upfront costs of investments, or the decision-making power to undertake meaningful investments. At the same time, it is estimated that 11-21% of the German population already experiences energy poverty, and is on the rise. Yet the phenomenon is not recognised by the government as an issue requiring a tailored response. Current energy policy is based on modelling assessments which assume a homogenous population, which can underestimate the impact on lower income households and overestimate the possible contributions from this sector towards achieving the overall objectives of the energy transition.

This research provides an empirical basis for recognising the significance of energy poverty outside of the current “vulnerable consumers” lens and within the energy transition process. Based on the TIMES-Germany model, the TIMES-Actors-Model-Households was developed to account for the differentiated needs and capabilities of the population. The suitability of the method developed are demonstrated through several scenarios to explore issues relevant to energy vulnerable households, such as access and affordability. The results showed that disaggregation is a useful methodology to assess the differentiated energy needs of households based on socio-economic parameters, but highlighted that disaggregation alone is not enough to represent the lack of financial capacity of households. The incorporation of budget constraints is a critical methodological inclusion to assess the significance of energy poverty in the energy system. This enabled an analysis of the impacts of policies designed to support lower income households, such as investment or consumption subsidies or the effects of carbon taxes, or schemes to redistribute funding. Another result facilitated through this method is the estimation of the supressed demand experienced as a key indicator of the energy welfare of households. This methodology provides a platform to support the analysis of a differentiated policy response – effectively strengthening the opportunity to achieve the desired active participation in the energy transition and support the energy welfare of households.

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