**Master Thesis Report**
June 2019

# Towards a more interdisciplinary political framework to steer down the EU residential energy consumption

**Lukas Jack Reiner Godé**

M.Sc. Sustainable Energy Planning and Management

AALBORG UNIVERSITY
DENMARK

POTSDAM INSTITUTE FOR
CLIMATE IMPACT RESEARCH

Dept. of Planning - Aalborg University
Technical Faculty of IT and Design
Rendsburggade 14 - 9000 Aalborg, Denmark

Future Lab "Social Metabolism and Impacts"
Potsdam Institute for Climate Impact Research
Telegraphenberg A56 - 14473 Potsdam, Germany

# Abstract

The intensive use of energy in the European Union (EU) put great pressure on the „planetary boundaries“ (Rockström et al, 2009), including the impacts on climate. Supply-side efforts to develop decarbonized energy sources are critical to address anthropogenic sources of climate change, but they remain bounded to other planetary boundaries. Their use at the current level of energy use in industrial regimes may therefore not be sustainable. Demand-side efforts should therefore be strengthened. As one of the largest end-use consumption sector in the EU, residential energy consumption should be of particular concern.

In this thesis, I discuss the relevance of a more interdisciplinary political framework to cut down residential energy consumption. I review the current EU political framework on residential energy consumption management and confront it with recent critics from the scientific literature. Household size declining trends are assumed to significantly drive the residential energy demand. Therefore, I then develop an explanatory model of residential consumption to quantitatively assess the potential to cut off residential consumption by developing co-housing opportunities. With the insights of a semi-structured interview, I eventually discuss the innovative transition governance models that could address the dynamics of social practices such as household size trends steering the residential energy consumption.

Here are my main findings. The EU current approach to residential energy demand is primarily based on a two legs strategy (Labanca et Bertoldi, 2018) promoting on the one hand technical efficiency improvements and on the other hand policy instruments to change individual behaviours and incentivizing the purchase of energy-efficient appliances. Efficiency efforts should be embedded in a conservation framework if net consumption savings targets are to be set, while a social-practice based approach could enable to collectively address the structural socio-material configurations largely influencing individual behaviours. Sufficiency approaches pave the way to conceptualizing deep socio-material transitions that promote both energy conservation and well-being, such as co-housing for instance. The explanatory model enables to confirm the significant effect of household size on the residential end-use consumption per capita in the EU context. According to this model, bringing the Swedish household size national average to the level it was in 1991 – for instance through the development of co-housing options - would enable to alleviate the national residential consumption by up to 9%. As concluded from the insights of the semi-structured interview, reflexive governance processes seem to be adapted to initiate such deep social-practice transitions by emphasizing co-processes of experimenting, learning and institutionalizing.

# Acknowledgements

First of all, I deeply thank my supervisor Søren Djørup from AAU for the fruitful insights and advice he provided all along the redaction of this thesis.

I am moreover extremely grateful to my two co-supervisors from PIK for their commitment in supporting this thesis. I am especially grateful to Helga Weisz for giving me the chance to write this thesis in her ”Future Lab on Social Metabolism and Impacts”. I also deeply thank Peter-Paul Pichler for his seamless involvement in assisting my daily struggles. I hope I have been able to transcribe in this report how inspiring their rigorous, challenging and constructive supervision was to me.

My gratitude also goes to Camille Belmin and Ingram Jaccard, first of all for their precious scientific insights and advise, but also for their very meaningful friendliness and personal support.

I am more generally extremely thankful to all my colleagues of the ”Future lab: Social Metabolism and Impacts” for their careful concern to keep me integrated in all the daily activities of the department, and for making my time at PIK so enjoyable thanks to all the interesting, inspiring and entertaining moments we spent together.

Last, my deepest thoughts go to my parents and my brother whose unconditionnal support and optimism never failed. I thank them for helping me keeping faith in what I have been undertaking during all these years of study.

# Contents

# List of Tables

# List of Figures

# Chapter 1

# Introduction

In this thesis, I am interested in exploring interdisciplinary political approaches to target the absolute reduction of final energy consumption in Europe. The justification of absolute final consumption reduction targets is however not self-evident. In particular, it could be argued that decarbonized energy technologies are able to provide final energy without any significant climate impact, and would therefore avoid to address the demand.
By prefacing my work with a metabolic description of human societies, I intend to stress that the supply and consumption of energy cannot be considered separately from the way they shape societies and interplay with other non-energy material flows. In the problem analysis, I then look more specifically at the challenges that the development of decarbonized sources of energy would have to face regarding the non-energy material flows they are associated to. This brings the necessity to consider both the development of decarbonized energy supply and the reduction of the final energy demand through the restructuration of energy services until a "sustainable energy balance" (Harris et al., 2008) between demand and supply is reached.

## 1.1 Contextual background: energy regimes in the Anthropocene

### 1.1.1 A metabolic understanding of human societies

Human societies are physically anchored in their environment through their social metabolism, or the flow of materials and energy around which they are organized. The notion of metabolism comes from biology where it originally designates the action through which an organism chemically converts energy and resources to sustain itself. This notion has been more recently generalized to human societies viewed as systems interacting with the nature, i.e. the material system existing outside human societies, absorbing and releasing material and energy flows to sustain (Fischer-Kowalski and Weisz, 1999).

The global social metabolic flows remained at a tiny fraction of the overall biosphere flows for a major period of human history while hunter and gatherer societies were prevailing. In hunter-gatherer societies, these flows are largely determined by human body metabolism. A first break occurred when some societies initiated a shift from hunter-gatherer towards agrarian societies. Under such a form, human societies take an active involvement in the production of the resources they consume to sustain, especially the biological ones such as food and biomass. The energy as well as the material flow resulting from this process of *"colonization"* of natural processes are assessed to be three- to tenfold those of hunter-gatherer societies. (Fischer-Kowalski and Weisz, 1999) A second break was initiated more than two centuries ago with the development of technologies enabling to convert energy chemically stored into fossil fuels deposits of coal and later on oil in mechanical work (Court, 2018). This propelled some former agrarian societies into industrial metabolism reaching a magnitude comparable to the overall metabolic input of the biosphere (Lenton et al., 2016). In these societies, the power of steam machines and later on of combustion engines progressively substituted human power and biological energy flows, e.g. wind, for uninterrupted mechanical work, thus deeply disrupting the organization of human societies and their interactions with their environment. Originally triggered in England in the 18th century, this transition towards industrial metabolism has been eventually spreading more largely over human societies since then (Lenton et al., 2016). The importance of these flows and their interplay with other major planetary biochemical cycles led to the definition of a new geological and environmental era, the Anthropocene, an era that is dominated by human influence (Crutzen, 2002).

This is how global energy use have reached new peaks in the last decades. The International Energy Agency (IEA) accounts 9.56 Gtoe of final energy consumed globally in 2016, representing 13.76 Gtoe of primary energy (International Energy Agency, 2018b). Following this momentum, the global final energy demand reported by the IEA increased by 2.1% in 2017, the fastest annual increase since 2010 (International Energy Agency, 2018a).

This current growth is largely resulting from increasing consumption in industrializing regions (International Energy Agency, 2018a). On the other hand, a large part of the humanity still relies on low energy/metabolic flows, based on an agrarian social metabolism (Lenton et al., 2016). Steinberger and Roberts (2010) points out that at low levels of human development, moderate increase of energy use has a great positive impact on the quality of life, while this effect is much more marginal at higher level of human development. Finally, the trend is to a moderate increase and stabilization of already high energy consumption in the more longstanding industrialized regions such as in Europe (Wiedenhofer et al., 2013b).

### 1.1.2 The need to restructure the unsustainable global energy regimes

The intensive energy regimes already reached in some parts of the world and to which other countries are also aspiring to are however of serious concerns when it comes to their environmental sustainability, beginning with their impact on climate change, but also other environmental pressures.

Regarding anthropogenic climate change which is regarded as one of the most urgent issue (Rockström et al., 2009) to be tackled along with biodiversity loss and nitrogen cycle disruption in the multi-faceted environmental crisis human societies are currently entangled in, the energy sector contributed up to 76 % to the Green House Gas (GHG) globally emitted in 2016 (Gütschow et al., 2016).
The combustion of carbon based primary energy to release heat that is either directly used or transformed into more sophisticated forms (mechanical work, electricity,...) is mostly accountable for GHG emission in the energy sector. The GHG emission intensity of these processes depends much on the fuel and the technology used. A large share of the efforts to mitigate energy-related GHG emissions has been therefore devoted to restructuring the energy supply chain in order to reduce the share of fossil fuel technologies, to shift to less carbon intensive fossil fuels (e.g. from coal to natural gas technologies), and finally to optimize the conversion efficiency over the the energy supply chain and in end-use appliances (Le Quéré et al., 2019). Technical efficiency efforts along with the shift to low-carbon fossil fuels and decarbonized supply technologies were widely advocated to keep on track with the Paris Agreement on a 2.0°C (and possibly 1.5°C) carbon budget (United Nations, 2015).

In fact, energy supply is globally still strongly based on fossil fuels (coal, oil, natural gas) which accounted for 81% of the primary energy consumption in 2016 (International Energy Agency, 2018b). The use of fossil fuels in heat and electricity provision, transportation and buildings accounted for up to 54% of the Greenhouse Gas (GHG) emitted globally in 2010, supplemented by the use of fossil fuels in industrial activities and waste incineration (up to 23% of the overall GHG in 2010) (Intergovernmental Panel on Climate Change, 2014).
Within the European Union (EU), the share of fossil fuels have lowered from 82% in 1990 to 72% in 2016 although the average fossil fuel intensity of around 2.25 $ktoe_{fossilfuels} \cdot capita^{-1}$ remains much higher than the global average which was of 1.50 $ktoe_{fossilfuels} \cdot capita^{-1}$ in 2016. In the non-OECD countries, the average fossil fuel intensity was of 1.07 $ktoe_{fossilfuels} \cdot capita^{-1}$ that same year (International Energy Agency, 2018b).
Above any other political consideration, this gives an ethical necessity for the EU to strongly strengthen to promptly cut down the use of fossil fuels, especially since this carbon budget is needed in developing countries where the implementation of basic energy services potentially enable substantial increases in living conditions (Wilhite and Norgard, 2004, Steinberger and Roberts (2010)).

### 1.1.3 What balance between supply- and demand-side strategies ?

The European Union (EU) climate-related energy political agenda is currently focused on the reduction of $CO_2$ emissions. It supports the development of renewable energy technologies (supply-oriented approach) and energy efficiency (demand-oriented approach). (European Commission, 2014) This agenda is primarily driven by the two following targets to be achieved by 2030: a 32% penetration of renewables in the European electricity grid and a 32.5% improvement of the electricity system efficiency.

#### 1.1.3.1 Challenges faced by supply-side solutions

Beyond climate change impacts, the development of decarbonized sources of energy supply remains nonetheless directly bounded to potential environmental pressures on the planetary boundaries.

First of all, and in spite of being virtually carbon-free, fission-based nuclear power faces many socio-environmental challenges regarding environmental risk management, fuel extraction and waste handling. The nuclear industry has been endeavouring to tackle some of these issues, in particular those relating to operational environmental risk management, and even more especially since the accident at Fukushima in 2011 (Taebi and Mayer, 2017, Saghafi and Ghofrani (2016)). The risk of a failure cannot however be totally eliminated, and so far no process has been developed at the industrial scale to properly manage nuclear waste (Richter, 2017). Adding to this the uncertainties on the integrated cost taking waste handling and decommission into consideration, nuclear power has a generally bad reputation in many European countries (Malischek and Trüby, 2016). This is even the case in countries like France that have been historically pioneers in the development of these technologies, and which nowadays plan to reduce their reliance on nuclear power (République Française, 2015). Consequently, the support of additional nuclear power capacity is currently not addressed in any of the 8 legislative acts of the "Clean Energy for All Europeans package" presented as the long-term energy strategy of the European Union (European Commission, 2017a). Finally, even though fusion-based nuclear power technologies are advocated as a long-term solution, they will not get mature fast enough to address the issue of climate change in time, that is to say in the next decade(s) (Lenton et al., 2016).

Renewable energy technologies on the other hand, tend to get much more political support and are at the core of the European Union strategy to face climate change (European Commission, 2014). In a pure energetic perspective, these enable indeed to provide final energy either with no accountable primary energy flow (wind, solar) or with a regenerable primary energy source (biomass, water storage). The development of renewables is however challenged by an increased need for specific materials compared with traditional fuel based systems (Arrobas et al., 2017) as well as by their potential use of land space.
The extraction of raw materials for renewable energy technologies and in particular the extrac-

tion of metals is associated with severe environmental damages in terms of local air pollution, land occupation and biodiversity loss in case of open-pit extraction. There are also risks of environmental damages such as water pollution, acid mine drainage and ensuing soil pollution (Bihouix and de Guillebon, 2010). Besides these environmental considerations, these resources may be the source of some social damages, geopolitical tensions and short-term supply restriction. This is especially true in the current context of a rapidly rising demand which limits the weight of recycling potential to meet demand, and a spatial asymmetry between the regions of extraction and the region of consumption of these resources (Pitron, 2018). This reality may be worsened by the fact that these technologies are often associated with the development of decarbonized end-use technologies which potentially require themselves the same resources (Pitron, 2018). Above their problematic need for specific resources, concerns are raised regarding the physical and economic possibility for renewable energy systems to maintain the high energy flows reached in the more developed countries. Fossil fuels have proved indeed to be convenient energy carriers, with large stock available, a high energy density and immediate availability. On the other side, renewable energy technologies are based on dispersed energy carriers, which are not always available (e.g. wind, solar) or not instantaneously available (e.g. biomass). Therefore, although the implementation of renewable energy systems have already shown success on small to medium scale, the possibility of their up-scaling at the level of the current global energy demand trends should be questioned (Labanca, 2017; Hall, 2017).

Finally, Carbon Capture and Storage (CCS) technologies have been also suggested as an option to mitigate already emitted GHG (Intergovernmental Panel on Climate Change, 2014). Their implementation may however be subject to innovation failure, unacceptable investment risks, public opposition against environmental risks, or a combination thereof (Grubler et al., 2018). Erecting a climate strategy on the basis of a carbon-budget debt in the perspective that CCS technologies will be eventually scaled-up appears therefore to be a risky strategy with potentially dramatic consequences if their implementation is to fail (Lenzi et al., 2018).

#### 1.1.3.2 Supplementing supply-side efforts with a strong demand-side strategy

Different challenges to develop a decarbonized energy supply at the current levels of consumption have been highlighted in the previous paragraph. The large-scale development of decarbonized energy supply may be jeopardized by non-climate-related socio-environmental challenges. I also stressed that the demand ultimately stems from the provision of services which may themselves require resources and have therefore their own environmental footprint. Therefore, framing supply-side policies within an approach aiming first at managing the way energy is used appears therefore as a relevant if not unavoidable approach to make energy systems evolve towards bearable environmental boundaries. This observation is shared by a part of the research community, where some researcher also point out the lack of attention for the exploration of demand-oriented strategies, and the subsequent weak political consideration for it (Creutzig et al., 2018).

Harris et al. (2008) highlight however that a demand-side approach may not be satisfactory as a policy goal if it only aims at a direction with no clear target on absolute level use. They introduce therefore the concept of sustainable energy balance where energy consumption aims ultimately at being limited to what can be sustainably produced, i.e. no net greenhouse gas emissions, and does not use up finite, stored energy resources (Harris et al., 2008). This suggestion could be extended to the other non-climate related socio-environmental boundaries. There is a lack of understanding on whether satisfying living standards can be reached for all within these boundaries, given current global demographic trends (Raworth, 2017; O'Neill et al., 2018). Evidence has been nonetheless given that all the countries reaching the higher living standards including all EU countries currently carry a footprint exceeding planetary boundaries (O'Neill et al., 2018).

## 1.2 Theoretical backgrounds: energy systems and political frameworks

### 1.2.1 A socio-technical understanding of energy systems

Approaching societies through a social-metabolism understanding enables to clarify the material embedding of human societies in their environment, as highlighted above. The concept of socio-technical system enables us to approach more specifically the dual socio-material reality of energy systems.

The path taken by energy flows in energy systems can be schematically described in four main stages as illustrated in Figure 1.1: an energy source is captured [a], before to be converted into a suitable form [b], then distributed [c] and finally converted into useful energy through an end-use device [d] with the aim of delivering a specific service [e]. Steps [a], [b] and [c] are usually referred to as the "supply side" of the energy system while steps [d] and [e] belong to the "demand side". While steps [a] to [c] can be considered as "active" processes of conversion, end-use devices are most often passive systems. This means that the conversion process is the exclusive result of the passive reaction of the end-use device to the final energy input without any other stimulation input.

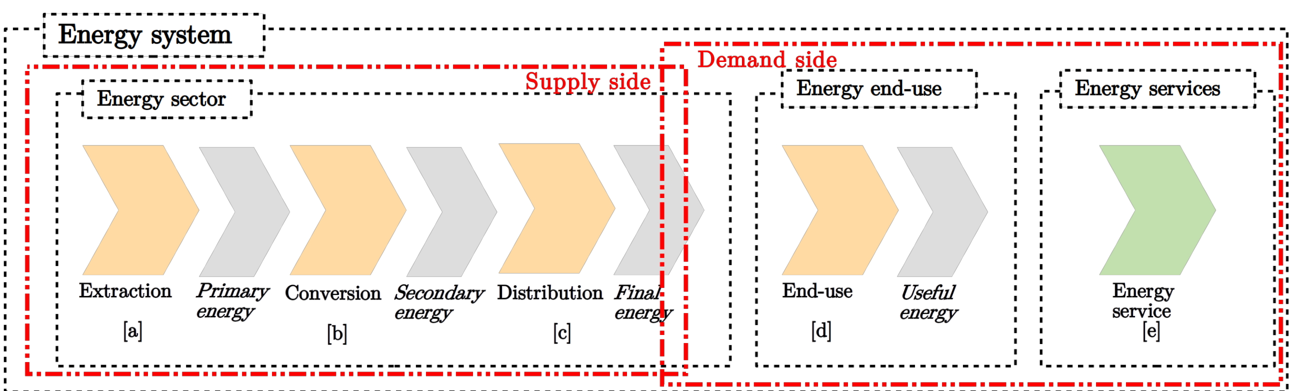



Figure 1.1: Description of an energy system, inspired from IIASA (2012) (Figure TS-8)

Moreover, the inclusion of energy services in this chain highlights that the use of energy does not serve a purpose per se, but is rather a physical carrier used to deliver services that meet some human demands (Brand-Correa and Steinberger, 2017): energy services [e] are the ultimate reason for an energy system to exist and steers the need for useful, final and primary energy. Labanca and Bertoldi (2018) argue that these consumption dynamics should be approached as "emergent qualities" of complex socio-technical systems embedding social norms, cultural meanings, the influence of infrastructures and market configurations beyond the power of the sole individual's supposedly rational choice. The behavioural trends arising from the influence of this socio-material structural context will be later on refer to as "social practices".

Energy systems therefore emerge as hybrid socio-technical systems in which the social realities (skills, cultural perceptions, knowledge, institutions, social practices,...) shape the material configurations of energy infrastructures and the demand for energy services. On the other side, material configurations retroactively influence social norms, cultural meanings and individual perceptions.

### 1.2.2 Interdisciplinary political frameworks in energy demand policies

In this section, I clarify the theoretical approach to interdisciplinary political frameworks relating to energy demand policies considered in this thesis.

#### 1.2.2.1 A conceptual understanding of political frameworks

In this thesis, I inspire my understanding of political frameworks from to description of policy arrangements developed in Arts and Tatenhove (2000). Policy arrangements relate to the organizational and rhetoric settings shaping a policy domain at a certain moment in time (Arts and Tatenhove, 2000). According to Liefferink (2006), such settings can be expressed through four intermingled dimensions, namely:

- the *"actors"*, and coalition of actors that are involved in the policy domain studied.
- the *"rules of the game"*, including the formal and informal regulations influencing the policy domain studied.
- the *"resources and power"*, and more specifically the distribution of resources (material and human capital, knowledge,...) shaping the approach to the policy domain studied, and the power on different aspects of this domain emerging from resource distribution configurations.
- the *"discourses"* of the actors involved in the policy domain studied, expressing their understanding and their narrative of the policy domain studied.

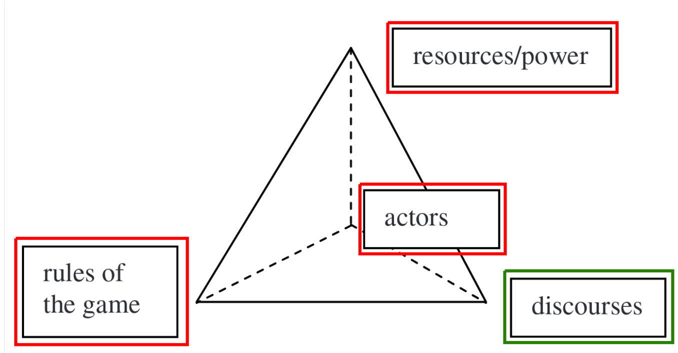



Figure 1.2: The four dimensions of political arrangement. Source: Liefferink (2006) (I added the red and green frames)

These four dimensions of policy arrangement interplay together as their representation in a tetrahedron shape taken from Liefferink (2006) suggest it (Figure 1.2). Red and green frames were added to highlight the respective organizational and rhetoric nature of the four different dimensions.

#### 1.2.2.2 A interdisciplinary approach to energy demand solutions

Wilhite and Norgard (2004) suggested already in 2004 a shift in the political and research agenda towards services in the focus of the energy demand research and political frameworks. This would consist in addressing the purposes of energy consumption prior to investigating how technologies, infrastructure and social arrangements can be best combined to serve these purposes. Such a shift would require to broaden the traditional techno-economic approach to demand-side management and bring together insights from psychology and behavioural economics, sociology, anthropology, economics and engineering (Creutzig et al., 2018). Investigating what structurally drives the need for specific energy-services opens up to much more ambitious targets, especially considering the relevance to decrease the demand for climate change mitigation and sustainable transitions. It also places the contribution of energy services to well-being at the core of the attention (Brand-Correa et al., 2018). Such an approach was for instance advocated in the 1990s in Germany in transport policies, with the development avoid-shift-improve framework: the priority is first given to avoiding “unnecessary” mobility (through for instance spatial planning or teleworking), then to shifting to the least carbon-intensive means of transport (such as biking), and ultimately improving vehicles to be more energy efficient and less carbon intensive (Creutzig et al., 2018).
Creutzig et al. (2018) stress the excessive focus on techno-economic frameworks in the energy studies informing policies of the Intergovernmental Panel on Climate Change (IPCC), where demand-side solutions had been essentially tackled through improved end-use efficiency management suggestions, and without clearly specifying the potential of demand-side solutions to mitigate climate change and their interplay with lifestyle, social norms and well being. This

will change in the upcoming sixth assessment report AR6 to be published in 2021 (Intergovernmental Panel on Climate Change, 2019), which will include for the first time a chapter on "demand, services and social aspects of mitigation" (Creutzig et al., 2018). The potential of demand-side solutions with a primary focus on services was also recently explored in the Low Energy Demand scenario developed by Grubler et al. (2018).

#### 1.2.2.3 Interdisciplinary political framework for energy demand policies

Based on the conceptual understanding of political frameworks taken from Arts and Tatenhove (2000) and Liefferink (2006) as well as on the suggestion for a interdisciplinary approach to energy-demand solutions developed in Creutzig et al. (2018), I suggest a theoretical approach on interdisciplinary political framework for energy demand policies in Figure 1.3.

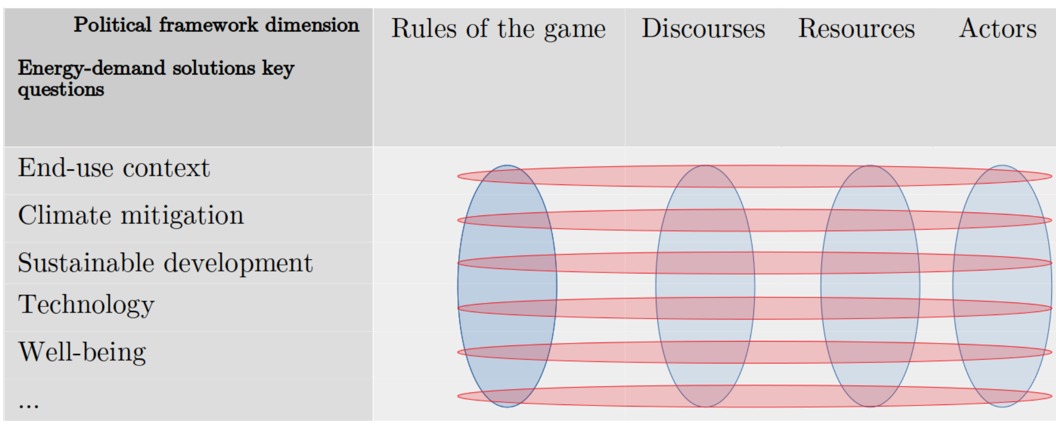



Figure 1.3: Interdisciplinary political theoretical framework for energy demand policies

In this interdisciplinary political framework, each of the four dimensions of political frameworks on energy-demand policies integrate the different key questions on energy-demand solutions identified. In the same way as the different political framework dimensions interplay together, the different approaches to energy-demand solutions are not compartmentalized disciplines, and must be considered in a holistic approach. The interplay between the dimensions of the political framework and the disciplines are highlighted respectively by blue and red circles on Figure 1.3.

## 1.3 Problem analysis: addressing the EU high residential energy consumption

Overall, buildings operational use represented 40% of the global energy consumption in 2015 (Nejat et al., 2015). Nejat et al. (2015) report that about three-quarters of the building final consumption relates to residential consumption. These patterns are in line with the trends observed in 2007 within the European Union, where the building sector accounted for 34% of the total final energy demand, of which 68% in residential buildings (Ürge-Vorsatz et al., 2012). Besides this, housing was identified as one of the highest contributors to the household carbon footprint in the EU, along with mobility (Ivanova et al., 2017). Residential consumption appears therefore as one of the priority sector to be tackled by conservation policies.

### 1.3.1 Residential consumption patterns in the EU

Figure 1.4 illustrates the final energy consumption per capita and its breakdown for different countries of the EU. Space heating represented the biggest share of the final energy consumption in 2016 (64.7% in average), then mainly followed by water heating and the use of lighting and appliances. The proportion of energy used for space heating differs broadly across the Union, although it remains the largest consumption category in most countries apart from Malta and Portugal where climatic factors may explain the lower share. While space cooling represents only a small fraction of the EU overall consumption, the use or not of space cooling influences heavily the consumption at the household level. Consumption patterns are relatively homogeneous for a group of about 13 countries (from Lithuania with $500kg_{oil.equivalent} \cdot capita^{-1}$ to Germany with $681kg_{oil.equivalent} \cdot capita^{-1}$). Large disparities remain however between the lower and the higher range, with countries such as Malta, Portugal or Bulgaria on the one side and Denmark, Luxembourg or Finland on the other.

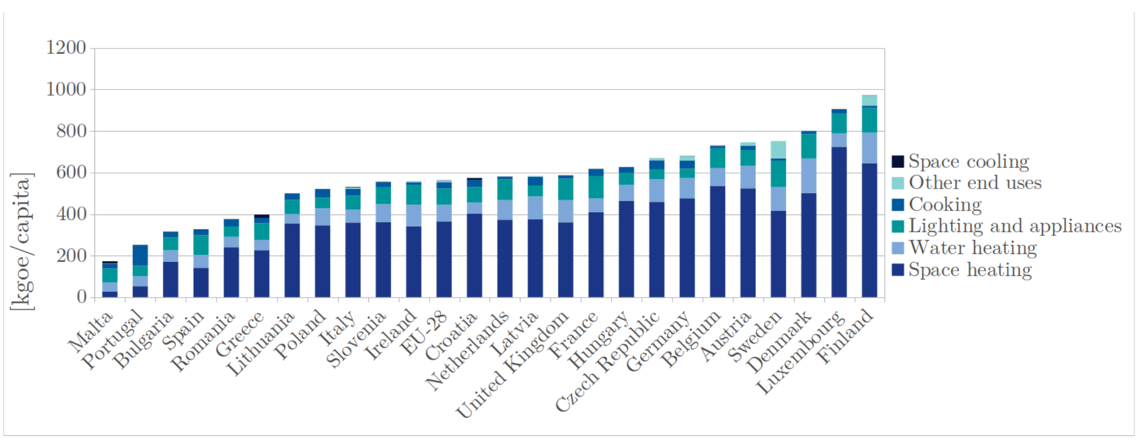



Figure 1.4: Residential final energy consumption per capita in the EU-28 in 2016, data from **?**

### 1.3.2 The drivers of residential consumption

Looking at settlement characteristics, socio-economic, climatic and urban-form configurations were identified to drive energy consumption and related GHG emissions(Baiocchi et al., 2015). Among them, population densification going along with compacter housing was found to have a significant impact on residential consumption (Wiedenhofer et al., 2013a; Baiocchi et al., 2015; Otsuka, 2018; Silva et al., 2018).
Looking at electricity consumption and its main socio-economic, dwelling and appliance drivers, a review confirms the unambiguous significant increasing effect on electricity use of 20 different drivers (Jones et al., 2015): 9 of these factors can be attributed to appliances and relate to the ownership, the use and the power demand of these appliances. 4 factors relate to the household socio-economic situation, namely the number of occupants, the presence of teenagers or not, the household income and the disposable income. Finally, 7 of these determinants relate to the dwelling characteristics: dwelling age, number of rooms, number of bedrooms, total floor area, presence or not of electric space heating, air-conditioning or electric water heating.
Regarding thermal consumption, e.g. space and water heating, influential consumption drivers identified relate to the outdoor temperature, the fuel prices, the household income, the number of occupants per household (household size), the floor space per capita and the building thermal performances (Fazeli et al., 2016; Serrano et al., 2016; Røpke and Jensen, 2018). Floor area per capita is itself significantly correlated with the number of occupants per household, with more number number of occupants per household tending to lead to smaller floor areas per capita, as highlighted in the US context by Moura et al. (2015).
Finally, the overall final energy consumption is assumed to have been mainly driven in the last years by the trends in decreasing in household size, growing affluence, increasing indoor space per capita, increasing thermal level comfort, as well as increasing levels of electricity-provided services (in particular IT) and increasing amount of time spent using these services (Urge-Vosatz et al., 2013; Enerdata, 2018). In this thesis, we consider more carefully the effect of the five following socio-material factors that are usually acknowledged to affect household energy consumption: the heating degree days, the household income, the household size, the floor area per capita, and the fuel prices.

### 1.3.3 Household size dynamics and their effects on residential consumption

According to the observations of Bradbury et al. (2014), the number of households has been continuously growing faster than the population size in most part of the worlds since the seventeenth century. These trends are correlated with urbanization and industrialization dynamics and may be driven by several parallel socio-cultural evolutions including declining fertility rate, an increasing aspiration for privacy and independence, women empowerment, increasing divorce rates and aging population (Bradbury et al., 2014). 1.5 illustrates how the trend is globally still to the decrease in all of the countries of the European Union (EU). The household size, or the number of inhabitant in a same household, was on average of 2.3 capita in 2017 in the EU. In 2017, the smallest average household size in the EU was reached in Sweden, with 1.9 capita/household.

Some studies identified a direct relation between household size and per capita environmental impacts (Bradbury et al., 2014), in particular with per capita direct/indirect energy consumption and carbon emissions (Underwood and Zahran, 2015). In particular, it was observed that part of the household footprint is either rather independent of the household size (e.g. the number of large appliances like washing machine for instance) or are not linearly correlated with the household size (e.g. floor area and ensuing heating or lighting) (Bradbury et al., 2014). According to Bradbury et al. (2014), these economies of scale are due to the sharing of part of the goods and services within households. Therefore, tackling the declining household size may have a significant positive impact on residential environmental footprint, including residential energy consumption.

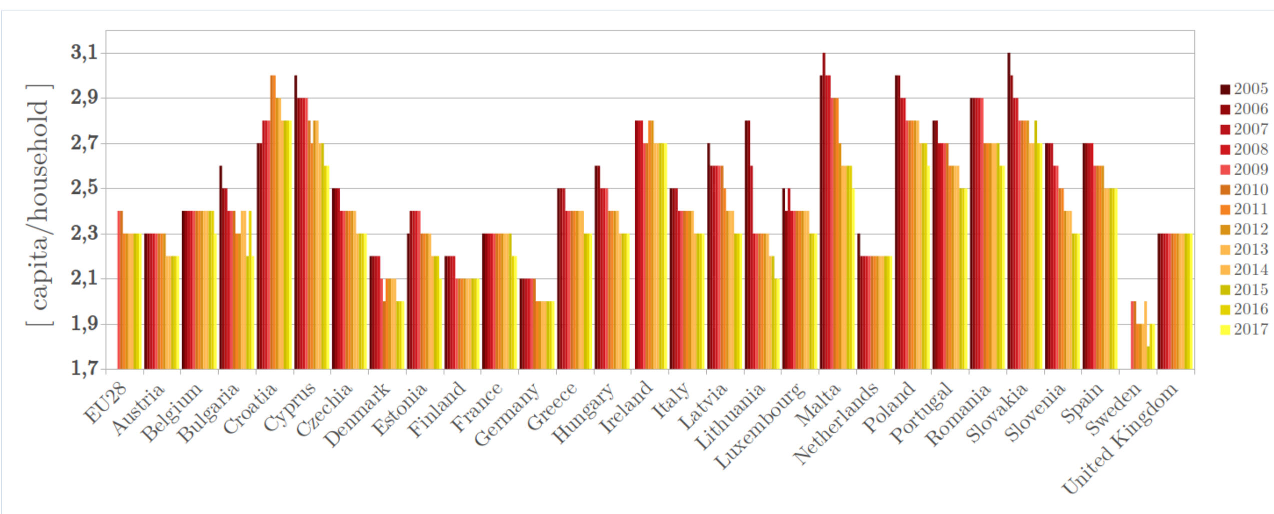



Figure 1.5: 2005-2017 evolution of the average household size in the EU-28, sourced from Enerdata (2018)

Based on an econometric model realized with households expenditures data between 1996 and 2009 in the United States of America, Underwood and Zahran (2015) argue that the direct carbon footprint of a person sharing a household drops by 23% as compared with the same person living alone. Still in the US context, Fremstad et al. (2018) appraise that each additional member to a household entails a drop of about 6% in the per capita emissions. Moreover, household size is also negatively correlated with floor space per capita which also significantly drives residential consumption as we noticed in the previous paragraph. **?** therefore observed in the US-context that in average, co-housing lead to reduce the average space per capita by 31% in comparison with conventional housing.

The concept of collective housing (or co-housing) refers in this thesis to all types of housing in which a part of the housing space and functionalities are shared between two or more dwellers. It includes broader dwellers constellations than just the family-based traditional ones. Collaborative lifestyles are embedded in the concept of co-housing although great flexibility in the housing design and co-housing governance enables different levels of housemates' independence (Williams, 2005).

# Chapter 2

# Problem statement and research design

## 2.1 Research questions

I highlighted that supply-side efforts to decarbonize energy systems should be framed into an overall strategy prioritizing demand-side solutions. For that, taking a service-oriented approach considering the wide range of consumption drivers including those relating to social practices may enable more ambitious targets for the reduction of the consumption while enhancing considerations for well-being. It would however require a large interdisciplinary approach to the understanding of energy services. As one of the largest end-use consumption sector in the European Union (EU), residential buildings are a privileged field of investigation for service-oriented policies. This first analysis brings us therefore to the following research question:

**How can the current political framework on residential energy demand in the EU benefit from more interdisciplinary insights to address net savings ambitions?**

Among the drivers of residential consumption described in the literature, declining household size trends were found to play a significant role in the residential consumption per capita and may be relevant to consider for handling comprehensively the potential to address residential consumption while enhancing well-being. Handling social-practices changes can however be challenging, and innovations may be needed in the current political framework as well as in the governance of transition processes. The two following supplementary sub-questions will therefore address these more specific concerns:

- *What empirical justification is there on the relevance to consider household size in an interdisciplinary political framework on residential consumption?*
- *What model of transition governance can enable to address social practice dynamics shaping residential energy demand such as household size?*

Addressing these two sub-questions will provide some specific insights to the main research question, which will then be synthesized in the conclusion.

## 2.2 Analysis structure

To answer these questions, my analysis follows the following overarching structure:

- I first get some general insights to the main question by reviewing the current EU legislative framework on residential consumption management, and the paradigms and discourse in which this legislative framework is embedded. This analysis is guided by the theoretical insights on interdisciplinary political framework. Taking a socio-technical approach to energy systems, I also consider the way the current EU legislative framework considers social configurations and practices steering consumption behaviours. I then confront these results with views from the scientific literature on the ability of such a framework to achieve absolute consumption decrease.

- Addressing the first sub-question, I then empirically emphasize the relevance to integrate social practice considerations in a political framework on residential consumption. To that end, I showcase the quantitative potentials that intervening on declining household size trends would have on residential energy consumption in Sweden. I first develop an explanatory model of the residential consumption per capita in Swedish one- and two-dwelling buildings using cross-sectional data at the aggregated municipal level. This model enables to characterize the sensitivity of residential consumption to its five structural socio-technical drivers previously identified, in particular household size. I then use the outcomes of the explanatory model to showcase the quantitative savings that would result from handling household size currently declining trends. In particular, I emphasize the potential of promoting co-housing among people living currently alone in Sweden.

- Having established the relevance to consider social practices in residential energy demand policies, I eventually address the second sub-question and investigate a governance model that could effectively implement social practices transitions. To this end, I analyze the outcomes of a semi-structured interview realized with an expert on planning and socio-technical transition issues. These outcomes provide some hints on the application of reflexive governance and transition management theories to address the social practices such as household size trends in which residential consumption is embedded. This interview takes a socio-technical approach to energy systems as the one described in the theoretical background.

Figure 4.1 is a graphical summary of the research strategy and methods used in this thesis.

| **Analysis** | 1. EU current framework on residential consumption | 2. Relevance to consider household size trends in residential consumption management policies | 3. Suggesting the integration of innovative methods to address structural drivers of residential consumption |
|---|---|---|---|
| **Scope** | - EU legislative framework<br>- Discourse analysis | - Study case : end use consumption in Swedish one- and two-dwelling buildings | - Reflexive governance<br>- Transition management |
| **Method** | - Policy review<br>- Literature review | - Explanatory multi-variate linear regression using cross-sectionnal data<br>- Static models of the effect of household size on residential consumption | - Semi-structured interview |

Figure 2.1: Graphical summary of the methods used

The methods used are detailed at the beginning of each analysis.

## 2.3 Delimitations of the analysis

- The EU political framework on residential energy consumption is analysed on the basis of the theoretical background on interdisciplinary political frameworks developed in Section 1.2.2. In this thesis, I focus is on legislative aspects and some discourse elements. The review of the legislative framework is here limited to the regulations to be found in the section "Energy/Energy efficiency" of the European Commission website. As Royston et al. (2018) notice, a much larger corpus of "non-related" policies do impact energy demand, including in the residential sector, although these are not investigated here.
- The empirical analysis on the relevance to consider household size in an interdisciplinary political framework on residential consumption is limited to a showcase.
  The choice of the showcase was guided by the availability of data : data on household residential energy consumption and its main drivers of consumption had to be publicly available for a sample large enough to develop a statistical explanatory model of consumption. Mandatory explanatory variables were selected according to the review of the main structural drivers of residential consumption highlighted in Section 1.3.1, namely the heating degree days, the household income, the household size, the floor area, and the fuel prices. Such data is arduous to find at the disaggregated household level on public databases, especially due to data privacy matters. Because of time and means limitations, relevant access-restricted databases potentially providing data at the household level could not be considered. A good compromise between relevance and availability of the data was found in the database of the Swedish statistical government agency Statistics Sweden (SCB).

Besides these practical concerns, Sweden proves to be a relevant study case in the European context for investigating the role of household size in steering residential consumption:

  – First of all, the average *per capita* final residential consumption in Sweden was one of the highest in the EU-28 in 2016: 752 $kg_{oilequivalent}$ per capita versus 563 $kg_{oilequivalent}$ per capita on average in the EU-28 (**?**). Therefore, taking an environmental justice approach where resources should be ideally distributed equally among countries (O'Neill et al., 2018) Sweden should be in the front line of the European countries to emphasize efforts for reducing residential consumption, even if climatic factors also partly explained increased needs for heating and lighting..
  – It was moreover highlighted in Section 1.3.1 that in average, Sweden had the lowest average household size rate in Europe in 2017, with an average 1.9 capita per household. This makes of Sweden a relevant field where to study the potential effect of steering up household size towards more standards levels.

- Only residential consumption in one- and two-dwelling buildings (small houses) was considered in the explanatory model, excluding apartment blocks from our study. This was mainly guided by time limitations, although extending this study to apartment blocks would enable to get a more thorough understanding of the different dynamics in these two types of housing.

- As Rickwood (2009) notices, investigating residential consumption drivers does not bring any informing tool for planners and policy making if they do not target more specifically the independent effect of the drivers within a well identified demographic group. According to Rickwood (2009), a typical planning-oriented approach would be for instance to investigate "the effect of moving the same household to a different dwelling" (Rickwood, 2009). Therefore and as a showcase, I investigate the quantitative energy savings that would theoretically result from the Swedish population currently living alone moving to a 3-person. The selection of this showcase is arbitrary. This showcase was retained mainly because it could be developed with the outcomes to the explanatory model: the household size mostly ranges from 1.3 to 3.7 in the dataset used (see appendix 7.1).

- Finally, reviewing the potential overall socio-environmental net benefits of co-housing would probably reinforce the attractiveness of these options, although it is out of the scope of this study. In fact, co-housing potentially entails overall positive environmental impacts since it enables to share part of the irreducible environmental footprint between the co-inhabitants and enable more compact forms of housing (Bradbury et al., 2014). Beyond direct energy consumption reduction, co-housing can potentially participate in reducing the use of land, building embedded energy and resource consumption (Williams, 2005). Williams (2005) also argues that co-housing is associated with higher collaboration, mutual assistance and co-learning that foster both positive social practices transitions and an eudaimonic achievement of well-being (Brand-Correa and Steinberger, 2017).

# Chapter 3

# The EU framework on residential energy demand

## 3.1 Methods: policy and literature review

The legislative elements and the overall discourse and strategy in which they are embedded are first reviewed and then confronted to criticism from the scientific literature. An iterative research design was used, based on identifying a first set of research papers over scientific journal databases, then expanded by the mean of backward citation tracking (Wohlin, 2014). A particular attention was given to scientific reviews, in order to minimize the bias on the diversity of perspectives to be found in the literature.
One step forward would have been to take a systematic approach to this review (Berrang-Ford et al., 2015) in order to make the review process explicitly outlined and reproducible.

## 3.2 Current approach to residential energy demand in the EU

At the EU level, the agenda on energy consumption management is justified by the Union as a mean to address "challenges resulting from increased dependence on energy imports and scarce energy resources, and the need to limit climate change and to overcome the economic crisis" (European Commission, 2012). Labanca and Bertoldi (2018) argue that energy consumption has been so far primarily tackled through a "two-legs" techno-behavioural strategy. The technical leg relates to fostering technical performances of both active (home appliances) or passive (house thermal envelope) demand-side infrastructures. The behavioural leg refers to the policy instruments developed by the EU to change individual behaviours avoiding end-use consumption waste, as well as incentivising the purchase of energy-efficient appliances (Labanca and Bertoldi, 2018).

In the EU legislation , residential building consumption is addressed by the *Energy Performance on Buildings Directive* (EPBD) (European Commission, 2010) which requires the Member States (MS) to:

- Meet a nearly zero-energy building[1] standard expressed in terms of specific primary energy use (kWh/m$^2$) for any new construction from 2020.
- Set cost-optimal minimum energy performance requirements for new buildings and the renovation of existing buildings.
- Develop financial schemes to support energy efficiency in the buildings.
- Develop inspection schemes for heating and air conditioning systems.
- Implement *Energy Performance Certificates* to be issued for any building or building unit being constructed, sold or rented out. These certificates shall also include specific recommendations for improving the building performance.

Besides the EPBD, the *Eco-design Directive* (European Commission, 2009) and the *Energy Labelling framework Regulation* (European Commission, 2017b) tackle appliance-related consumption (lamps, ICT, electronics, residential appliances): the Eco-design Directive provides a framework to set energy efficiency standards whereas the Energy Labelling framework Regulation aims at fostering the purchase of certified "efficient" products by clearer information on energy performances.

Finally, the Energy Efficiency Directive (EED) voted in 2012 (European Commission, 2012) and amended in 2016 (European Commission, 2016) has been also acting as a structuring framework by requiring the Member States to design the policies that would enable to achieve a 32.5% efficiency target in comparison with a "business as usual" projected consumption. For the residential sector, the EED requires the Member States to include long term renovation schemes in their *"National Energy Efficiency Action Plan"*, a document which reports how the different MS pledge to translate the overarching 32.5% efficiency target into concrete policies.

While the four first items of the EPBD described above, the Eco-design Directive and the EED relate mainly to the efficiency strategy leg described above, the last item of the EPBD and the Energy Labelling framework Regulation relate to the individual behaviour one.

## 3.3 Challenges of the current EU efficiency strategy

It was highlighted that the technical efforts of the EU legislation on residential (and other) energy demand management are primarily driven by an efficiency strategy. Such a strategy aims at optimizing all of the intermediate conversion ratios between primary and useful energy through technical improvements processes on the supply-side and the demand-side (European Commission, 2012, European Commission (2018)). Overall, energy efficiency efforts consist in

[1] Nearly zero-energy building: *"a building that has a very high energy performance"*, the exact methodology of performance calculation being left up to the MS (European Commission, 2010).

minimizing as much as possible the energy intensity needed to provide an energy-related service, considering that the service to be provided is an exogenous factor (Labanca and Bertoldi, 2018). It can be differentiated with conservation efforts whose primary target relate to absolute savings (Edelstein and Shriberg, 2011).

An efficiency discourse is more consensual than a conservation one since it does not raise any debate on the purposes of energy use. Labanca and Bertoldi (2018) argues that it discharges public institutions to handle a collective management of the demand, leaving it rather up to the individuals, in line with the liberal approach to private and economic activities prevailing in the European Union.

However, this approach has been raising some objections coming to its ability to effectively address ambitious climate and/or energy consumption targets. It was indeed observed that focusing on improving technological efficiency does not guarantee proportional consumption gains, or even a decrease at all: while efficiency measures do have a direct impact on the energy needed to deliver a given service, they are at the same time also acknowledged to have subsequent and potentially significant impacts on the nature and the quantity of energy-related services delivered (Arrobbio and Padovan, 2018). New services represent additional consumption, as efficiently as they may be delivered, and whatever their net contribution to well-being is (Bertoldi, 2017). As the name of the "Green Paper on Energy Efficiency or Doing More With Less" released by the European Commission in 2005 (European Commission, 2005) suggests, net decrease targets are not at the centre of the discourse of the EU on energy demand management. In consequence, energy efficiency may actually trigger additional energy consumption rather than enabling absolute savings, and can alone therefore not be considered as a tool to manage absolute consumption (Bertoldi, 2017). This is how in the building sector, the current intensive performances standards (e.g. given in $kWh/m^2$ for space heating) do not guarantee overall improved performances (e.g. two houses with similar $kWh/m^2$ performances but different sizes). Efficiency efforts may even foster increased consumption because they potentially support products with at the same time a higher intensive performance (e.g. a fridge with high kWh/L performance) and an overall higher consumption (e.g. bigger fridges) (Wilhite and Norgard, 2004).

In the EU legislation, efficiency achievements are calculated on the basis of the difference between absolute (primary or final) consumption and the consumption that had been forecasted in business-as-usual scenario with no particular political intervention (European Commission, 2012). This is how, the efforts of the EU are deemed to have enabled up to 101Mtoe virtual savings[2] from 2000 to 2016, while the annual net final energy demand has only decreased by 6Mtoe, as Figure 3.1 illustrates.

[2]Virtual savings are the savings calculated in comparison with what the demand would have been without these efforts. They are calculated on the basis of the basis of historical demand dynamic trends.

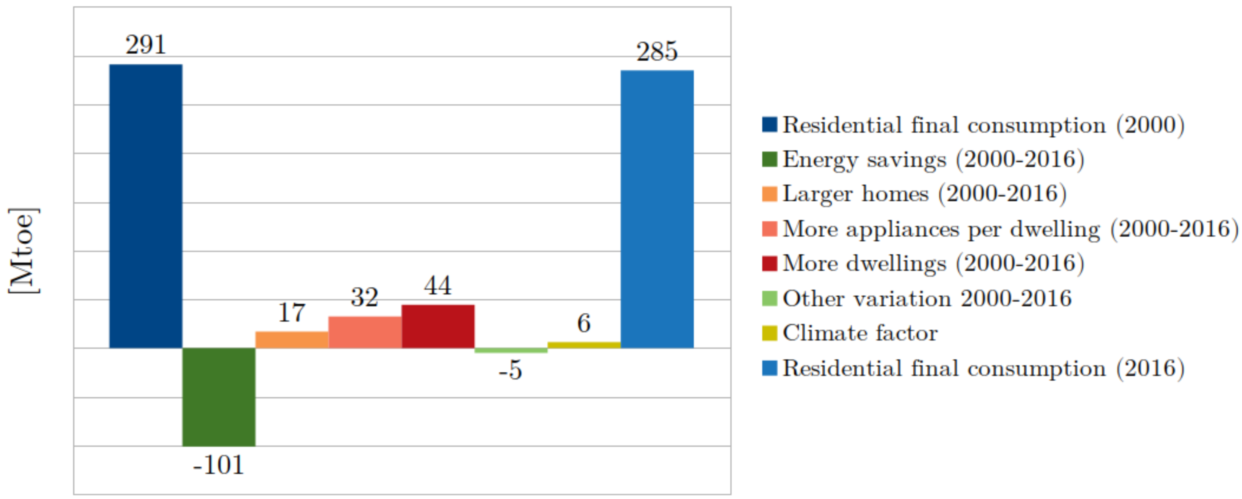



Figure 3.1: Variation households consumption - European Union - Mtoe (2000-2016), sourced from Enerdata (2018)

According to prevailing economic analysis, Bertoldi (2017) suggests the following categorization of demand pattern evolution dynamics counteracting efficiency efforts, which are usually grouped under the "rebound effects" term:

- Direct rebound effect: a drop in the price of an energy-related service due to efficiency gains encourages an increased use of this service until a certain saturation level.
  - *e.g.: the size of fridges and TV increased along with efficiency improvements in the EU. Distance travelled by car is correlated to travel cost, and therefore to its efficiency.*
- Income effect on other goods: monetary savings from efficiency improvements can be invested in new energy-related services.
  - *e.g.: savings from house insulation can be spent in a plane trip for holidays.*
- Energy price feedbacks: structural efficiency improvements could lead in a first time to lower fuel prices and therefore potentially to an increase in consumption.
- Long-run effects on productivity, consumer tastes and economic structures: gains recovered by efficiency improvements affect people's long term standards of living and social organization patterns.
  - *e.g.: more fuel-efficient cars can influence people's choice to live further from their working place.*

The magnitude of the different rebound effects is still not well understood and is complex to assess because they can be of very different nature and involve a wide range of socio-economic influences (Maxwell and McAndrew, 2011; Bertoldi, 2017). This may partly explain why rebound effects are only rarely taken into account in key energy studies informing policies and political agendas (Maxwell and McAndrew, 2011). Although there has been investigation on the magnitude of direct rebound effect and the income effect on other goods, estimations vary in a wide range for the different energy use considered. It was however observed that the additional consumption attributed to these two effects remain well below 100% of the savings made, with most common values around 10-50%. No estimation of energy-price feedbacks and long-run effects on structures had been done so far in 2017 according to Bertoldi (2017), though their impact may be significant.

The existence of these feedback dynamics is now acknowledged by the scientific community (Arrobbio and Padovan, 2018). However, the issue was still absent from the EU energy management agenda and current political framework in 2011 as warned in a report commissioned by the Directorate General (DG) Environment (Maxwell and McAndrew, 2011). That the same year, the existence of rebound effects were mentioned for the first time in an official communication from the European Commission (Arrobbio and Padovan, 2018; European Commission, 2011). The advisory European Environment Agency (EEA) of the EU also identified in 2015 the necessity to consider rebound effects in the management of resources and energy (European Environment Agency, 2015).

## 3.4 Potentials of social practices and sufficiency approaches

On top of rebound effect potential complications, there is moreover suspicion that energy efficiency efforts alone cannot be fast and substantial enough to meet sufficient GHG emission reduction targets within 2050 if services and demand patterns are not dealt along (Bjørn et al., 2018).

Besides efforts to improve residential technical energy efficiency, behaviour is acknowledged to have a potential substantial influence on residential consumption (Ürge-Vorsatz et al., 2012). Ürge-Vorsatz et al. (2012) mention a study realized by the Business Council for Sustainable Development/Energy Efficiency in Buildings which concludes that residential consumption can be reduced by 30% through behavioural changes and without any investment, while on the other side “misbehaviours” can increase the consumption by up to 60%. Therefore, individual behaviours do have a potential great impact on consumption levels.

Current energy behaviour oriented policies have been however criticized for their underlying premise that the responsibility for global energy consumption dynamics lies within individuals, and that those behaviours can be influenced by exogenous levers (Labanca and Bertoldi, 2018; Royston et al., 2018). On the other side, it is advocated that these consumption dynamics should be approached as “emergent qualities” of complex socio-technical systems also embedding social norms, cultural meanings, the influence of infrastructures and market configurations beyond the power of the sole individual supposedly rational choice (Labanca and Bertoldi, 2018). Royston et al. (2018) argue that by shaping infrastructural and technological configurations as well as collective social conventions (or “social practices”), many non-energy policies have a decisive influence on energy demand consumption patterns, which are yet often insufficiently considered - if only considered at all - in mainstream energy policies.

Gaining currently momentum in the scientific debate (Thomas et al., 2017; Toulouse and Gorge, 2017; Potocnik et al., 2018), the concept of sufficiency develops a synthetic approach gathering both socio- and technical considerations on energy consumption management. Just as with conservation approaches, sufficiency focuses on absolute consumption management through both quantitative and qualitative shifts in energy services. Sufficiency can be differentiated from conservation approaches by the emphasis given to well-being (Steinberger and Roberts, 2010; Spengler, 2016). In the area of household consumption management, sufficiency proponents suggest to question the socio-material configurations in which energy consumption behaviours are embedded (Spangenberg and Lorek, 2019), for instance by addressing the increasing living area per capita (Røpke and Jensen, 2018; Lorek and Spangenberg, 2019). In order to supplement current efficiency efforts on technological innovations, Harris et al. (2008) also suggest to implement progressive efficiency and/or absolute performance standards. Progressive efficiency standards would set higher performance requirements for larger appliances to counteract the natural increasing efficiency of certain appliances with their level of use / size (such as TVs or refrigerators) (Harris et al., 2008). On the other side, absolute performance standards would set absolute metrics (e.g from $kWh/m^2$ to $kWh/capita$ for thermal performances) standards in place of the current specific performance standards used in the EU (Wilhite and Norgard, 2004; Harris et al., 2008).

However as Spangenberg and Lorek (2019) notices, the concept of sufficiency has been emerging from many different fields of research (climate science and ecology, sustainable consumption, energy economics, ecological and behavioural economics, happiness research, philosophy, ...) and lacks for now a institutionalized definition.

## 3.5 Key results and discussion

The EU political framework on residential energy consumption is currently restricted to a dual strategy addressing technical efficiency and changes in individual behaviours. The legislation on technical efficiency strategy promotes intensive performance standards along the energy supply chain and in the end-use systems. The behaviour strategy currently promotes the prevention of end-use consumption waste and fosters the purchase of energy-efficient equipment. This current framework is summarized in black in Figure 3.2. In spite of their necessary contribution to achieve consumption net decrease ambitions, efficiency targets do not address *per se* net decreases of the final consumption, and let alone, may even impede it. In fact, the current discourse of the EU on energy demand does not promote net savings. On the other side, it was noticed that individual behaviours are largely influenced by the intermingled socio-material configuration context in which they are embedded. There is therefore improvement potentials to broaden the current political framework towards more interdisciplinarity.

I suggest in red in Figure 3.2 that efficiency efforts could be embedded into a conservation frame that would enable to redirect efficiency efforts towards the effective limitation of residential energy demand. This could be concretely achieved through the establishment of progressive or absolute performance standards in addition or in place of the current intensive ones. Also suggested in red in Figure 3.2, embedding efforts to promote changes in individual behaviours into a social-practice-based understanding of these behaviours appears therefore as a basic conditions to address the structural socio-material drivers influencing behaviours in the daily life on energy demand.

Finally, the efforts addressing both the social and the technical potential to address residential energy consumption could be framed into a sufficiency strategy which sets an overarching course towards conservation and well-being goals.

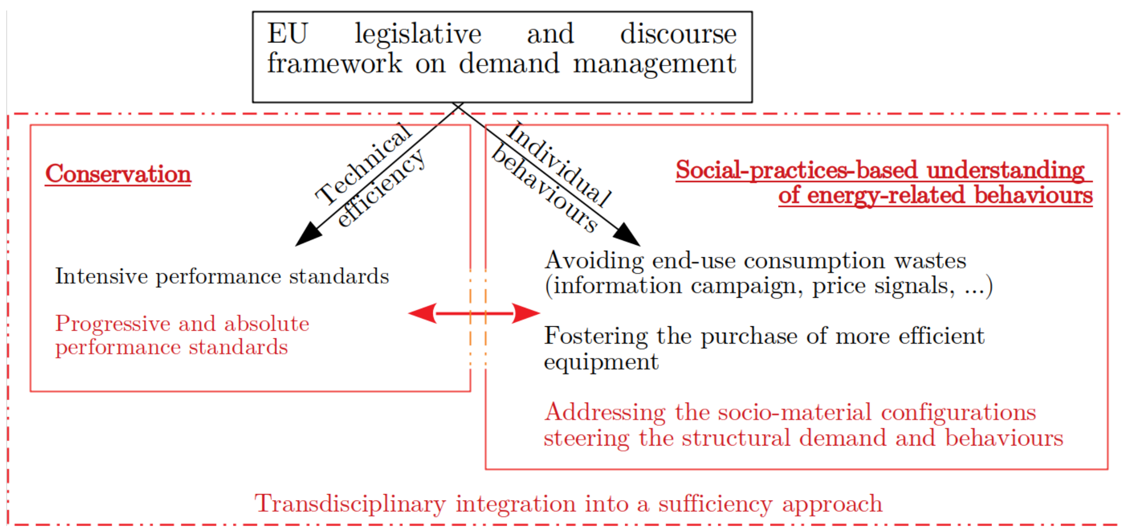



Figure 3.2: Suggestions (in red) to broaden the current EU political framework on residential demand management (in black)

# Chapter 4

# Co-housing options to limit residential consumption

I previously pointed out that broadening the current EU political framework on residential energy consumption to insights from social practices theories would support an effective management of residential energy consumption. Household size was also previously identified as one of the main social drivers of consumption per capita. In this analysis, I therefore showcase the quantitative savings that steering up household size trends could possibly entail, looking at the residential consumption in Sweden.

## 4.1 Methods

### 4.1.1 Cross-sectional explanatory model of residential consumption in Sweden

In this analysis, I develop an explanatory model of the residential consumption per capita in small houses. It is based on cross-sectional data over the 290 municipalities of Sweden for year 2013. The data for residential consumption per capita and the different drivers considered are average data at the aggregated municipal level provided by Statistics Sweden (2019). Taking this aggregated approach, the sensitivity of the model to individual behaviours is minimized and enables instead to point out larger societal trends. This is adapted for the purpose of this model which is designed to be later on used to showcase the potential that steering up household size trends could have on the national overall residential consumption, without focusing at the individual effects at the household level.

By developing a model on cross-sectional data, time dynamics are ruled out from the model. These could have been considered in a panel design for instance. Time-series differentiated observations were available in the dataset used, but only as modelled values and not direct observations: the consumption observations were modelled from 2013 to 2017 on the basis of a statistical study realized in 2010 giving an estimation of the distribution of residential energy end-use across the 290 municipalities of the country. This distribution was then applied by Sweden Statistics to yearly national accounts on electricity, gas and district heating to provide municipal-aggregated estimations of the residential consumption for further years (see more details in appendix 7.1). Therefore, the only time effect reflected in these modelled values relate to national dynamics and was therefore not relevant to consider. I retained the consumption estimations for year 2013, because this was the closest year to 2010 (year of distribution sampling) where the data for all the covariates considered was available.

### An OLS multivariate linear regression

The model developed is an Ordinary Least Squares (OLS) multivariate linear regression on cross-sectional data. (Sheather, 2009, p. 331).

The generic equation of a multivariate linear model on cross-sectional data is the following:

$$y_i = \beta_0 + X_i \cdot \beta + \epsilon_i$$

where $y_i$ is the variable of interest (in this case the household residential final energy consumption $E_{residential} \cdot cap^{-1}$), $X_i$ the vector of explanatory variables, $\epsilon i$ the error term, and $i$ the municipality observed. $\beta$ is the vector of the slopes for each explanatory variables and $\beta_0$ the intercept of the model. (Copiello and Gabrielli, 2017)

After different tests, a logged model proved to be the more fitted. In such a model, the logged value of the variable of interest is considered and is linearly correlated to the other covariates. Therefore, the following generic equation was considered :

$$log(E_{residential} \cdot cap^{-1})_i = \beta_0 + X_i \cdot \beta + \epsilon_i$$

### Dataset and variables

The dataset used originally covers the 290 municipalities of Sweden for year 2013. Municipalities where at least one of the covariate values was missing were removed, and one further dubious observation was removed (see Section 7.1). Therefore, 267 observations were eventually considered.

The variable of interest is $E_{residential} \cdot cap^{-1}$, the residential final energy consumption per capita in one- and two dwelling buildings, averaged at the municipal scale *[in MWh]*. This one include the domestic electricity final consumption, as well as the thermal final consumption, either provided by local fuel combustion or district heating.

Based on the drivers identified in the literature on residential consumption (Section 1.3.1), the following covariates are considered:

- $hhsize_i$: the average household size at the municipal scale.
- $income \cdot cap^{-1}{}_i$: the average disposable household income per capita (household income divided by the household size) at the municipal scale *[in SEK]*.
- $floorspace \cdot cap^{-1}{}_i$: the average useful household floor area per capita at the municipal scale *[in sq.m]*.
- $share.stock_{construction>2000-i}$: the percentage of the dwelling stock constructed after 2000. It is used as proxy for the overall technical performance of the building stock *[in %]*, including thermal performances. By using this proxy, it is assumed that the higher the share of the dwelling stock constructed after 2000 is, the higher the overall technical performances are. There is no evidence that this indicator reflects well the building stock overall condition over a municipality. It is nonetheless considered as the best proxy for technical performance that was available.
- $HDD_i$: the annual average heating degree days, given at the NUTS2 geographical subdivision scale (Eurostat, 2018b).

The exact specifications on all the variables are given in appendix 7.1 to this report.

### Variable selection and hypothesis testing

A forward selection algorithm is used to determine the best combination of covariates maximising the $R^2_{adjusted}$.

The $R^2_{adjusted}$ is an adjusted version of the coefficient of determination $R^2$ which discriminates the number of covariates used. Using the $R^2_{adjusted}$ enables to identify good fitting models that remain as simple as possible. At the opposite, adding more covariates can only improve the $R^2$. Ideally, a model with a $R^2$ of 1 perfectly fits the sample data. (Sheather, 2009, p.233)

The model selected is also submitted to the following hypothesis testing:

- T-test on each covariate retained, testing the null hypothesis $H_0$: "$\beta_k = 0$"
- F-test on the model eventually retained, testing the null hypothesis $H_0$: *"the fit of the intercept-only model and the constructed model are equal"*

The 1% threshold is retained for the p-value to reject the null hypothesises.

### Model diagnostic

OLS regressions can only be used under certain conditions on the data used. Therefore, a diagnostic is to be realized to check that all these conditions are met for the model.

The details on the diagnostic of the model can be found in appendix 7.2 of the report.

### 4.1.2 Quantifying national energy savings from co-housing options

The estimations on the regression coefficients obtained in the explanatory model are then used to study the effect of steering household size trends on residential consumption, in order to appraise the relevance to consider co-housing opportunities in a interdisciplinary political framework on residential consumption.
First, the theoretical savings are appraised as a function of the national average household size and its variations from its current value. This enables to emphasize the overall consumption reduction that steering household size up possibly lead to.

The equations used to calculate the savings in function of either the household size variations or the number of single people moving to a 3-person household are detailed below.

#### Effect of household size variations on residential consumption

Since a linear relation between $log(E_{residential} \cdot cap^{-1})$ and $hhsize$ was considered,

$$\delta(log(E_{residential} \cdot cap^{-1}))_{hhsize} = \beta_{hhsize} \cdot \delta(hhsize)$$

The following equation is obtained by integrating this equation, which can be equally expressed in terms of average residential consumption per capita or national residential consumption:

$$log(\frac{E_{residential} \cdot cap^{-1}}{E_{residential} \cdot {cap^{-1}}_0}) = log(\frac{E_{residential} \cdot cap^{-1} \cdot pop_{tot}}{E_{residential} \cdot {cap^{-1}}_0 \cdot pop_{tot}}) = log(\frac{E^{nat}_{residential}}{E^{nat}_{residential0}}) = \beta_{hhsize} \cdot \Delta hhsize$$

Where $E^{nat}_{residential0}$ is the current national residential consumption, and $E^{nat}_{residential}$ the national residential consumption obtained from the variation of the national average household size. On the basis of the exponential form of the previous equation, the average savings per capita can be expressed in function of the variation of the household size as following:

$$\Delta(E^{nat}_{residential})_{hhsize} = E^{nat}_{residential0} \cdot (1 - e^{\beta_{hhsize} \cdot \Delta hhsize})$$

#### Quantitative savings potential of one specific migration process

As explained in Chapter 2, the quantitative energy savings that would theoretically result from the Swedish population currently living alone moving to a 3-person household are investigated.

At the national level, the average household size can be expressed as following: $hhsize = \frac{\sum_{n=1}^{N} n * population_n}{population_{total}}$, where N is the maximum number of people living in the same household to be found, and $population_n$ the number of people living in a household of size n.

Therefore, looking more specifically at the effect on household size of a move of population from single- to 3-person household, the variation of the national average household size can be expressed as following:

$$\delta hhsize = \frac{1 \cdot \delta population_1 + 3 \cdot \delta population_3}{population_{total}}$$

With $\delta population_{1to3} = \delta population_3 = -\delta population_1$ and therefore

$\delta hhsize = 2\frac{\delta population_{1to3}}{population_{total}}$.

Once this equation integrated, the variation of the national average household size in function of the number of single people moving to a 3-person household can be expressed as following:

$\Delta hhsize = 2\frac{\Delta population_{1to3}}{population_{total}}$

Embedding this expression of $\delta hhsize$ in the last formula developed in the previous paragraph, the following relation is obtained and used in the analysis:

$$\Delta(E^{nat}_{residential})_{hhsize} = E^{nat}_{residential0} \cdot (1 - e^{2 \cdot \beta_{hhsize} \cdot \frac{\Delta population_{1to3}}{population_{total}}})$$

## 4.2 Cross-sectional explanatory model of residential consumption in Sweden

As a prerequisite to the appraisal of the potential savings that steering up household size trends could entail, I develop an explanatory model of residential consumption in one- and two-dwelling buildings in Sweden.

In the purpose of results reproducibility, the datasets and R script used to develop this model are given as supplementary file to the thesis (See the “explanatory-model” folder).

### 4.2.1 Dataset description

The residential energy consumption per capita $E_{residential} \cdot cap^{-1}$ observed relates to both thermal (space and water heating) and electricity use. Table 4.1 summarizes the dataset used, which contains 267 observations. The average residential final consumption per capita in one- and two-dwelling buildings is about 10MWh in this dataset, or $860 kg_{oil.equivalent}$. This is 14% higher than the national average of $752 kg_{oil.equivalent}$ reported by Eurostat in 2016 (Figure 1.4) for all types of buildings. The range on which variations in household size will be later on studied is determined by the range of the household size samples. These have values between 1.3 and 4.6 inhabitants per household. The relative standard deviation of the sample distribution is of

Table 4.1: Variables description

| Statistic | N | Min | Median | Mean | Max | St. Dev. |
|---|---|---|---|---|---|---|
| MWh.end.use_per.cap | 267 | 4.81 | 9.92 | 10.44 | 21.70 | 3.16 |
| hh.size | 267 | 1.30 | 2.10 | 2.18 | 4.60 | 0.47 |
| income_per.cap | 267 | 94.83 | 181.75 | 185.50 | 395.52 | 36.29 |
| hdd | 267 | 3,551.90 | 3,997.71 | 4,302.09 | 6,144.02 | 751.55 |
| share.stock.2000 | 267 | 0.002 | 0.03 | 0.05 | 0.25 | 0.04 |
| floor.area_per.cap | 267 | 30 | 44 | 45.14 | 71 | 6.77 |

21%. This indicates that the samples are quite concentrated around the dataset mean value of `round(mean(summary_per.cap_total.cons_small.house$hh.size)*100,digits = 0)`.

The distribution plots of the data set can be found in Appendix 7.1.

### 4.2.2 Outcomes of the model

#### Model construction

A forward stepwise algorithm is applied to the dataset to appraise what linear combination of the covariates gives the more fitted model with the least covariates as possible. The algorithm returns the different values of the $R^2_{adj}$ obtained with different combinations of the covariates. The algorithm determines which covariate maximizes the $R^2_{adj}$ of the model in a single-variable model. It then iteratively adds the other covariates of the set and summarizes how the different combination of these covariates influences the $R^2_{adj}$. The results of the algorithm are summarized in Figure 4.1. This graph is to be read as following: drawing a horizontal line somewhere at a certain value of the $R^2_{adj}$, one crosses black cell meaning that the covariate is considered, and white cells meaning that the covariate is omitted.

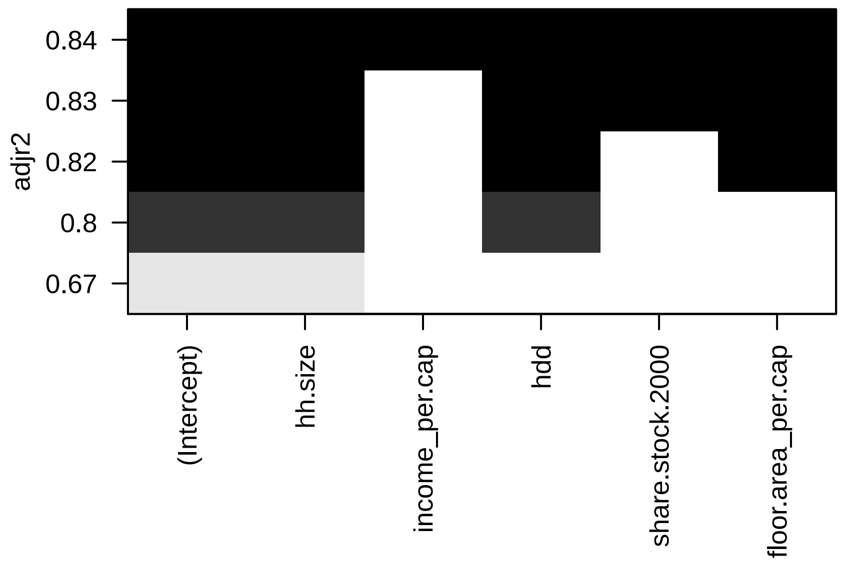



Figure 4.1: Results summary graph of the forward selection algorithm - adjR$^2$ indicator

The household size $hhsize$ appears to be the most significant covariate to consider in the model, and enables alone to reach a $R^2_{adj}$ of 0.67. The household size appears to be a good proxy for explaining consumption variations. Still, the highest $R^2_{adj}$ is reached when all of the covariates a priori considered are used.

The following explanatory model is thus retained for further hypothesis testing:

$$log(E_{residential} \cdot cap^{-1}{}_i) = \beta_0 + \beta_{hhsize} \cdot hhsize_i + \beta_{floorspace \cdot cap^{-1}} \cdot floorspace \cdot cap^{-1}{}_i + \beta_{hh_{income}{}^{-cap}} \cdot hh_{income_i}{}^{-cap} + \beta_{share.stock_{construction>2000}} \cdot share.stock_{construction>2000_i} + \beta_{hdd} \cdot hdd_i + \epsilon_i$$

Table 4.2 summarizes the performances of the overall model. For each regression coefficient, the standard errors are given in brackets.

The five covariates considered enable to develop a relatively highly fitted explanatory model, reaching a $R^2_{adj}$ of 0.84.

Table 4.2: Regression Results

| | *OLS* |
|---|---|
| hh.size | $-0.296^{***}$ (0.028) |
| hdd | $0.0001^{***}$ (0.00001) |
| floor.area_per.cap | $0.007^{***}$ (0.001) |
| share.stock.2000 | $-1.274^{***}$ (0.264) |
| income_per.cap | $0.001^{***}$ (0.0003) |
| Constant | $1.960^{***}$ (0.133) |
| Observations | 267 |
| $R^2$ | 0.841 |
| Adjusted $R^2$ | 0.838 |
| *Note:* | $^{*}$p<0.1; $^{**}$p<0.05; $^{***}$p<0.01 |

**Correlation significance**

A T-test testing the null-hypothesis "$\beta_k = 0$" was applied to each of the covariates a priori considered in the explanatory model retained in Section 4.2.2. This is to check whether these can be inferred to be linearly correlated with $E_{residential} \cdot cap^{-1}$. The test statistic coefficient appraised is $t_{\beta_k} = \frac{\widehat{\beta}_k}{SE(\widehat{\beta}_k)}$, $SE(\widehat{\beta}_k)$ being the standard error of the $k^{th}$ regression coefficient estimate using an OLS regression method. Table 4.3 gives the t-statistic coefficients and their related p-values for each covariate of the model.

Table 4.3: Hypothesis testing: correlation significance

| | term | t-statistic | p-value |
|---|---|---|---|
| 1 | intercept | 14.79 | <0.001 |
| 2 | hh.size | -10.37 | <0.001 |
| 3 | hdd | 12.69 | <0.001 |
| 4 | floor.area_per.cap | 5.15 | <0.001 |
| 5 | share.stock.2000 | -4.82 | <0.001 |
| 6 | income_per.cap | 3.00 | 0.003 |

The p-value is lower than the 1% threshold retained for all of the covariates of the model. Therefore, the null hypothesis "$\beta_k = 0$" is rejected for all the covariates a priori considered, namely the $hhsize$, ${hh_{floorarea}}^{-cap}$, $share.stock_{construction>2000}$ and $hdd$. On the basis of the scientific literature (see Section 1.3), I had made the assumption that residential energy consumption per capita in Sweden was mainly driven by the household size, the income per capita, the floor space per capita, the heating degree days and the share of the dwelling stock constructed after 2000 as a proxy for technical efficiency. All of these drivers show strong correlation significance with the logged residential energy consumption per capita.

### Overall significance

The overall significance of the model is appraised by testing the null hypothesis "$H_0 : \beta_1 = \beta_2 = \beta_3 = \beta_4 = 0$". $H_0$ is tested by assessing the p-value of the $R^2$ form of the F-statistic $F = \frac{R^2/k}{(1-R^2)/(n-k)}$. Here, F = 275.54 and the associated p-value is lower than the 1% threshold retained (see Table 4.2). Therefore, the null hypothesis is rejected and the model is assessed to be globally significant.

## 4.3 Quantifying national energy savings from co-housing options

Having developed an explanatory model inferring the effect of household size on residential energy consumption, I now highlight the potential to limit residential consumption through addressing the household size current declining trends.

In the purpose of results reproducibility, the datasets and R script used to develop the two models presented below are given as supplementary file to the thesis (See the "co-housing-potential" folder).

### 4.3.1 Effect of household size variations on residential consumption

The following model to appraise the overall savings at the national level that would be entailed by reverting the trends of national average household size upwards is here used (see methods, Section 4.1.2):

$$\Delta(E^{nat}_{residential})_{hhsize} = E^{nat}_{residential0} \cdot (1 - e^{2 \cdot \beta_{hhsize} \cdot \Delta hhsize})$$

This model is applied in the Swedish national context, using the estimations on $\beta_{hhsize}$ obtained from the explanatory model previously developed and given in Table 4.2. In order to take stake of the uncertainty of the model, the lower and the upper values of the 95% confidence interval are used rather than the coefficient itself. Considering the standard errors $SE_{\beta_{hhsize}}$ given in Table 4.2, the 95% confidence interval is approximately $[\beta_{hhsize} - 2 \cdot SE_{\beta_{hhsize}}; \beta_{hhsize} + 2 \cdot SE_{\beta_{hhsize}}]$.

Thus:

- $(\widehat{\beta}_{hhsize})_{lowerCI}$ = -0.239
- $(\widehat{\beta}_{hhsize})_{upperCI}$ = -0.352

According to this model, steering up the household size to the level it was in 1999 (2.17[1]) would therefore enable to save **6.2 (lower CI) to 9.1% (upper CI)** of the current residential consumption, translating into 24.3 to 35.2 TWh savings per year (see Figure 4.2).
Pushing up the Swedish national average household size further to the EU-28 average of 2.3 in 2017 (Enerdata, 2018) would enable to increase the savings to **9.1 (lower CI) to 13.1% (upper CI)**.

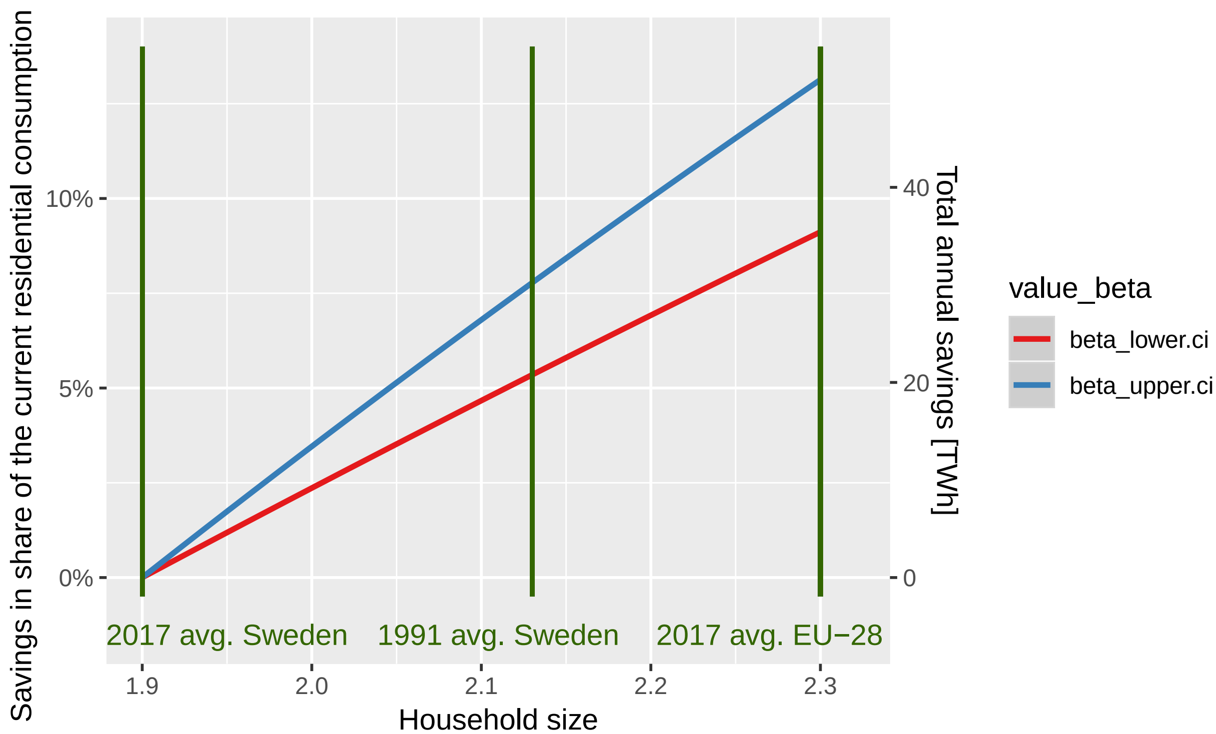



Figure 4.2: Effect of national average household size changes on residential consumption

### 4.3.2 Quantitative savings potential of one specific migration process

An attempt at reverting the trends of declining household size is not straightforward, and would concretely translate in internal migration dynamics. Investigating how would different household restructuration processes would influence the overall household size trends expressed by the national average household size is therefore critical. The overall savings at the national level that the relocation of people living currently alone in small houses to 3-person households

[1]see table “hbs_car_t312” of Eurostat (2019).

would entail are here appraised, on the basis of the following model (see methods, Section 4.1.2):

$$\Delta(E^{nat}_{residential})_{hhsize} = E^{nat}_{residential0} \cdot (1 - e^{2 \cdot \beta_{hhsize} \cdot \frac{\Delta population_{1to3}}{population_{total}}})$$

The same estimations on $\beta_{hhsize}$ as in the previous paragraph are considered.

Figure 4.3 illustrates the scale of the potential residential energy savings as a function of the number of people that would move from a single to a 3-person household in the Swedish context.

In this model, the potential savings are bounded by the (unrealistic) eventuality of every people living currently alone moving to a 3-person household. According to Statistics Sweden (2019), there was 0.646M people living alone in small houses in Sweden in 2017. Considering that the national population in Sweden was of 10.12M people that same year, the eventuality of every people living currently alone in small houses moving to a 3-person household would translate into a shift to a national average household size from 1.9 (Enerdata, 2018) to 2.03. This is in the range of the model which considers observation with household sizes of 1.3 to 4.6. According to the model, the effect on residential energy consumption would be an overall reduction of **4.4 (lower CI) to 3% (upper CI)**, or **17.1 to 11.7 TWh per year**.


Figure 4.3: Effect of population move from a 1- to a 3- person household on residential consumption

## 4.4 Key results and discussion

The explanatory model developed enables me to empirically confirm the significance of household size in driving the residential consumption *per capita* in Sweden. Thanks to this model, I could appraise the sensitivity of the residential consumption per capita to household size. For this, I realized a simple appraisal on the quantitative savings that addressing currently declining household size could entail. Thus, bringing back household size trends in Sweden to the level they were about 20 years ago would enable to cut off the national residential consumption by up to 9.1%. Bringing back the national average to the EU average in 2017 would bring these savings to 13.1% of the current national residential consumption. Developing co-housing practices is one of the numerous option to steer household size up. As an order of magnitude, gathering people living currently alone in small houses together in 3-person households would entail up to 3% reduction of the national residential consumption.
These results enable to get a first quantitative glimpse of what the theoretical potential of collective housing to tackle residential energy consumption can be.

The validity of these results is weakened by the following characteristics of the models used:

- No dynamic feedback effect on the residential energy consumption per capita is considered, although moving to a collective housing may influence other drivers of consumption, and entail some long-run rebound effects (see Chapter 3).
- Traditionally, collective forms of housing relate in majority to family-housing. In such housings, a large part of the living spaces and domestic appliances is shared between all the members of the household, thus dividing the related consumption per capita between all the members of the household. On the other hand, it was assumed that household size could be reverted through the development broader dwellers constellations than just the family-based traditional ones. The patterns of consumption may therefore differ due for instance to diverging housing designs, or levels of desired privacy and independence. This is however not taken into consideration in the model developed.

Nonetheless, the significant positive effect of co-housing on residential consumption is now clear in the case of Sweden, empirically emphasizing the relevance to consider household size in an interdisciplinary political framework on residential consumption.

# Chapter 5

# Transitions of energy-related social practices

I concluded from the previous analysis that higher household size have a positive impact on reducing the residential consumption per capita, and that steering the national average household size in Sweden towards realistic levels such as the country's one in 1991 or the average EU one in 2017 could significantly impact the residential energy consumption at the national scale. Concretely, developing co-housing practices could steer up household size trends. In this section, I focus on how innovative governance methods may enable to consider co-housing opportunities in planning processes.

To that end, the outcomes of the interview realized with Charlotte Louise Jensen are here analysed. Charlotte Louise Jensen is assistant Professor in Sustainability and Theories of Social Practice at Aalborg University (Denmark), Work-package leader on WP2 „Typologies of Energy Initiatives" in the H2020 funded ENERGISE project, member of the SCORAI EU Steering Committee. The main topic addressed during this interview was the application of reflexive governance and transition management methods in the ongoing ENERGISE project of which the interviewee is one of the leader.

The complete transcript of the interview can be found in Appendix 7.3 to this report.

## 5.1 Methods: semi-structured interview

A semi-structured interview informs the last analysis of this thesis.
This qualitative social research method is characterized by being conducted with one respondent at a time on the basis of a semi-open dialogue. It is both constituted of closed- and open-ended question (Adams, 2015). The aim of this interview was to gather some theoretical insights on energy systems interpreted as socio-technical systems, as well as some feedbacks on the reflexive governance methods developed within the EU funded ENERGISE research program to address

social practices in residential energy consumption. The respondent is acknowledged for her expertise in the topics tackled during this interview as an Associate Professor in Sustainability and Theories of Social Practice at Aalborg University (Denmark), one of the leader of the ENERGISE project and a member of the Steering Committee for the SCORAI EU network, from which the ENERGISE project stemmed. A first list of questions was redacted and sent to the respondent a few days before the interview took place in order to let her time to prepare to the topics addressed. The list of questions is given in appendix 7.3.
The semi-structured format was assessed to be more adapted than a fully-structured interview, enabling to set a framework to the topics discussed, but also letting enough liberty to the respondent to open the discussion on particular points of relevance during the interview. This is especially relevant in this case, where the respondent was expert in her field and could therefore bring topics to the discussion that could have been omitted by the interviewer (Adams, 2015).
A transcript of the interview is available in appendix 7.3 to this report.

## 5.2 Reflexive governance, an innovative planning process

The ENERGISE project is interested in understanding how energy is used as part of daily life routines in the residential context and how, in the EU context, do social practices influence the way people use energy services in different cultural contexts. In collaboration with households in 8 different countries, the field part of the project consisted in understanding and challenging the habits of these households relating to doing laundry and space heating. This project particularly stands out by the innovative methodology it develops and promotes to trigger positive changes in people's use of energy services.

The methodology applied is inspired from reflexive governance theories (Voß and Bornemann, 2011), in which it is argued that any actor aiming at promoting a transition is in itself embedded in the system in which this action is developed, preventing therefore any "neutral" diagnosis of the situation. Planning processes in themselves should therefore already be subject to the analysis of their own bias.
Transition management processes are suggested to adapt socio-technical planning processes to this impossible neutrality: rather than aiming at triggering a transition whose outcome were predefined "from the outside", transition agendas should be initially set up by the stakeholders involved themselves, of which interaction and co-learning processes can be facilitated by planning processes. This agenda can be used afterwards as a valid basis taking stake of the different stakeholders' experiences and interests, to produce a collective vision for sustainable transitions.

Considering the impossible neutrality of planning processes, the ENERGISE project methodology was therefore developed with this idea to let the users of energy-services express their own experience with two energy-related services (laundry and space heating). The way the respondents experienced challenges in their daily routines relating to these services was then investigated. The development of "living-labs" in the 8 countries involved in the project provided some direct insights on these issues from both community and individual perspectives. After having established a "baseline" of their laundry and space heating practices routines, the attendants to the living labs were proposed some challenges to do less frequent laundries and use alternative laundry methods, or reducing the ambient space heating temperature. Of course, these changes in habits reduce energy consumption, but why is that then that people heat at a certain temperature, or do the laundry at a certain frequency? To what extent do social practices and routine lock-ins play a role in the relation of the respondents to these services? How challenging these practices is experienced by the respondents, how does it impact their daily life and perceived well-being? These are the kind of questions which can only be learned from practice, and which are paramount to socio-technical transition debates.

Beside understanding the underlying dynamics of transitions, reflexive governance used in a transition management frame aims at providing a tool for planners to initiate a co-process of both understanding, but also creating "safe spaces" for socio-technical transitions to be experimented by the respondents (Voß and Bornemann, 2011). According to transition management theories, the lever of action for planning processes lies in facilitating the emergence of practices niches and promoting these at different governance levels. In the closing interviews to the ENERGISE project, it was therefore noticed that some respondents to the living-labs had been keeping some of the practices they learnt about during the experimentation time, because they had realized that above reducing their energy consumption, these practices had actually a larger positive impact on their daily life. In enabling the creation of such practices niches, planning processes can facilitate the emergence of new social practices around socio-technical systems and their spreading until these eventually affect the whole system landscape (see Figure 5.1). The eventual adoption of a practice niche at higher level of the socio-technical landscape relies nonetheless on practitioners themselves adopting or rejecting them, and planning processes should only aim at catalysing these dynamics, as the red arrows added on Figure 5.1 suggest. In developing, applying and promoting a method which applies reflexive governance theories to let the users of energy services express and challenge their experience to socio-technical systems, the ENERGISE project may pave the way for a more systematic consideration of reflexive governance in planning processes, in particular in the energy field.

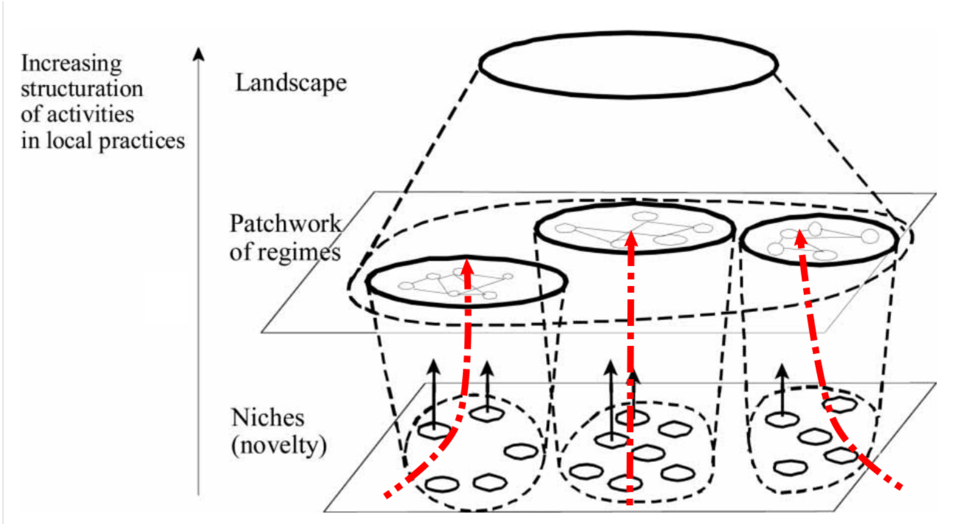



Figure 5.1: Strategic niches management: from niche practices to socio-technical landscape structural changes. Source: Geels (2002) (I added the red arrows)

## 5.3 Key results and discussion

I had concluded in Section 3 that enlarging current energy policy frameworks to more integrated options also considering social practices would be relevant to limit residential energy consumption. I suggested then in Section 4 that the impact of household size on residential consumption was significant in Europe, and the development of co-housing to intervene on household size declining trends was suggested. Nonetheless, planners' role should be limited to facilitating socio-technical transition to happen without having to implement an specific outcome that was designed externally, as it was highlighted in the outcomes of the interview.
Therefore, if the development of co-housing was to be identified as a political goal, the interview gives us insight on how could this arise from reflexive governance processes inspired from transition management. In fact, co-housing potentially implies major shifts in comparison with traditional single or family-based housing, for instance in terms of lifestyle and personal experience but also building design or housing governance. The practice-based learning methods used in the ENERGISE project could inspire the creation of experimenting and co-learning spaces involving voluntary dwellers, architects, funders, etc., and where risks of negative experience, project failure, money losses, etc., is limited. These arena of experimentation should also enable to gain insights from the different stakeholders' experience, thus enhancing co-learning processes between the different institutional levels and the mutual adaptation of both political frameworks and practical development strategies. This should also allow for more deliberative interactions between the actors of the political framework, and a fairer distribution of power between the actors involved in the design of the political framework.

# Chapter 6

# Conclusion

In this thesis, I investigated the relevance to consider a more interdisciplinary framework for policies addressing residential energy consumption if consumption net decrease targets were to be set in the European Union (EU).

I first reviewed the current EU political framework on residential energy demand. This one is currently based on a two-leg strategy addressing demand through technological efficiency innovation on the one side, and individual behaviours on the other. Efficiency efforts do not follow any absolute consumption savings goal. They are enforced by the development of intensive technical efficiency standards for thermal insulation and end-use appliances. The EU efficiency efforts are supplemented by behaviour-oriented efforts fostering individuals to avoid waste consumption in their daily life and to buy more efficient technologies.
On the basis of ongoing scientific debates, I suggested that these efforts should be framed within conservation efforts to reach net consumption savings targets. Regarding technical efforts, conservation efforts would translate for instance into progressive or absolute performance standards rather than the intensive performance standards currently developed. Moreover, supplementing behaviour-related efforts by a social-practice based approach of behaviours could enable to collectively address the structural socio-material configurations largely influencing individual behaviours. Sufficiency approaches pave the way to conceptualizing conservation-driven deep socio-material transitions that promote well-being, such as co-housing.

I then realized an empirical study of the energy savings that steering up household size do potentially entail. These outcomes give some elements of answer to the following the sub-question of this thesis:
*What empirical justification is there on the relevance to consider household size in an interdisciplinary political framework on residential consumption?*
An explanatory model of the residential final energy consumption in Sweden confirms that household size trends has a significant influence on consumption trends. According to this model, bringing back household size trends in Sweden to the level they were about 20 years ago would enable to cut off the national residential consumption by up to 9.1%. Moreover, I

pointed out that developing co-housing practices could have a significant influence on residential consumption by steering up household size trends.

With the insights of a social practice and transition management expert, I explored the potential of reflexive governance to better consider the influence of social practice dynamics in planning practices relating to residential energy consumption. This enable me to answer the following sub-question of this thesis :
*What model of transition governance can enable to address social practice dynamics shaping residential energy demand such as household size?*
Reflexive governance seem to be adapted to developing co-housing practices thanks to a co-process of experimentation, learning and institutionalization. Such governance models may help to better take stake of the embeddedness of planners in the system they aim to change, and to develop more inclusive planning processes. In that sense, appraising how the different stakeholders potentially involved in co-housing practices could be involved in some arenas of experimentation would be worth furter investigation.

These reflections provide some insights to give an overall answer to the research question of this thesis: *How can the current EU policies on residential energy demand benefit from more interdisciplinary insights to address net reduction ambitions?*

We have seen that in the perspective of steering down the current unsustainable energy demand in Europe, there are great opportunities to enhance the current EU political framework on residential final consumption by framing it in a sufficiency perspective including conservation targets and social-practice-based approaches. The empirical investigation supports the relevance to consider social practices around household size into such an interdisciplinary framework. Reflexive governance approaches seem moreover suited to the effective management of such social practices transitions.

# Chapter 7

# Appendices

## 7.1 Variables of the explanatory model

The source and the exact specification of the data used in the explanatory model developed in Section 4.2 are given below.

**Variable of interest**: Residential final energy consumption per capita in one- and two dwelling buildings averaged at the municipal scale $E_{residential} \cdot cap^{-1}$ *[in MWh]*:

- Data source: the data was processed from 2013 to 2017 on the basis of the 2010 "energy statistics for dwellings and non-residential premises" (*"Energistatistik för smähus, flerbostadshus och lokaler"* in Swedish) of the Swedish Energy Agency (*"Energimyndigheten"* in Swedish). These statistics give an estimation of the distribution of residential energy end-use $E_{residential}$ through the 290 municipalities of the country. This distribution was then applied by Sweden Statistics (SCB) to yearly national accounts on electricity, gas and district heating (*"Årlig energistatistik (el, gas och fjärrvärme)"* in Swedish) to provide an estimation of single-house based yearly residential consumption aggregated at the municipal level.
- Quality of the data source: this data is subject to high uncertainty. First of all, it is indirectly observed through the processing of national accounts. Moreover, the distribution of these national accounts between municipalities is based on observations made in 2010 which do not take into account the evolution of the distribution over the next years that the diverse developments in the municipalities may entail. Moreover, the 2010 distribution of residential consumption between municipalities was estimated on the basis of a survey of about 7,000 single-family homes over a total of about 2,000,000 homes, and is therefore judged by Sweden Statistics to be relatively uncertain. On the other hand, the national annual consumption accounts are assessed by Sweden Statistics to be quite reliable. (Statistics Sweden, 2019)
- $E_{residential} \cdot cap^{-1}$ is obtained from the source data $E_{residential}$ by dividing it by the stock

of one- or two-dwelling buildings $stock_{1-2-dwelling-buildings}$ and the average household size $hhsize$ in rented one- or two-dwelling buildings for each municipality.

**Explanatory variables**

According to the drivers commonly found in the literature on residential thermal consumption (Section 1.3.1), the following covariates are considered:

- Average disposable household income per capita at the municipal scale $hh_{income_{i,t}}^{-cap}$ *[in SEK]*:
  - Defined by Statistics Sweden as *"the sum of all taxable and tax-free income minus taxes and negative transfers. The income includes gains/losses, that is, the gain/loss arising from a sale (realization) of assets, for example, stocks, mutual funds or real estate."* (Statistics Sweden, 2019).
  - Here given as a aggregated mean value at the municipal scale for all people aged over 18 in all types of households, divided by the average household size at the municipal scale $hh_{size-i,t}$ (see below).
  - The data is sourced from the table 000000KD (*"Disposable income for households by region, year, type of household, age and observations"*) of Statistics Sweden (2019), and divided by $hh_{size-i,t}$ (see below).
- Average household size at the municipal scale $hh_{size-i,t}$:
  - The number of occupant in a household, given as an aggregated mean value for rented one- or two-dwelling buildings at the municipal scale.
  - The data is taken from the table 000000TT (*"Number of persons per household by region and type of housing"*) of Statistics Sweden (2019).
- Average useful floor area per capita at the municipal scale $hh_{floorarea_{i,t}}^{-cap}$ *[in sq.m]*:
  - The total surface used per capita in a household, given as an aggregated mean value for all one- or two-welling buildings at the municipal scale.
  - The data is taken from the table HE0111DJ (*"Average useful floor space per person by region, year and type of housing"*) of Statistics Sweden (2019).
- Annual average heating degree days at the NUTS2 scale $HDD_{i,t}$ *[in °C · day]*:
  - Defined by Eurostat as *"the severity of the cold in a specific time period taking into consideration outdoor temperature and average room temperature (in other words the need for heating)"*, with an average room temperature considered to be 18°C. See Table "nrg_chdd" from Eurostat (2019) for detailed information on the HDD calculation.
  - Here, the mean value of the annual HDD at the NUTS2 (European Commission, 2007) geographical scale is considered for each municipality of the dataset.
  - The data is taken from the nrg_chdd indicator of Eurostat (2019).
- Percentage of the dwelling stock to have been constructed after 2000 $Share-stock_{construction>2000-i,t}$:
  - Reflects the technical quality (in particular insulation) of the building stock.
  - Is calculated for each municipality on the basis of the of data from the table

BO0104AB (*Number of dwellings by region, type of building and period of construction. Year 2013 - 2018*) of Statistics Sweden (2019).

**Other data used**

The following data is used in the calculation of either the variable of interest or the explanatory variables:

- Stock of one- or two-dwelling buildings per municipality $stock_{1-2-dwelling-buildings}$:
  - The data is taken from the table from the table BO0104AB (*Number of dwellings by region, type of building and period of construction. Year 2013 - 2018*) of Statistics Sweden (2019)
- Classification of the Swedish municipalities according to their counties, in accordance to the NUTS2 classification:
  - The data is taken from Eurostat (2018b).

Here, one- or two-dwelling buildings are defined as the *"detached one- and two-dwelling buildings as well as semi-detached, row and linked buildings (excluding buildings for seasonal and secondary use)"* (Statistics Sweden, 2019).

**Histograms of the dataset**

Figure 7.1 shows the histogram distribution of the variables used in the model. See Table 4.1 for a quantitative description of the dataset.

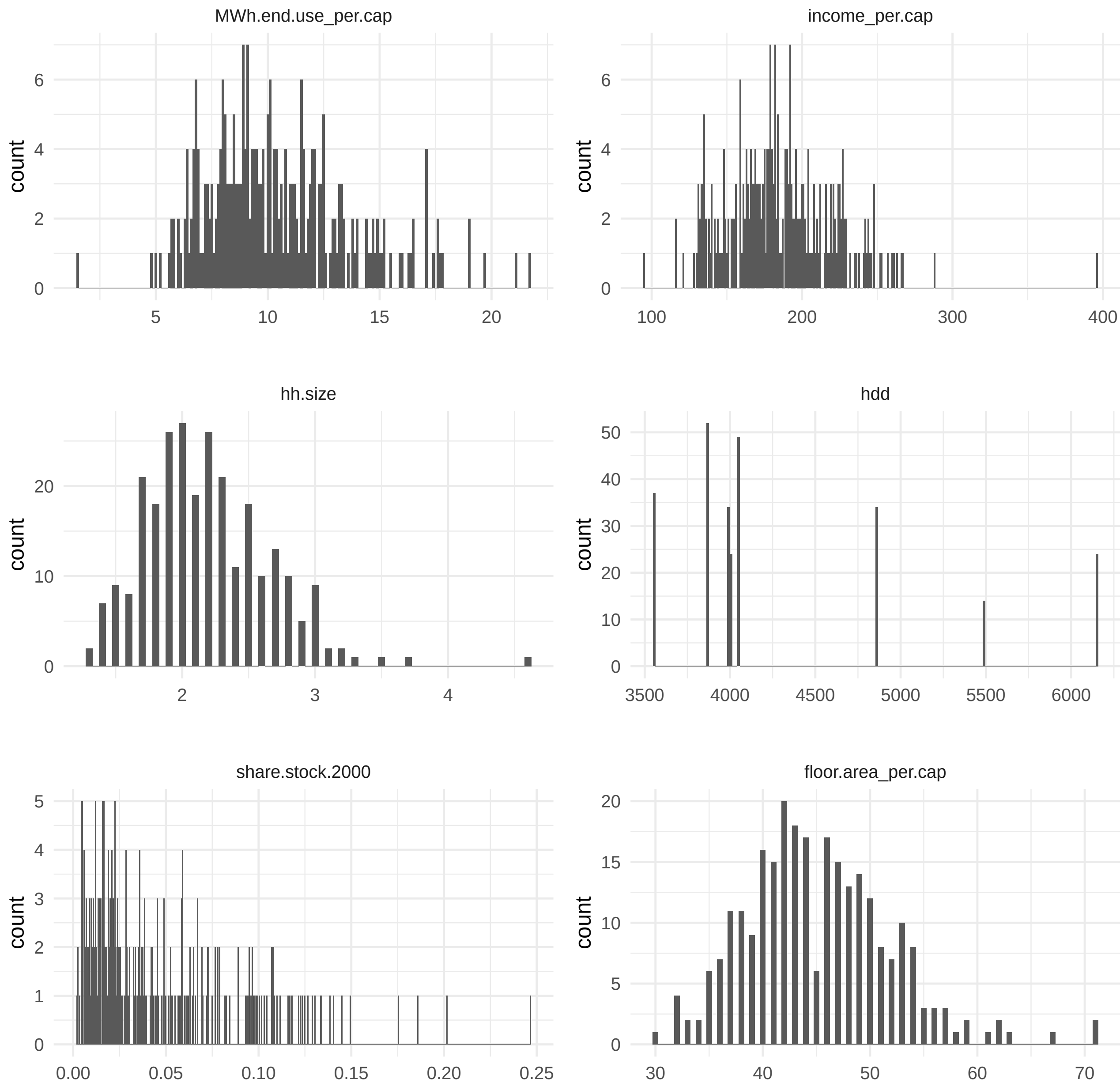



Figure 7.1: Distribution of the dependant and independant variables used

### Omission of certain observations

One will notice a one very low value in the histogram of the end use consumption per capita. This one relates to the following observation:

```
## # A tibble: 1 x 3
##   municipality.id year  MWh.end.use_per.cap
##   <chr>           <chr>               <dbl>
## 1 1441            2013                 1.46
```

Looking at the consumption accounted for this municipality in other years in the dataset used, the consumption was much higher from 2016 than in the case identified above:

```
## # A tibble: 4 x 3
##   municipality.id year  MWh.end.use_per.cap
##   <chr>           <chr>               <dbl>
## 1 1441            2013                 1.46
## 2 1441            2014                 1.31
## 3 1441            2016                 6.55
## 4 1441            2017                 6.39
```

These variations are unreasonably high considering that the distribution of the end use consumption between the municipalities is a fixed rate (see above): the only variations between the different years of observation should come from the variations of the total consumption accounted at the national level. These do not follow such big order of magnitude (here >500%...). Moreover, an average overall residential consumption of less than 2MWh per capita over a whole municipality in Sweden is also suspicious considering that the average consumption per capita in this country, which was of 8.7MWh/capita (Eurostat, 2018a). Therefore, the observation **1441/2013** is considered to be dubious, and was omited from the dataset.

## 7.2 Model diagnostic

This appendix establishes a diagnosis of the following explanatory model of residential consumption developed in Section 4.2:

$$E_{residential}{}^{-cap}{}_i = \beta_0 + \beta_{hhsize} \cdot hhsize_i + \beta_{floorspace \cdot cap^{-1}} \cdot floorspace \cdot cap^{-1} + \beta_{income \cdot cap^{-1}} \cdot income \cdot cap^{-1} + \beta_{share.stock_{construction>2000}} \cdot share.stock_{construction>2000} + \beta_{hdd} \cdot hdd + \epsilon_i$$

### Exogeneity in the residuals

None of the independent variables should be correlated with the residuals. The correlation coefficients between each independent variables and the residuals are calculated, and should be as close from 0 as possible.

```
cor(summary_per.cap_total.cons_small.house$hh.size,residuals)
```

```
## [1] -1.59685e-17
```

```
cor(summary_per.cap_total.cons_small.house$hdd,residuals)
```

```
## [1] 2.138087e-16
```

```
cor(summary_per.cap_total.cons_small.house$share.stock.2000,residuals)
```

```
## [1] -1.970595e-17
```

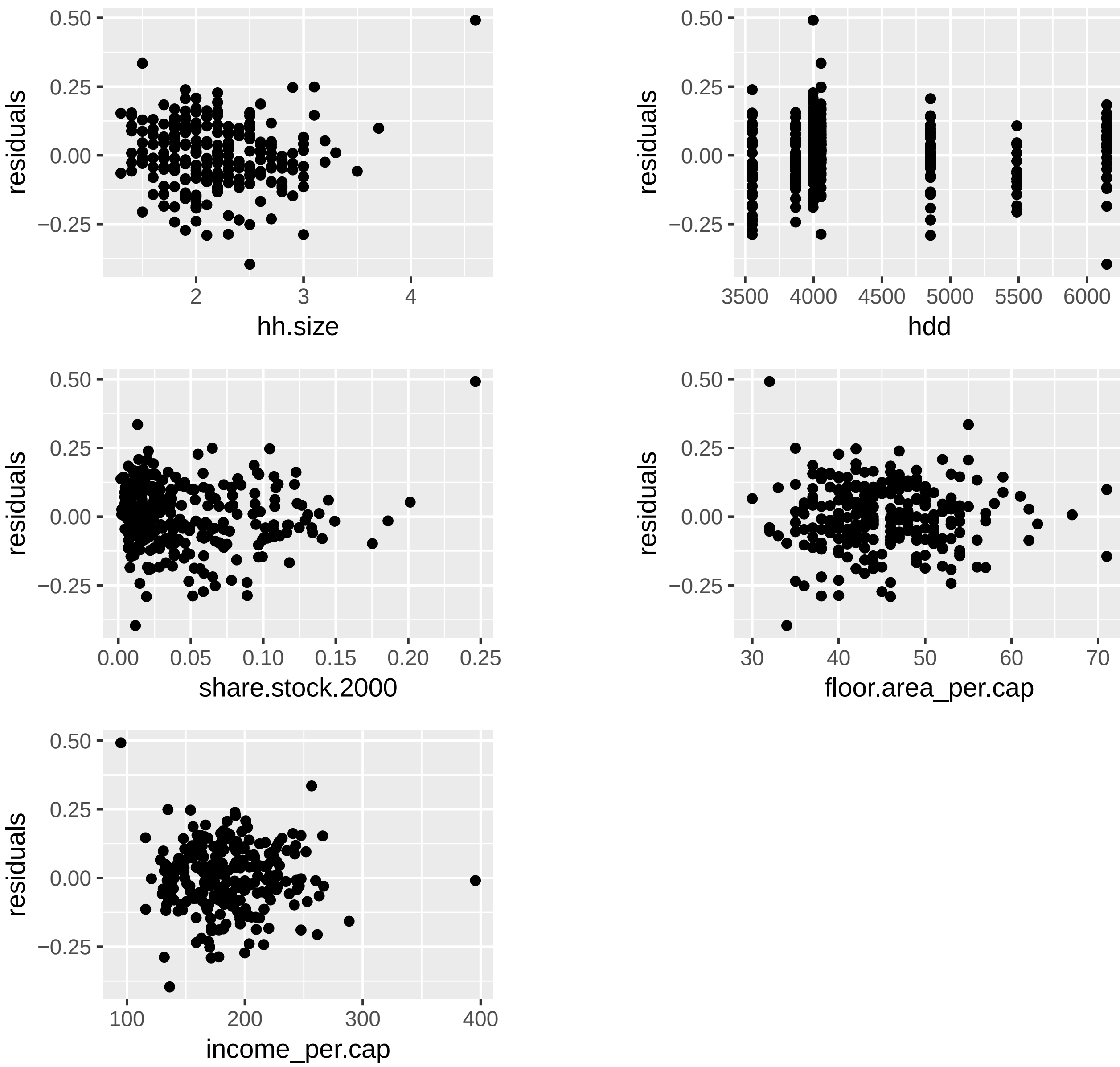
```
cor(summary_per.cap_total.cons_small.house$floor.area_per.cap,residuals)
```

```
## [1] 2.605362e-18
```

```
cor(summary_per.cap_total.cons_small.house$income_per.cap,residuals)
```

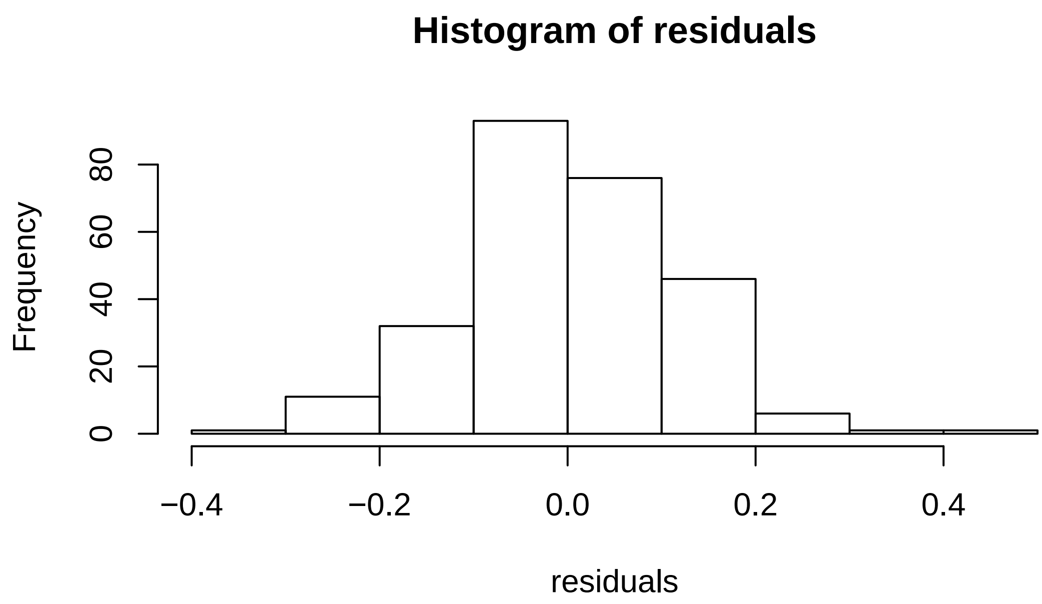
```
## [1] -3.393882e-17
```

This is completed by a visual check of the plots of each independent variable against the residuals: residuals should have mean zero and be randomly scattered.

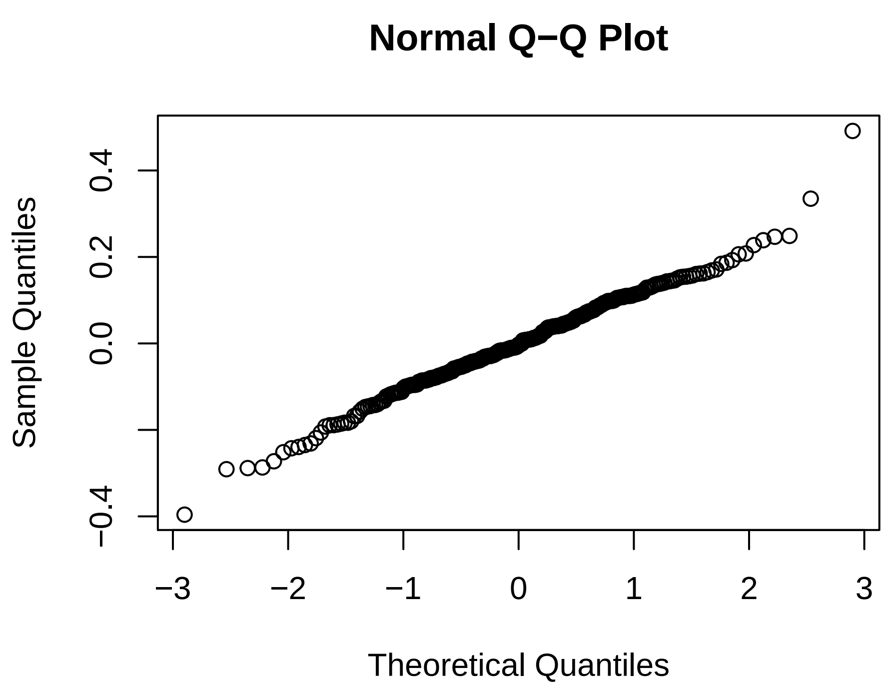



## Normal distribution of the residuals

A visual inspection of the histogram of the residuals is realized, the distribution should be normal.

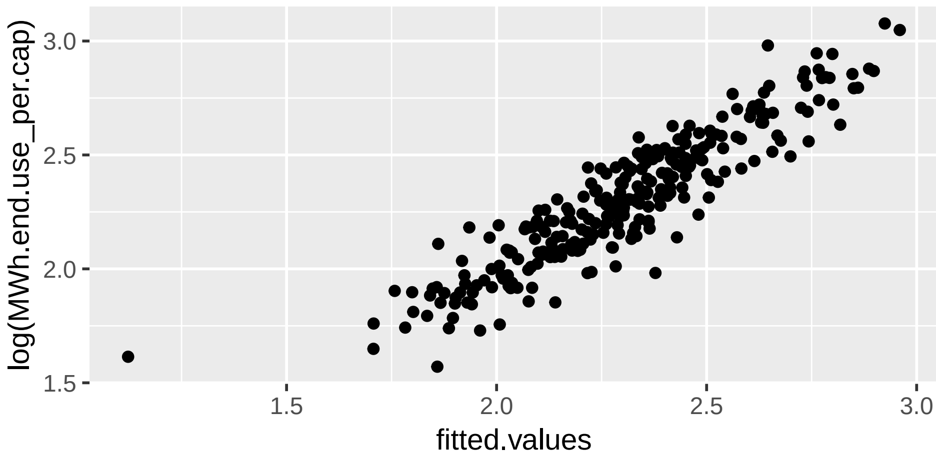



This is completed by a visual inspection of the Q-Q normal plot (residuals quantiles against the quantiles of a perfectly normal distribution). The Q-Q plot follows the linear straight $y = x$ in case of perfect normality.



### Linear relationship between the variable of interest and the covariates

A visual inspection of a plot of the fitted values of the variable of interest log(MWh.end.use_per.cap) against the sample data is made. The pattern observed should be as linear as possible.

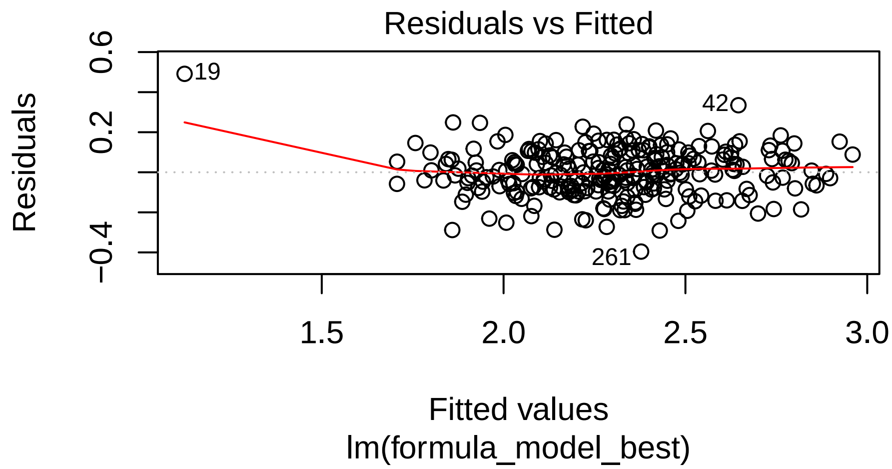



There is an outlier in the bottom-left corner which visually stands out from the linear pattern met by the other observation. This outlier relates to the observation for the municipality of Sundbyberg (Municipality ID 0183):

```
## # A tibble: 1 x 2
##   municipality.id MWh.end.use_per.cap
##   <chr>                         <dbl>
## 1 0183                           5.02
```

In this municipality, the average household size is particularly high (4.6 for rented one- and two-dwelling buildings) and stands out from the rest of the sample (see the histogram distribution on Figure 7.1). It seems therefore that the model is not well fitted anymore at such household size range. This however doesn't affect the conclusions made with this model, since this is out of the range investigated in household size variations in Section 4.3. It should be however checked that this outlier doesn't affect too significantly the overall model (see the "No extreme outlier" paragraph below)

The plot of residuals against fitted-values is also scrutinized, to check the presence of any non-random looking pattern or a non-zero mean of the residuals which would invalidate the linearity assumption.

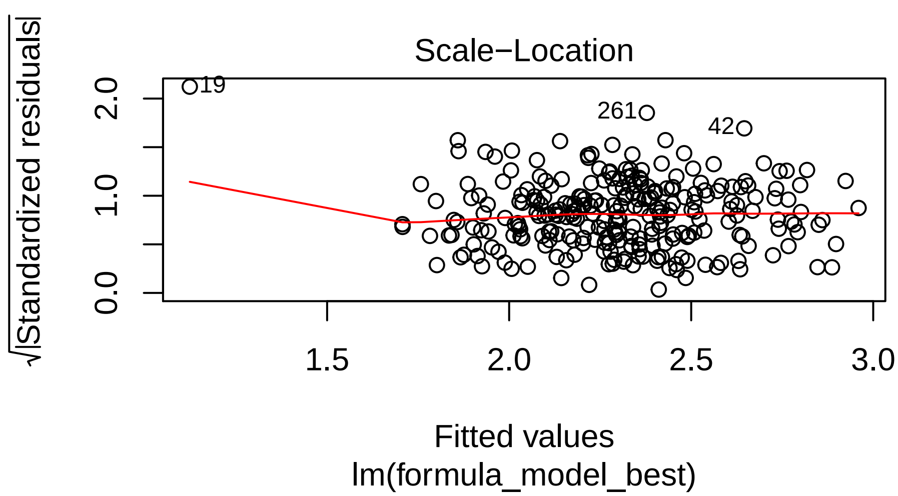



The point "19" relates to the observation for the municipality "0183" just mentioned. Apart from it, the plot looks visually randomly distributed.

## Homoscedasticity

The standard deviation of the residual should be the same across all values of the variable of interest.

A visual inspection of the plot of the residuals against fitted values is realized to check that no cone-shaped pattern (indicating a potential variable standard deviation) is recognisable. Again, the point "19" relates to the observation for the municipality 0183.



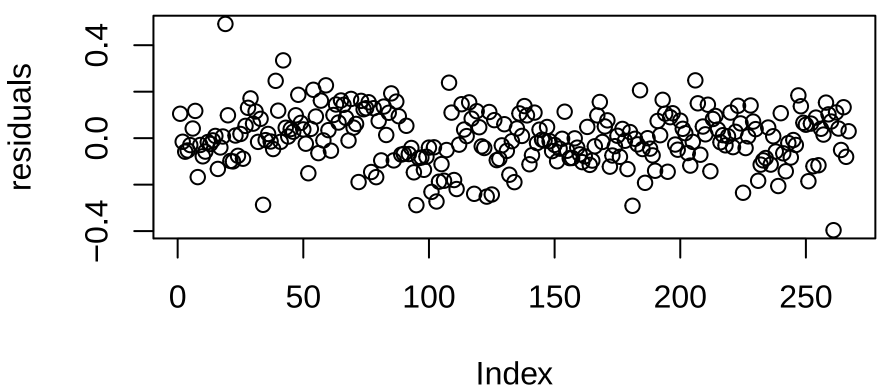
## Uncorrelated covariates

The covariates should not be too closely correlated with each other. The collinearity between each of the covariate retained is calculated and indexed in a multi-collinearity matrix.

| | hh.size | floor.area_per.cap | share.stock.2000 | hdd | income_per.cap |
|---|---|---|---|---|---|
| hh.size | 1.0000000 | -0.5719647 | 0.5699898 | -0.2555129 | -0.6105633 |
| floor.area_per.cap | -0.5719647 | 1.0000000 | -0.4356182 | 0.1702191 | 0.3728658 |
| share.stock.2000 | 0.5699898 | -0.4356182 | 1.0000000 | -0.3875072 | -0.0130787 |
| hdd | -0.2555129 | 0.1702191 | -0.3875072 | 1.0000000 | 0.0241219 |
| income_per.cap | -0.6105633 | 0.3728658 | -0.0130787 | 0.0241219 | 1.0000000 |

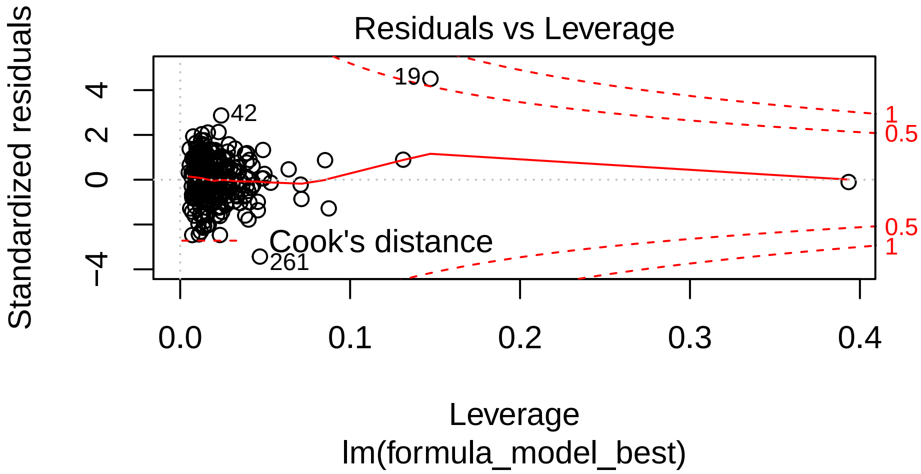
## Independence of residuals

No group, cluster or non-random pattern should be recognisable in the plot of the residuals.




## No extreme outliers

A plot of the standardized residuals against the residual vs. leverage values is inspected to check for any value in the upper right or lower right corner, which would reveal the presence of influential outlying values that would need specific attention. As a discrimination criterion, it will assumed that plots having a Cook's distance > 1 can be considered as extreme outliers of which the influence on the model should be further investigated.




Again, the point "19" relates to the observation for the municipality 0183 pointed out in the "Linear relationship" section beforehand. It has a Cook's distance $< 1$ and is therefore not considered as an extreme outlier. Therefore, even if the model does not fit as well the observation 0183 as the others, the influence of this observation on the overall model is not considered to be significant.

## 7.3 Semi-structured interview

### 7.3.1 Preparatory list of questions

The list was sent to the respondent a few days before the interview took place. The respondent considered that certain questions were out of her field of expertise and were therefore not addressed during the interview. These are marked in italics below.

**Introduction**

- Could you briefly introduce yourself and your background?
- Do you perceive a change in the place given to socio-technical approaches in the research and the political world since you started to focus on this kind of topics?
- Why can energy systems be considered as socio-technical systems?

**ENERGISE**

- General questions:
  - Could you briefly present the project? Your role as leader of the WP2?
  - How and why was initiated this project focusing on the socio-cultural drivers of energy consumption?
  - What outcomes are expected from the project? To whom will they be targeted?
  - To what extent do you think these outcomes could ideally impact current energy consumption policies, research and actions?
  - What did you learn yourself throughout this project?
  - In the presentation of the project, the risk of failure of traditional behavioural/efficiency actions through rebound effect is acknowledged. What exact types of „rebound effects“ is here regarded? (direct/indirect/economy-wide,etc..)
- Work Package 2:
  - How were the actions you considered in this referencing work selected? In particular, were political measures (at different levels) also considered?
  - What conclusions about current energy consumption initiatives in Europe could you draw from this work?
    - What particular projects or type of projects going beyond the traditional triad rational consumer choice/efficiency/information-based approach retained more particularly your attention?
  - Did you identify any projects tackling explicitly/implicitly household size and/or floor area per capita?
  - How do you think the outcomes of the WP2 can be valued to inform planning actors? (and which actors would be then targeted)

**Floor space and residential consumption**

- How did you come to work with Inge Røpke on this paper on the need in the Danish

context to tackle floor space to limit residential consumption?
- What can you say about the differentiated influence of household size and/or floor area per capita on both the thermal (space and water heating) and non-thermal-related consumption? (lighting, other appliances,...)
- Is there to your knowledge any example of actions/policies that has tackled floor space per capita and/or household size with the explicit aim to manage residential (energy) consumption?
- Do you have any example of policies promoting (indirectly?) larger housing spaces / smaller household size?
- *You wrote in this paper that "the opportunity for capital gains seems to be one of the main barriers for redistribution", could you develop on this?*
- *How do you think the policies you suggested in your paper to reallocate building stocks more soundly according to households' actual needs could be practically implemented?*
- What do you think are the main socio-cultural barriers to the implementation of such policies, and do you think they could be overcome?
- *How do you think already existing housing practices promoting smaller dwelling space and higher household size (shared apartment, student blocks with common areas, ...) could be more developed?*
- You write in your paper that living labs to experiment new approaches of living involving smaller living space per capita could be used. Do you have any example of such concrete „labs" already existing?
- How do you think efforts to limit consumption through dwelling space/household size could be combined with efforts focusing on other structural factors of residential energy consumption? (income, urban planing, technical improvement and insulation policies,...).

**Other conceptual topics**

- GOVERNANCE:
  - While governance is currently becoming increasingly complex, especially in the European context, how do you perceive the distribution of roles to manage a transition towards much less energy-intensive regimes?
  - In particular, how do you think the responsibilities of politics (at the local/regional/national/EU scale), researchers, civil organizations and individuals are currently distributed and/or should be distributed?
- SUFFICIENCY:
  - Are you familiar with the concept of sufficiency? If yes how would you define sufficiency?
  - Is sufficiency explicitly approached in the ENERGISE project? If not, do you think it is done implicitly?
  - To what extent do you think a sufficiency approach at the residential scale would enable to embrace dwelling-space related direct energy consumption in a more holistic sustainability frame?

### 7.3.2 Transcript of the interview

**Date**: 11th April 2019
**Location**: Skype conference
**Interviewee**: Charlotte Louise Jensen[1] (CLJ)
**Interviewer**: Lukas Godé (LG)

*LG: Could you introduce yourself? How did you get to socio-technical transitions?*

CLJ: I may have had somewhat the same kind of jounrney as you have at the moment, cause I'm a trained engineer of the TU of Denmark where I became increasingly frustrated about the technological focus, that we would only focus on maths and physics and technological development, and we would pay only a little attention to society and what we were actually preparing these technologies for. So I went in a bit of a different direction during my studies and tried to take some courses on environmental management as well, and the theories of sciences, and tried to take whatever I could in terms of the few options that included some social sciences, so I started looking into that. And my master was on innovation and environmental management where we had a lot of courses that were more kind of STS focus; we worked with Active Network theories and Social Practices theories. And that's where I got to know Inge, she was my teacher back then. I then did my PhD here at AAU, which was this socio-technical study of lighting, and was really inspired of these theories of social practices.

*LG: And was these socio-technical approaches already developed at that time in that department at AAU?*

CLJ: No. My PhD was actually part of a big research project called "Sustainable Transitions", and it was a project that was run between AAU and DTU. But when I applied to it, I would be based in AAU; and my main supervisor was here at AAU and I had a co-supervisor from DTU. So I was connected to the institute of Planning, and have always been connected to that institute in my whole time here. We have an energy group in that department, but I haven't been directly involved in the work they do.

*LG: Have you perceived a change in the way socio-technical approaches are considered in the research/political world since you got involved in that field?*

CLJ: Yes, I have noticed a few changes. Somehow they are a little contradictory, which is interesting. In terms of funding, if you look at the EU funding, e.g. the H2020, is acknowledging more and more the social side of energy consumption. E.g., the ENERGISE project was one of the first project, along with two or three other projects that were funded by the same fund within the H2020 program. These were the first project submitted where the social aspect of consumption was ingrained in the [funding] proposal. So I have definitely experienced that some funding bodies are acknowledging the social side more and more. But at the universities, and

[1] *Assistant Professor in Sustainability and Theories of Social Practice at Aalborg University (Denmark), Work-package leader on WP2 „Typologies of Energy Initiatives" in the H2020 funded ENERGISE project, member of the SCORAI EU Steering Committee.*

particular DTU, it was kind of de-prioritized for a while. In the political landscape, e.g. with our current government, there is little focus on sustainability research, and particularly not on the social-technical aspect; it's really the technological approach.

*LG: It means that more and more knowledge are being produced, and "ready to be applied" but not really considered at the end actually.*

CLJ: That's our understanding of it. If you want to read a little bit more about it, we have some deliverable coming out of the ENERGISE project. One of the deliverable from Work Package 2 holds a lot of country reports that discusses some of these things. And also from our Work Package 6, you'll see a discussion of the role of social sciences in energy consumption research, and how it has changed in different countries, and also at the EU level.

*LG: To you, how can energy systems be considered as socio-technical systems?*

CLJ: It doesn't make sense to only look at energy systems as a technological thing, because the reason why we have energy systems is because people and things use energy. Energy system only makes sense if you look at how it's embedded in the social world so to speak; how people use energy and for what. That's why it only makes sense to look at the energy system as a socio-technical system.

*LG: What particularities do energy systems have in comparison with other socio-technical systems?*

CLJ: Energy is a funny thing: you can't see it, you can't touch it, it's an abstract thing. The closest thing you get to thinking about consuming energy is when you turn on a light for instance; a light kind of turns energy visible so to speak. But other than that, it's making a lot of things available, it's making a lot of our daily activities possible, but we never consider the use of energy as something in itself. For instance, if you look at the food system, it would be different because food is something is something tangible that you can see. I thing that's one of the trickiest things about energy research in any sense, that it's something that is not visible. For instance, this talk you and I have right now: I'm not thinking about our talk consuming energy. That's not really what's meaningful to me; it's the conversation we have, and it's made available through a technological system, but ẃhat is meaningful to me is that we are able to have this conversation, and the energy consumption part is secondary so to speak. And that's why it makes it quite difficult to talk about energy consumption, because what is it what we consume: we actually consume the situations, the experiences, what we share. That's what's meaningful to us, and not so much the act of consuming energy.

*LG: Let's move to the ENERGISE project now. Could you, as one of the leader of this project, present it briefly with your own words?*

CLJ: ENERGISE is a big project with 10 partners across Europe. Most of these partners already knew each other from the network "SCORAI". It's a network that was established in North Americam but we have a European one as well, that developed maybe already 10 years ago or a little bit less. A lot of the people involved in ENERGISE are also involved in the SCORAI Europe as well. We met at a conference that the lead of ENERGISE, the Irish partner, was organising based on another project they had done. They had invited a lot of people to come as keynote speakers to collaborate and to discuss the findings of the project. At the same time they organized for us to meet their local Horizon 2020 advisor.

*LG: In which year was that?*

CLJ: I think that was in 2013 or 2014, I can't remember exactly. And we actually then agreed to write up a proposal for the Horizon 2020 program. And the proposal which then became ENERGISE was based on some ideas that had been developed over the years from the SCORAI group; especially in terms of talking about resource use, and how consuming different types of resources means different types of things, so we can talk about efficiency, sufficiency... So we took a point of departure in the document that had been developed in SCORAI, which was primarily led by Frances Fahy, who is our project lead, and Henrike Rau who is the Work Package 1 leader. They invited the rest of us to take part of writing up this Horizon 2020 proposal. The ENERGISE project is interested in understanding how we use energy as part of our everyday life, related to households. We are also interested in understanding whether - you can call it culture, you can call different configuration of practices in different types of countries - may influence the way we consume energy in different ways. So it's really a cross-cultural comparison we want to do in ENERGISE. Then we also wanted to experiment, we wanted to include real households, and find ways of experimenting with consumption domains; we later chose to focus on laundry and heating. So we have been doing a lot of field work, which was just concluded in December 2018. The whole fall of 2018 was field work, working with households in 8 different countries, where they experimented with different ways of doing laundry - and not doing - laundry, and then also reduce the heating in homes.

*LG: Why especially household consumption? Did you already have a group in the SCORAI working on that special field of energy consumption?*

CLJ: Yes, it's always been a focus in the SCORAI, because we look at consumption: SCORAI stands for Sustainable Consumption Research and Action Initiative. So we've always been interested in sustainable consumption, and we chose the household level because we wanted to try out different approaches. We have two living labs in each country - and when I say "living labs" I don't mean the original definition of a living lab which is often quite technical. Ours are more kind of experiments. So we have two kind of experiments in each country: we do a collective approach, and an individual approach to see what kinds of changes that come about with different types of approaches. And the household level was chosen as a unit of analysis where different practices come together. So instead of just looking at only one practice and also not looking at very big systems, we chose something in between.

*LG: So you took this bottom-up approach, working with these households in different countries; how do you think that this brought a better understanding of consumption dynamics? Also the fact to bring people that are not necessarily familiar with physical concepts of energy to think about the way they use energy and how energy is embedded in their life? Was this something* *already done? If yes, what did this project bring to that?*

CLJ: It's a good question, because actually it has been a really big discussion in the ENERGISE project: how bottom-up this project is. Because we could have designed our living labs and the experiments we had in a manner of co-production and co-design with households; with households being involved in the process of deciding what types of consumption should we look at. But we decided not to do that; we decided to base our design on research already carried out where it's quite norm now that heating is a big part of household energy consumption. So we wanted to challenge that. There are also a lot of studies showing that laundry is often considered as a really flexible practice; particularly in "smart grids". Therefore, we designed some challenges that we posed to our participants, and then they had to try out these challenges. The challenge with laundry was to cut laundry cycles by half. We did a baseline with the households where they registered how often they did the laundry and why they did the laundry, and then for a 4-week period we asked them to cut it in half according to the baseline. And then experiment with a lot of different ways of being able to meet these challenges. And with heating we asked them to turn down to 18°C, which is really cold. But that was a way of making sure that it would be a challenge. And then we monitored what was easy, what was difficult, what seemed completely impossible, what did they already do to figure out, when change come about, then how does it come about and why. And when it doesn't come about, then why is that so. So we try to mimic some ethnographic approaches, but we have not been able to do really long term observations.

*LG: But you already managed to monitor the participants over a season; I never heard about any other similar project in the energy field, in the European context.*

CLJ: I think so too. The longevity of the project is one of the strong outcomes. It works if you ask someone to do something for a while, and it becomes part of their everyday life, to some extent. We have experienced some changes but not actually huge changes.

*LG: Now that the project is over, is there a kind of monitoring, maybe in a year, to see how this project influenced these people also in their life, whether they kept doing some of these practices?*

CLJ: Actually our project is not entirely over yet, it ends in November. But I should clarify this, because I was the Work Package lead of Work Package 2 which is over. I can come back later to Work Package 2 if you want to hear something about it. But just to kind of finalize this discussion about the living labs which is part of our Work Package 4, we have just had a follow-up with our participants 3 months after they ended their experiments, to see if people held on to some of the things that they did. And they have kept doing some of the things, especially in terms of laundry. It's super interesting that they decided to keep not doing laundry; they have a lot of non-water approaches now, where they put the clothes outside just to air it during the day or night, or they take away spots just by rubbing it off with a cloth instead of washing the whole item. They probably do it because it's much easier not to do laundry than to do laundry, whereas the heating thing is very different. It was much less easy for people to adapt, and that's obviously, I think, because you cannot ask someone to live at really cold conditions. Of course it's a cultural thing in terms of how hot you like your home to be, and you see differences across countries.

*LG: Were these big differences?*

CLJ: Actually yes, in the UK they have somewhat lower average temperature, which is probably very much related to the houses being very poorly insulated. So they are used to colder houses. But in some of the other countries, especially in the Northern hemisphere, we have Finland, Denmark, Germany, they have similar indoor temperature which are quite high.

*LG: It probably depends on insulation, and maybe income also - the possibility to pay for heating?*

CLJ: Yes it does but it's rarely a problem in Finland and Denmark, so we don't see that as a barrier so to speak. But what we see is really the unfamiliarity with the heating systems. It's very difficult to figure out your own heating system, whereas it plays a big role in how you manage the way you heat your home. It's not so transparent how you should regulate, and where the heating is coming from, … whereas laundry is something you have very close to you, you have your clothing close to your body and you have a sensoric approach to figuring out whether to do laundry or not.

*LG: That's interesting to see that they are already such differences in the way to manage these two types of consumption…*

CLJ: Yes, it is. And the size of the households is really one of our main outcome and conclusion, that if you want to cut down on energy consumption related to heating, the way how to do it is to live in a smaller house, because then you don't have to heat up a lot of square meters.

*LG: So not so much the temperature at the end…*

CLJ: Well, you can reduce a little bit, and our participants actually did reduce in average 1.5°C, which is not insignificant, but it's not really significant either. But we can see a change, and some actually felt more comfortable at home, especially in the bedroom when it was a little bit colder. So you can of course argue that you can trend down heating, and you can live with a lower temperature, but there is a limit so if you want to reduce even more, you'll have to tackle the square meters you heat up - especially when we don't use them.

*LG: We may come back to that later. Let's finish with the general questions on ENERGISE. When the project will be over in next November, what do you expect of the outcomes of this project? How do you hope that they can impact the research and the political world?*

CLJ: It's a good question and it's difficult to answer… I think that one of the really cool thing about our project is the experimental approach we had with the households, so that you actually co-produce change with households over a specific time where households can try out different ways of doing things. It's a safe space to try out, you provide a stage for people to try out new things, and they can commit to it as much as they want, and they all see what makes sense and what doesn't make sense in their everyday life. I think that's a strong take-away from the project, especially because several of our participants mentioned that they had liked that it had lasted for so long, and that it become more like a habit. So we don't just advise and provide information, but actually produce a temporary space for trying out other things. Maybe that will generate particular types of changes, maybe it won't. We see for instance that the type of the heating system and the way you manage it and the way it's not manageable plays a huge role in how you heat up your home. So I think we will be able to showcase that you have to consider consumption as something that happens across systems as well. Therefore you have to think about how you design homes, how you design heating systems, and of course you also have to think about how we live our lives, and how we live as a society, what we see as a good life. We can get into the whole debate of sufficiency to some extent; instead of thinking about efficiency, we think about sufficiency. This is also what you wanted to talk about earlier when you said that we should think about why we need to transport ourselves, and maybe challenge this need as well. So that's what we do, we really challenge the need of doing laundry, why do you do it that often; is it really because you need it, or is it because you think you need it.

*LG: That's for sure something to co-produce, some sort of knowledge that you also need to get these people who are actually using these devices. Those are actually the ones concerned who should also maybe give their opinion on whether they think this is useful or not, rather than it coming from elsewhere, and someone decides for the others what is useful and what is not.*

CLJ: Exactly, and I really think that our project can support this kind of approach.

*LG: The rebound effects are mentioned in the abstract of the project; how do you think they are regarded by the project, and how do you think the outcomes of the project could be limited, regarding the impact of these rebound effects?*

CLJ: I've actually just been looking at it as part of our analysis. We've asked participants in terms of how much money they think they have saved, if they think they have saved money or if they think they've saved time; because they won't be able to see it on their energy bill, so it's really a manner of trying to ask them about how do they think this has made any changes in terms of the energy use, money and time. Then we've asked about if they have experienced that they've saved time, then we've asked what did you use the time for. It's a bit of an abstract thing to do as a participant, but what I saw is that participants generally think that they only saved a bit of money, and that the savings will just be part of their regular everyday life, the way they would manage the households. In terms of time, some of the participants have actually experienced that they've saved on it, particularly in terms of laundry. They have used the time mainly to sleep longer, or for work or social activities. We asked if anyone wanted to use the savings for a travel or to buy a new product; and no one said that that would be the case. But I assume it's because the savings are not very big; if they had saved a lot of money I think a lot of them would have used it for a holiday, and then we would see this rebound effect.

*LG: Let's move on now to the Work Package 2 you've been leading. I read a little bit about what is it about; if I understood well, you tried to reference all the projects that were relating to energy consumption, and sort them out and find the more interesting ones to work on. Am*

*I right so far?*

CLJ: Yes, almost. The story of Work Package 2 is interesting; we wanted to explore really good examples of initiatives in Europe that are dealing with the energy consumption reduction in alternative ways. So we started this big review of initiatives to see if we could find any good examples. We had a bit of an abductive approach, we started to look at the field and we saw that there was a good foundation for developing a problem framing typology. That problem framing typology would then say something about the way that these different initiatives we have reviewed approach the problem of energy consumption. Not very surprisingly, we saw a lot of them take on a rather technical approach, or a behavioural approach, which is limited to telling someone to save water when showering; but it doesn't really tell you in what way you could do it, so it's really information based. And maybe some of the projects run some competition, then it's fun for a while, but that is really it. So we saw that there wasn't a lot of project going on that would consider the social organisation of our daily lives, and that you would have to target practices or broader systems. So we did that typology and we ended up with four different categories, which you may have seen. These categories relate to whether change is seen as a technological concern, a behavioural concern, as a matter of changing everyday life patterns, or if you see it as a matter of changing complex systems. That's really what we ended up with in our database, and also we have a few publications in the pipeline, talking about the policy implications.

*LG: How do you value that in the political world then?*

CLJ: That's really the tricky part, because it would probably require a whole different way of doing policies. The way policy is done now is often based on this neoclassical way of thinking about changes that are economically driven, and that you would only change something if you have an economic incentive; or that you have a rational way of choosing one thing over another. That's implicietly embedded in a lot of policies. If you have this embeddedness in the way you produce a policy, it will be very difficult to take into consideration a practice theoretical perspective that really argues for totally different ways of seeing change and continuity.

*LG: How would you apply this kind of typology you made to policies within different countries? Was it actually something already done?*

CLJ: No, we have only done this typology and we then discuss the policy implications; the reason why it's difficult to do it is because there is a tendency to not evaluate all the initiatives that happen. You've maybe seen that one of our concerns with the initiatives that we have looked at is that they are rarely evaluated, and if they are, they are evaluated in different ways. Therefore it's actually difficult to see what the outcome is - in terms of money saved or in terms of the CO2 emissions saved. This is one of the things that we argue for; that first of all, we should establish different ways of evaluating projects; no matter what kind of problem framing they build on, it should always be evaluated so that it's easy to compare the outcomes. We then suggest a whole different way of discussing the matters of concern - what should be the concern as policy maker if you adapt some of the problem framing that we suggest would be beneficial to adapt, and also what types of actors would you have to involve in this kind of policy. But that's really how far we've gone, and we do some final workshops based on our living lab process, where we invite different types of actors to discuss across sectors. Here in Denmark we will do a workshop in the end of May where we discuss the implications of change and the different spaces for action within which you can do something as a politician, a citizen or a business; I think that will be a very interesting output as well.

*LG: I would have a few questions around residential consumption before we wrap it up. First and relating to the typology of projects you realized, did you notice some projects that were also considering this relationship between floor space and residential consumption?*

CLJ: Actually not explicitly, which was interesting. We did come across a few projects that would have kind of a sufficiency approach - an absolute reduction approach - where they would think about what is your carbon budget; or what is your kilo-watt hour budget, and in that way of framing it, they potentially can address floor space; but I don't think they do it.

*LG: There has been some evidence in very different contexts in different countries in the world, and also in urban/non-urban contexts, but I didn't really see any project or bottom-up assessment looking at how was that actually tackled in practice, and I have the feeling that it's just not done, from what I could not find…*

CLJ: Yes, and that's also about, as Inge is writing in the paper that she's leading (Røpke and Jensen, 2018), how the policies, or the lack of policies in that case regulate these things. It's not really something I have done explicit research on, but if you think about the way consumer are considered, as individuals who have a complete sovereignty in their decisions, so no one can actually put a cap on - how big a house I can have, how many cars I should own - it's very difficult to regulate that because it can be perceived as an attack on freedom.

*LG: Is there actually a point developing policies that would specifically focus, or whether that should actually come from indirect policies on carbon emission restrictions, resource consumption restriction, which would then probably limit the energy consumption and eventually probably influence the size of the houses, because you would realize that the smaller house you have, the lower your consumption is.*

CLJ: I think that's a good way forward, but you would also probably have to consider the goals; why do we have big houses, can we make it actually nicer to have a small house. If it's only a restriction, you would probably spend the carbon you saved on something else…but from my personal opinion and without being an expert on that, I agree that indirect policies are probably better.

*LG: If you want to reduce consumption through this sufficiency approach where people would deliberately choose more sober ways of life, how fast do you think these changes can happen, taking into consideration that we are talking about socio-cultural norms deeply embedded in societies. You can see for instance with food that there are big changes in habits that are happening now, so how do you think that relates to the emergency we have now to have more* *sober energy systems?*

CLJ: I have the feeling that some of these things take for a while, and that it's also difficult to plan for these kind of changes. For instance we've seen in Denmark a boom in people drinking oak milk instead of cow milk, and there is this discourse going out right now, that it's a great way of reducing carbon emissions. That has happened quite quickly actually, of course it's not something that everyone is doing, but it has happened surprisingly quickly whereas other changes take a much longer time.

*LG: Especially when it comes to housing...*

CLJ: Yes and we have this big housing and building stock that is difficult to change. Of course when you build new houses if you think about building smaller houses then it can be one way forward but you still have all the older big houses, and it's not sustainable neither to put them apart and build new ones. It's a tricky question and it's not something I can answer for sure, but based on my experience and my research focus, these things happens because of a lot of different reasons, and you can't really be a transition manager.

*LG: Should actually be governed these kind of transitions? Aren't they finally observable but not really triggerable? Or how can a self-transition that maybe interplay with any planning process?*

CLJ: I would always argue for a practice-based planning. If you've read anything from Schatzki, he talks about the invisible hand which planners often have; and Elizabeth Shove has been talking about it also recently: planners in their position have an opportunity to plan for disrupting some certain practices and give space to other practices; but that's really all what they can do. If for instance you are planner and you plan a road then you can give a lot of space to bikes and buses and little space to cars, and see what happens. That's really the way to go about it, and then also employ more co-production; involving people and be sensitive to what activities and practices do they engage in. You have to understand why it happens, so that if you take part in disrupting it you have to be empathetic about that. That's really my stand on transitions. I don't think you can be a transition manager who sees everything from the outside: you as a transition manager will always be part of what you change. I believe in reflexive governance, but I'm not sure exactly how you should go about it.

# Bibliography


Adams, W. C. (2015). Conducting Semi-Structured Interviews. In Newcomer, K. E., Hatry, H. P., and Wholey, J. S., editors, *Handbook of Practical Program Evaluation*, pages 492–505. John Wiley & Sons, Inc., Hoboken, NJ, USA.

Arrobas, D. L. P., Hund, K. L., Mccormick, M. S., Ningthoujam, J., and Drexhage, J. R. (2017). The Growing Role of Minerals and Metals for a Low Carbon Future. Technical report, World Bank Group, Washington, DC.

Arrobbio, O. and Padovan, D. (2018). A Vicious Tenacity: The Efficiency Strategy Confronted With the Rebound Effect. *Frontiers in Energy Research*, 6.

Arts, B. and Tatenhove, J. V. (2000). Environmental policy arrangements: A new concept. In *Environmental Policy Arrangements: A New Concept (CRC Press/Balkema)*, pages 223–238.

Baiocchi, G., Creutzig, F., Pichler, P.-P., and Minx, J. (2015). A spatial typology of human settlements and their CO2 emissions in England. *Global Environmental Change*, 34:13–21.

Berrang-Ford, L., Pearce, T., and Ford, J. D. (2015). Systematic review approaches for climate change adaptation research. *Regional Environmental Change*, 15(5):755–769.

Bertoldi, P. (2017). Are current policies promoting a change in behaviour, conservation and sufficiency? An analysis of existing policies and recommendations for new and effective policies. *ECEEE Summer Study Proceedings*.

Bihouix, P. and de Guillebon, B. (2010). *Quel futur pour les métaux? Raréfaction des métaux: un nouveau défi pour la société*. Edp sciences edition.

Bjørn, A., Kalbar, P., Nygaard, S. E., Kabins, S., Jensen, C. L., Birkved, M., Schmidt, J., and Hauschild, M. Z. (2018). Pursuing necessary reductions in embedded GHG emissions of developed nations: Will efficiency improvements and changes in consumption get us there? *Global Environmental Change*, 52:314–324.

Bradbury, M., Peterson, M. N., and Liu, J. (2014). Long-term dynamics of household size and their environmental implications. *Population and Environment*, 36(1):73–84.

Brand-Correa, L. I., Martin-Ortega, J., and Steinberger, J. K. (2018). Human Scale Energy Services: Untangling a 'golden thread'. *Energy Research & Social Science*, 38:178–187.

Brand-Correa, L. I. and Steinberger, J. K. (2017). A Framework for Decoupling Human Need Satisfaction From Energy Use. *Ecological Economics*, 141:43–52.

Copiello, S. and Gabrielli, L. (2017). Analysis of building energy consumption through panel data: The role played by the economic drivers. *Energy and Buildings*, 145:130–143.

Court, V. (2018). Energy Capture, Technological Change, and Economic Growth: An Evolutionary Perspective. *BioPhysical Economics and Resource Quality*, 3(3).

Creutzig, F., Roy, J., Lamb, W. F., Azevedo, I. M. L., Bruine de Bruin, W., Dalkmann, H., Edelenbosch, O. Y., Geels, F. W., Grubler, A., Hepburn, C., Hertwich, E. G., Khosla, R., Mattauch, L., Minx, J. C., Ramakrishnan, A., Rao, N. D., Steinberger, J. K., Tavoni, M., Ürge-Vorsatz, D., and Weber, E. U. (2018). Towards demand-side solutions for mitigating climate change. *Nature Climate Change*, 8(4):260–263.

Crutzen, P. J. (2002). Geology of mankind. *Nature*, 415.

Edelstein, J. and Shriberg, M. (2011). Energy Conservation Framework. *Sustainability: The Journal of Record*, 4(5):245–250.

Enerdata (2018). ODYSSEE database on energy efficiency data & indicators. http://www.indicators.odyssee-mure.eu/energy-efficiency-database.html. Last accessed on 26.5.2019.

European Commission (2005). COM(2005) 265 final: Green Paper on Energy Efficiency or Doing More With Less.

European Commission (2007). Commission Regulation No 105/2007 amending the annexes to Regulation No 1059/2003 of the European Parliament and of the Council on the establishment of a common classification of territorial units for statistics.

European Commission (2009). Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products. *Official Journal of the European Union*.

European Commission (2010). Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. *Official Journal of the European Union*.

European Commission (2011). Roadmap to a Resource Efficient Europe. COM, 571.

European Commission (2012). Directive 2012/27/EU of the European Parliament and of the Council on energy efficiency of 25 October 2012 amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC. *Official Journal of the European Union*.

European Commission (2014). Energy Strategy and Energy Union. https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union. Last accessed on 28.2.2019.

European Commission (2016). COM(2016) 761 final: Proposal for a Directive of the European Parliament and of the Council amending Directive 2012/27/EU on energy efficiency.

European Commission (2017a). The ”Clean energy for all Europeans” package. https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/clean-energy-all-europeans. Last accessed on 20.3.2019.

European Commission (2017b). Regulation 2017/ 1369 of the European Parliament and of the Council of 4 July 2017 setting a framework for energy labelling and repealing Directive 2010/ 30/ EU.

European Commission (2018). List of energy efficient products Regulations: By product group. https://ec.europa.eu/energy/en/list-regulations-product-groups-energy-efficient-products. Last accessed on 7.2.2019.

European Environment Agency (2015). *The European Environment State and Outlook; Synthesis Report 2015*. EEA, Copenhagen.

Eurostat (2018a). Energy consumption in households. https://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_consumption_in_households#cite_note-1.

Eurostat (2018b). Regions in the European Union - Nomenclature of territorial units for statistics - NUTS 2016/EU-28, edition 2018. *Publication Office of the European Union*, page 158.

Eurostat (2019). Eurostat Database. https://ec.europa.eu/eurostat/data/database. Last accessed on 28.4.2019.

Fazeli, R., Davidsdottir, B., and Hallgrimsson, J. H. (2016). Residential energy demand for space heating in the Nordic countries: Accounting for interfuel substitution. *Renewable and Sustainable Energy Reviews*, 57:1210–1226.

Fischer-Kowalski, M. and Weisz, H. (1999). Society as hybrid between material and symbolic realms: Towards a theoretical framework of society-nature interaction. *Advances in Human Ecology*, 8:215–254.

Fremstad, A., Underwood, A., and Zahran, S. (2018). The Environmental Impact of Sharing: Household and Urban Economies in CO2 Emissions. *Ecological Economics*, 145:137–147.

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. *Research Policy*, 31(8-9):1257–1274.

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., Rao, N. D., Riahi, K., Rogelj, J., De Stercke, S., Cullen, J., Frank, S., Fricko, O., Guo, F., Gidden, M., Havlík, P., Huppmann, D., Kiesewetter, G., Rafaj, P., Schoepp, W., and Valin, H. (2018). A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nature Energy*, 3(6):515–527.

Gütschow, J., Jeffery, M. L., Gieseke, R., Gebel, R., Stevens, D., Krapp, M., and Rocha, M. (2016). The PRIMAP-hist national historical emissions time series. *Earth Syst. Sci. Data*, 8:571–603.

Hall, C. A. S. (2017). *Energy Return on Investment: A Unifying Principle for Biology, Economics, and Sustainability*. Number volume 36 in Lecture Notes in Energy. Springer, Cham.

Harris, J., Diamond, R., Iyer, M., Payne, C., Blumstein, C., and Siderius, H.-P. (2008). Towards a sustainable energy balance: Progressive efficiency and the return of energy conservation. *Energy Efficiency*, 1(3):175–188.

IIASA (2012). *Global Energy Assessment: Toward a Sustainable Future. Key Findings, Summary for Policy Makers, Technical Summary*. Cambridge Univ. Press, Cambridge.

Intergovernmental Panel on Climate Change (2014). *Climate Change 2014 Mitigation of Climate Change: Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge.

Intergovernmental Panel on Climate Change (2019). AR6 Climate Change 2021: The Physical Science Basis. Scientific Report.

International Energy Agency (2018a). Market Report Series: Energy Efficiency 2018. Technical report, OECD/IEA.

International Energy Agency (2018b). World Energy Balances 2018: Overview. Technical report.

Ivanova, D., Vita, G., Steen-Olsen, K., Stadler, K., Melo, P. C., Wood, R., and Hertwich, E. G. (2017). Mapping the carbon footprint of EU regions. *Environmental Research Letters*, 12(5):054013.

Jones, R. V., Fuertes, A., and Lomas, K. J. (2015). The socio-economic, dwelling and appliance related factors affecting electricity consumption in domestic buildings. *Renewable and Sustainable Energy Reviews*, 43:901–917.

Labanca, N. (2017). *Complex Systems and Social Practices in Energy Transitions*. Green Energy and Technology. Springer International Publishing, Cham.

Labanca, N. and Bertoldi, P. (2018). Beyond energy efficiency and individual behaviours: Policy insights from social practice theories. *Energy Policy*, 115:494–502.

Le Quéré, C., Korsbakken, J. I., Wilson, C., Tosun, J., Andrew, R., Andres, R. J., Canadell, J. G., Jordan, A., Peters, G. P., and van Vuuren, D. P. (2019). Drivers of declining CO2 emissions in 18 developed economies. *Nature Climate Change*, 9(3):213–217.

Lenton, T. M., Pichler, P.-P., and Weisz, H. (2016). Revolutions in energy input and material cycling in Earth history and human history. *Earth System Dynamics*, 7(2):353–370.

Lenzi, D., Lamb, W. F., Hilaire, J., Kowarsch, M., and Minx, J. C. (2018). Don't deploy negative emissions technologies without ethical analysis. *Nature*, 561(7723):303–305.

Liefferink, D. (2006). The Dynamics of Policy Arrangements: Turning Round the Tetrahedron. In Arts, B. and Leroy, P., editors, *Institutional Dynamics in Environmental Governance*, number v. 47 in Environment & Policy, pages 45–68. Springer, Dordrecht. OCLC: ocm71298892.

Lorek, S. and Spangenberg, J. H. (2019). Energy sufficiency through social innovation in housing. *Energy Policy*, 126:287–294.

Malischek, R. and Trüby, J. (2016). The future of nuclear power in France: An analysis of the costs of phasing-out. *Energy*, 116:908–921.

Maxwell, D. and McAndrew, L. (2011). Addressing the Rebound Effect. Technical report, European Commission DG ENV.

Moura, M. C. P., Smith, S. J., and Belzer, D. B. (2015). 120 Years of U.S. Residential Housing Stock and Floor Space. *PLOS ONE*, 10(8).

Nejat, P., Jomehzadeh, F., Taheri, M. M., Gohari, M., and Abd. Majid, M. Z. (2015). A global review of energy consumption, CO 2 emissions and policy in the residential sector (with an overview of the top ten CO 2 emitting countries). *Renewable and Sustainable Energy Reviews*, 43:843–862.

O'Neill, D. W., Fanning, A. L., Lamb, W. F., and Steinberger, J. K. (2018). A good life for all within planetary boundaries. *Nature Sustainability*, 1(2):88–95.

Otsuka, A. (2018). Population Agglomeration and Residential Energy Consumption: Evidence from Japan. *Sustainability; Basel*, 10(2).

Pitron, G. (2018). *La guerre des métaux rares; La face cachée de la transition énergétique et numérique*. Les liens qui libèrent edition.

Potocnik, J., Spangenberg, J., Alcott, B., Kiss, V., Coote, A., Reichel, A., Lorek, S., and Mathai, M. (2018). Sufficiency. Moving beyond the gospel of eco-effiency. Technical report, Friends of the Earth Europe, Brussels, Belgium.

Raworth, K. (2017). *Doughnut Economics: Seven Ways to Think like a 21st-Century Economist*. Random House Business, London.

République Française (2015). LOI n° 2015-992 du 17 août 2015 relative à la transition énergétique pour la croissance verte.

Richter, J. (2017). Energopolitics and nuclear waste: Containing the threat of radioactivity. *Energy Research & Social Science*, 30:61–70.

Rickwood, P. (2009). Residential Operational Energy Use. *Urban Policy and Research*, 27(2):137–155.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S. I., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R. W., Fabry, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., and Foley, J. (2009). Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society*, 14(2).

Røpke, I. and Jensen, C. L. (2018). Reducing the heated dwelling space in Denmark. *Paper presented at Third International Conference of the Sustainable Consumption Research and Action Initiative (SCORAI), Copenhaguen, Denmark*.

Royston, S., Selby, J., and Shove, E. (2018). Invisible energy policies: A new agenda for energy demand reduction. *Energy Policy*, 123:127–135.

Saghafi, M. and Ghofrani, M. B. (2016). Accident management support tools in nuclear power plants: A post-Fukushima review. *Progress in Nuclear Energy*, 92:1–14.

Serrano, S., Ürge-Vorsatz, D., Barreneche, C., Palacios, A., and Cabeza, L. F. (2016). Heating and cooling energy trends and drivers in Europe. *Energy*, 119:425–434.

Sheather, S. J. (2009). *A Modern Approach to Regression with R*. Springer Texts in Statistics. Springer, New York, NY.

Silva, S., Soares, I., and Pinho, C. (2018). Electricity residential demand elasticities: Urban versus rural areas in Portugal. *Energy*, 144:627–632.

Spangenberg, J. H. and Lorek, S. (2019). Sufficiency and consumer behaviour: From theory to policy. *Energy Policy*, 129:1070–1079.

Spengler, L. (2016). Two types of 'enough': Sufficiency as minimum and maximum. *Environmental Politics*, 25(5):921–940.

Statistics Sweden (2019). Statistical database. http://statistikdatabasen.scb.se. Last accessed on 9.4.2019.

Steinberger, J. K. and Roberts, J. T. (2010). From constraint to sufficiency: The decoupling of energy and carbon from human needs, 1975–2005. *Ecological Economics*, 70(2):425–433.

Taebi, B. and Mayer, M. (2017). By accident or by design? Pushing global governance of nuclear safety. *Progress in Nuclear Energy*, 99:19–25.

Thomas, S., Thema, J., and Kopatz, M. (2017). Energy sufficiency policy: How to limit energy consumption and per capita dwelling size in a decent way. *ECEEE Summer Study Proceedings*.

Toulouse, E. and Gorge, H. (2017). Stimulating energy sufficiency: Barriers and opportunities.

Underwood, A. and Zahran, S. (2015). The carbon implications of declining household scale economies. *Ecological Economics*, 116:182–190.

United Nations (2015). Adoption of the Paris Agreement - Proposal by the president. *Framework Convention on Climate Change*.

Ürge-Vorsatz, D., Eyre, N., Graham, P., Harvey, D., Hertwich, E., Jiang, Y., Kornevall, C., Majumdar, M., McMahon, J. E., Mirasgedis, S., Murakami, S., Novikova, A., Janda, K., Masera, O., McNeil, M., Petrichenko, K., Herrero, S. T., and Jochem, E. (2012). Energy End-Use: Buildings. In Johansson, T. B., Nakicenovic, N., Patwardhan, A., and Gomez-Echeverri, L., editors, *Global Energy Assessment (GEA)*, pages 649–760. Cambridge University Press, Cambridge.

Urge-Vosatz, D., Petrichenko, K., Staniec, M., and Eom, J. (2013). Energy use in buildings in a long-term perspective. *Energy Systems*, 5.

Voß, J.-P. and Bornemann, B. (2011). The Politics of Reflexive Governance: Challenges for Designing Adaptive Management and Transition Management. *Ecology and Society*, 16(2).

Wiedenhofer, D., Lenzen, M., and Steinberger, J. K. (2013a). Energy requirements of consumption: Urban form, climatic and socio-economic factors, rebounds and their policy implications. *Energy Policy*, 63:696–707.

Wiedenhofer, D., Rovenskaya, E., Haas, W., Krausmann, F., Pallua, I., and Fischer-Kowalski, M. (2013b). Is there a 1970s Syndrome? Analyzing Structural Breaks in the Metabolism of Industrial Economies. *Energy Procedia*, 40:182–191.

Wilhite, H. and Norgard, J. S. (2004). Equating Efficiency with Reduction: A Self-Deception in Energy Policy. *Energy & Environment*, 15(6):991–1009.

Williams, J. (2005). Sun, surf and sustainable housing—cohousing, the Californian experience. *International Planning Studies*, 10(2):145–177.

Wohlin, C. (2014). Guidelines for snowballing in systematic literature studies and a replication in software engineering. In *Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering - EASE '14*, pages 1–10, London, England, United Kingdom. ACM Press.

The tables of this report were generated with the “stargazer” R package version 5.2.2 for R ( https://CRAN.R-project.org/package=stargazer )