Dissertation

Energy Demand Assessment for Space Conditioning and Domestic Hot Water: A Case Study for the Austrian Building Stock

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To my family

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Abstract

In the past 10-15 years the building sector has increasingly come into the focus of European and national energy policies, as it plays a crucial role in any climate change mitigation strategy. Significant progress has already been made, especially regarding the thermal standard of new buildings. However, not all expectations regarding the decline of the national energy consumption of the considered end-use energy sector have been met.

One objective of this thesis is to (a) develop a model framework which is capable of assessing the mid- to long-term trajectories of the energy needs of heating, cooling and domestic hot water. It also assesses the associated final energy demand and how this development might be affected by different (policy) framework conditions. Furthermore, it (b) develops an input dataset for the model of the Austrian building sector, and (c) analyzes different futures for the assessed sector.

The outcomes of the first two objectives result in the Invert/EE-Lab model, a comprehensive modeling framework and a highly disaggregated numerical description of the Austrian building stock. Methodologically, the developed model is an engineering-based bottom-up model augmented by statistical bottom-up elements. The model kernel consists of three modules: the building physics energy calculation engine, the building demolition and building element replacement calculation module, and the investment decision module based on the concept of logit models combined with a technology diffusion model.

The Austrian energy demand for space heating and hot water under constant climate conditions and the energy carriers applied to supply the demand until 2030, are analyzed in three policy scenarios. The first two scenarios, the “with existing measures” (WEM) scenario and the “with additional measures” (WAM) scenario, describe (a) the currently implemented policy measures (implemented in 2012) and (b) additional measures, which are likely to be enforced within the next few years. According to these settings, the final energy demand will be reduced by between 15% (WEM) and 17 % (WAM) until 2030, compared to level of 2012. The third policy scenario implements additional, more ambitious policy settings after

2020. These policy settings in the WAM+-scenario will trigger additional energy savings of 8 TWh, resulting in a total reduction of 25% until 2030 compared to the level of 2012.

Finally, the impact of the climate change on the energy needs for the heating and cooling of the Austrian building stock until 2080 is evaluated. Under IPCC-A1B climate conditions (~3°C-scenario) the energy needs for heating will decline by about 25% until 2080 (~12% in 2050) compared to constant climate conditions. The analysis also reveals that the cooling is more sensitive to increasing temperatures. Depending on the regional climate model, cooling needs will increase by about 60%-100% until 2080 (40%-60% until 2050) compared to current climate conditions.

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Abbreviations

A1B	IPCC scenario family with rapid economic growth and a balance across all energy sources
AB	Apartment building
AC	Air conditioning
BGBl	“Bundesgesetzblatt” (Federal Law Gazette)
BMLFUW	“Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft“ (The Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management)
BMWFJ	“Bundesministerium für Wirtschaft, Familie und Jugend“ (The Austrian Federal Ministry of Science, Research and Economy)
CDD	Cooling degree days
CGE	Computable general equilibrium
CNRM	Centre National de Recherches Météorologiques
CP	Consumer preferences: If consumers are willing to accept higher prices / costs for certain technologies then also the expression Willingness-to-pay is used.
CRPC	Cost-resource-potential-curves
CSDM	Commercial Sector Demand Module of the NEMS model
DH	District heating
DHW	Domestic hot water: Water used, in any type of building, for domestic purposes, principally for drinking, food preparation, sanitation and personal hygiene (but not including space heating, swimming pool heating, or the use for processes such as commercial food preparation or clothes washing)
EIA	U.S. Energy Information Administration
EnEV	“Energieeinsparverordnung“ (German Energy Saving Regulations)
EOBS	The ENSEMBLES Observational gridded dataset: Observed climate conditions for the period 1981-2006 (sometimes also referred to as E-OBS).

	Also, a climate dataset for the period 1951-1980 exists, but is not used in this work.
EPBD	Energy performance of buildings Directive
GCM	Global climate model
GEV	Generalized extreme value
GFA	Conditioned gross floor area: This area includes all conditioned space contained within the thermal insulation layer.
HDD	Heating degree days
IG-L	“Immissionsschutzgesetz – Luft” (Air immission protection law)
IIA	Independence from irrelevant alternatives hypothesis
IIN	Independence of irrelevant nests (hypothesis)
IPCC	Intergovernmental Panel on Climate Change
LPG	Liquefied petroleum gas
MNLM	Multinomial logit model
MS	Member States of the European Union
NEMS	National Energy Modeling System
NFA	Conditioned net floor area, corresponds to the term of useful floor area as used in Directive 2012/27/EC
NLM	Nested logit model: Common approach in the field of discrete choice models
NREAP	National renewable energy action plan submitted in 2010 according to the (*Directive 2009/28/EC on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC*, 2009)
ÖROK	“Österreichische Raumordnungskonferenz“ (Austrian Conference on Spatial Planning)
RCM	Regional climate model
RDM	Residential Demand Module of the NEMS model
RES	Renewable energy sources
RES-H	Renewable energy sources for heating
RES-H/C	Renewable energy sources for heating and cooling
SSCD	Semi synthetic climatic data

TOC	Total costs of heating and domestic hot water preparation: Comprises form consumption-dependent (energy) costs, consumption-dependent annual operating costs and the levelized investment costs.
WAM	With additional measures; scenario with policy measures which are under discussion in Austria and are most likely to be applied within the upcoming years.
WAM+	With ambitious measures; scenario with additional ambitious policy measures introduced in 2021.
WEM	With existing measures; scenario with policy measures which were implemented in Austria by spring 2012.

Symbols, units, sets and subscripts

Nomenclature

A	*Area [m^2]*
a	*Age [yr]*
b	*Index (building segment)*
bca	*Index (building category)*
c	*Annual specific costs (per area or energy) [€/m^2, €/(k)Wh]*
CiDD	*Cooling indoor-degree days [Kd]*
E	*Energy in general (including all energy carriers and energy needs, except heat and work [Wh]*
ec	*Index (energy carrier)*
ecr	*Index (energy carrier region)*
f	*Policy factor technology factor or calibration factor [-]*
H	*Hear transfer coefficient [W/K]*
h	*Surface coefficient of hear transfer [W/m^{2}K]* *or hours [h]*
HDD	*Heating degree days [Kd]*
I	*Capital costs [€]*
k	*Shape factor Weibull distribution [-]*
n	*Discrete number of countable objects [-]*
	Simulation step width [yr]
Q	*Quantity of heat [(k)Wh]*
q	*(Area-)Specific quantitiy of heat [(k)Wh/m^2]*
r	*Ratio [-]*
s	*Share [-]*
t	*Time [yr]*
P	*Electrical or thermal Power [W]*
x	*Factors [-]*
Y	*Household income or budget [-]*
b,l,i,j,k,m,n	*Scalar* $\in \mathbb{N}$

Greek letters

α	*Elasticity [-]* *Annuity factor [yr^{-1}]*
β	*Scaled variance of decision parameter [-]*
ε	*Sensitivity, uncertainty or random-error indicator*
δ	*Decay rate [-]*
η	*Efficiency [-]*
κ	*Technology factor [-]*
λ	*Characteristic lifetime of elements [yr]*
μ	*Penalty (neg. utility function, aka “costs”) of alternative [-]*
θ	*Centigrade temperature [°C]*
σ	*Standard deviation*
Φ	*Cumulated failure rate [-]*

Sets

B	*Buildings*
BCA	*Building categories*
EC	*Energy carriers*
ECR	*Energy carrier regions*
I	*Technology options*
HSCAT	*Heating system categories*
SOL	*Solar thermal technologies*

Subscripts

35	*35°C supply line temperature*
a	*Area*
adapt	*Adapted*
air	*Air*
ambient	*Ambient energy (utilized by heat pumps)*
aux	*Auxilliary (power)*
B	*Set of buildings*
b	*Building (segment)*
BC	*(Set of) Buidling class(es)*
bca	*Building category*

boiler	*Heat generation (boiler) and storage*
BS	*(Set of) Buidling segment(s)*
build.	*Building*
building side	*Building location specific*
C,nd	*Energy needs for space cooling*
corr	*Corrected*
cost	*Cost*
CR	*Climate region*
C,sys	*Energy use for domestic cooling*
cum.replaced	*Cumulated replaced*
dec	*Decrease*
demolition	*Demolition*
DHW	*Domestic hot water*
DWHloss,revover	*Recoverable losses from DHW distribution*
DHW,nd	*Energy needs for domestic hot water*
DHW,sys	*Energy use for domestic hot water*
distr	*Space heating or DHW distribution system*
district heating	*District heating*
dw	*Dwelling*
dyn	*Dynamic*
e	*External (outdoor)*
ec	*Energy carrier*
econ_feas	*Economically feasible*
ecr	*Energy carrier region*
FED	*Final energy demand*
fl	*Floor area*
fossil	*Fossil energy carrier*
gfa	*(Heated) Gross floor area*
hdd	*Heating degree days*
H,gain	*Energy gains for space heating*
H,nd	*Energy needs for space heating*
household	*Household*
HP	*Heat pump*
hs	*Space heating system*
H,sys	*Energy use for heating*

i	*Technology option*
inc	*Increase*
Info	*Information*
initial	*Initial*
Invert/EE-Lab	*Defined in the Invert/EE-Lab model*
j	*Technology j*
LDM	*Logistic diffusion model*
m	*Mid point or technology index*
max	*Maximum*
measure	*Measure*
min	*Minimum*
MNLM	*Multinomial logit model*
N	*Nominal (power)*
nest,R	*Nest R of Nested logit model*
nfa	*Net floor area*
NLM	*Nested logit model*
non-ren	*Non-enewable energy carriers*
Norm	*Calculation according to calculation standard*
op	*Operative (set temperature)*
opt	*Operation (hours)*
orig	*Orignal status (before renovation)*
P	*Pumps (heat distribution)*
r	*Technology index r*
ren	*renovation*
ref	*Reference*
run	*Running*
s	*Set-point*
scale	*Scale*
set	*Set-point*
sim.step_width	*Simulation step width*
simplified	*Simplified compared to Calculation standard EN 15603*
sol	*Solar*
t	*Simulation period or temporal temperature setback*
tr	*Transmission*
use	*User factor tr Transmission*

ve	*Ventilation*
θ_{SL}	*Supply line temperature of heat distribution system*

1 Introduction

1.1 Motivation

The European directives and policy framework documents require member states to monitor and report regularly the progress regarding renewable energy employment and energy efficiency improvements (see section 1.4). In order to properly assess the effects of implemented policy measures as well as the impact of future target settings, well-established and scientifically-based tools are required. Therefore there is a growing need for tools investigating the energy demand in the building stock, the potential for greenhouse gas (GHG)-reduction by thermal renovation activities, and renewable heating and cooling (RES-H/C), as well as pathways for the exploitation of these potentials.

A number of such tools with specific strengths, limitations, features and focuses have been developed so far (see section 2). Considerable challenges have to be addressed by these models with respect to data requirements and data availability and the scope aimed at in the subsequently performed analyses. Thus, different top-down and bottom-up approaches have been chosen to overcome these challenges, and models which are either mainly built on statistical data (e.g. econometric models, input-output top-down models, statistical bottom-up models) or which rather describe the underlying processes, technical or socio-economic (e.g. CGE-models, engineering-based bottom-up models) were developed. Furthermore, approaches can be distinguished according to their underlying mathematical solving mechanisms, such as optimization or simulation, and/or the degree of freedom (e.g. tools with or without endogenous decision-making algorithms).

The work presented in this thesis contributes to this field of research by developing and applying the Invert/EE-Lab model. This is a techno-socio-economic bottom-up cohort model of the building stock. It endogenously calculates the replacement of buildings and building components and the market acceptance of different renovation measures and heating systems. This thesis develops the methodology and discusses selected scenarios and their results in the case of Austria.

1.2 Objective and scope

The main objective of this thesis is to (a) develop a comprehensive modeling tool capable of

- determining the current energy needs for heating, cooling and domestic hot water and the associated final energy demand,
- analyzing their possible mid- (2030) to long-term (2050) trajectories,
- endogenously assessing how the development might be affected by different framework conditions such as energy policy settings, energy or CO_2 prices, the climate change or resource availability.

It aims to (b) gather building- and energy-related data to set-up a disaggregated cohort model of the Austrian built environment and to (c) analyze future trajectories for the end-use sector in question.

To meet this objective, the following modeling-related questions are addressed in this work:

- What is a suitable structure for a bottom-up model capable of processing a highly disaggregated description of the building stock?
- How to integrate an appropriate engineering-based calculating method for deriving the buildings' energy needs in such a building stock model?
- How to model the end-of-service lifetime and corresponding replacement of buildings and building components?
- How to model the decision-making process for different renovation and heat supply related measures?

Concerning its scope, this thesis considers the following system boundaries:

- This work focuses on the energy demand of space conditioning (heating and cooling) and domestic hot water preparation and associated measures impacting these properties. The energy needs are calculated including internal loads due to occupation, lighting and appliances. However, lighting and appliances are not modeled endogenously. Furthermore, the air conditioning systems are not within the scope of the model. Thus only the energy needs for cooling but not the energy use (or delivered energy) for cooling is calculated.

- The regional system boundary of this work is Austria. The modeling approach itself is not restricted to Austria and has also been applied to other countries. Yet, they do not form the focus of this thesis.
- The time horizon of the developed policy scenarios is set by the year 2030. To investigate the impact of the climate change, model runs were also carried out until 2080.

1.3 Methodology

This thesis applies a quantitative model-based approach. To address the questions raised above, the following tasks were carried out:

1. **Setting up the methodological framework**

A comprehensive tool, the Invert/EE-Lab model was developed by the author during the last 5 years. The developed model is a dynamic, highly disaggregated, techno-socio-economic bottom-up simulation tool. With this tool the existing energy needs, the final energy demand, and the delivered energy for space heating, space cooling and domestic hot water preparation of the building stock of a specific region or country, as well as its possible future developments, can be described and analyzed. The energy-calculation module is based on a quasi-steady-state monthly energy balance approach augmented by statistical top-down and bottom-up factors (section 4.4).

The developed model allows investigating the effects of different drivers and barriers such as policy settings (in particular different economic and regulatory instruments), energy prices, behavior and technological development on the energy carrier mix, CO_2 reductions and costs for support policies. The implemented decision algorithm applies the following concepts:

- The end-of-service lifetime of buildings and building components is calculated based on Weibull-distributions and a calibration of historical investment and renovation cycles (assuming the Weibull-characteristics in the past renovation activities) is performed, see section 4.5.

- The market uptake of different renovation measures and heating systems are calculated using a nested logit approach, see section 4.7.
- Different barriers related to diffusion and resource restrictions are considered, see section 4.7.

2. Collecting data

Based on an input dataset for the Austrian residential building stock (Schriefl, 2007), this thesis develops an updated and highly disaggregated (quantitative) description of the total heated Austrian building stock and its energy-related parameters. The developed dataset enhances existing sets in several ways. First, to the author's knowledge, it is so far the only calibrated quantitative description[1] of the Austrian residential and non-residential[2] building sector. The current final energy consumption of space heating and domestic hot water per energy carrier is calibrated on the level of federal states. Furthermore, it differs from other databases for the Austrian building stock in its highly spatially disaggregated definition, which is based on work that was conducted by the author of this thesis within the projects "PRESENCE" (Müller et al., 2014a, Kranzl et al., 2014a) and "Solargrids" (Müller et al., 2014c), both funded by the Austrian climate and energy fund. Building on spatially distributed settlement areas on a 250x250 meter grid (Figure 3.3), the future development of the heated floor area are estimated for 20 building categories on the level of 2380 municipalities. For the policy scenario analysis the data are aggregated into 73 regions (section 3.2). The availability of energy carriers and the share of buildings located in air-imission-protection law regions are estimated for 26 regions[3]. However, the data structure allows a redistribution of the scenario results on the level of municipalities or even the 250x250 m grid[4].

Scenario specific data were defined and developed in several projects with major contributions of the author of this thesis. Most importantly, the projects "Energieszenarien bis

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[1] Again, only energy related parameters are considered.

[2] Service sector and industry are included except for buildings without regular heating systems such as agricultural buildings (barns, stables, greenhouses, etc.), or large-scale industrial production halls.

[3] Three regions per federal state are defined, except for Vienna which is only divided into two regions.

[4] Due to the applied generic algorithm, redistributing to the 250x250 grid has its limitations.

2030: Wärmebedarf der Kleinverbraucher“[5] (Müller and Kranzl, 2013a, 2013b) and the project “PRESENCE” (Kranzl et al., 2014a) have to be mentioned in this context.

3. Carrying out simulation runs

Finally, simulation runs were carried out and scenarios derived. The results of the model runs are analyzed with considering two dimensions. First, the stability of results and uncertainties related to the actual implementation of the model and its input parameters are tested (see chapter 5). In a second step, the third purpose of this thesis, namely the possible future development of the energy demand of the Austrian building stock and the impact of policy instruments and general framework conditions is assessed (see chapter 7).

1.4 Policy Background

During the last decade the building sector has increasingly come into the focus of European energy policies (Directive 2002/91/EC, Directive 2010/31/EU, Directive 2006/32/EC, Directive 2009/28/EC), as it is evident that this sector plays a crucial role in any ambitious climate change mitigation strategy. Significant progress has already been made in some region and building classes, especially regarding the thermal standard of new buildings. At the same time, not all expectations regarding the reduction of measured energy consumption on a national level have been met. The inertia of the building stock’s energy infrastructure, the slow uptake and diffusion of innovative technologies and rebound effects have to be taken into consideration in a comprehensive in-depth analysis of the sector, as well as for deriving effective and efficient policy instruments.

On a European level, three framework directives directly address the energy needs, the final energy demand of and the delivered energy to buildings. The Directive 2010/31/EU (EPBD recast) on the energy performance of buildings (EPBD), which is the recast of the EPBD 2002 (Directive 2002/91/EC), is probably the most important directive for the building sector. The EPBD recast fosters the requirements on the energy needs and final energy consumption compared to that defined in the predecessor. Within the directive, a number of requirements for the energy demand of buildings are defined:

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[5] Translates to “Energy scenarios until 2030: Heat demand of the households and service sector”.

- Article 3 states that Member States of the European Union have to apply a methodology for the energy performance calculation of buildings according to a common general framework set out as defined in the Annex I of the directive. This should ensure that the energy performance calculations individually performed in each member state are based on common ground so that the different countries can be compared.
- Article 4 and article 7 demand of member states to (a) define minimum energy performance requirements for buildings, and (b) to make sure that these requirements are close to the cost-optimal levels when applying a life-cycle-cost approach.
- Article 6 defines that in new buildings a high-efficiency alternative heating system (such as cogeneration, heat pumps, district heating, and renewable energy carriers) have to be installed if this is technically and economically feasible.
- Article 9 specifies that Member States have to ensure that by the end of 2020 all new buildings are nearly zero-energy buildings[6]. This standard is defined as "*a building that has a very high energy performance […]. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby;*"

The second important European directive, the renewable energy directive (Directive 2009/28/EC) has an impact on the built environment insofar, as it defines a minimum share of energy per Member State that has to be supplied from renewable energy carriers. Although no targets for sectors are defined in the directive, studies have shown that the building sector needs to contribute significantly in order to meet the defined targets in a cost-efficient way (see Beurskens and Hekkenberg, 2011; Ragwitz et al., 2012; Türk et al., 2012). Moreover, article 13(4) requests member states to *"introduce in their building regulations and codes appropriate measures in order to increase the share of all kinds of energy from renewable sources in the building sector."*

Finally, the energy efficiency directive (Directive 2012/27/EU) targets the energy consumption of buildings in several ways:

- Article 4 addresses building renovation and demands from the member states (MS) of the European Union to establish a long-term strategy for mobilizing investments in the

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[6] For publicly owned and occupied new buildings this target has to be reached by end of 2018.

renovation of the building stock. This strategy should contain policies and measures to stimulate cost-effective deep renovations of buildings.

- Article 5 emphasizes the exemplary role of the buildings of public bodies. This article states that MS *“shall ensure that, as from 1 January 2014, 3 % of the total floor area of heated and/or cooled buildings owned and occupied by its central government is renovated each year”*. The renovated buildings have to *“meet at least the minimum energy performance requirements as set in application of Article 4 of Directive 2010/31/EU”*.
- Article 6 demands from public bodies a preference for buildings with higher energy performance indicators when renting or buying buildings, insofar as they are cost-effective and economically feasible as well as technically suitable.
- Article 9 addresses the individual metering of delivered energy to final costumers of electricity, natural gas, district heating, district cooling and domestic hot water. MS have to ensure that the energy meters installed in buildings accurately reflect the customers’ energy consumption and provide information on the actual time of use.
- Article 14 addresses efficient heating and cooling and demands that MS carry out a comprehensive assessment of the application of efficient cogeneration and district heating and cooling. If heat generation units exceeding a thermal input of 20 MW are planned or if existing units in district heating networks are substantially refurbished, a cost-benefit analysis for applying cogeneration or for using waste heat from nearby industrial installations has to be performed.

On the Austrian level, the “EnergieStrategie Österreich”[7] (BMLFUW and BMWFJ, 2010) defines the short-term energy policy framework conditions. In this document, a final energy consumption target of 1100 PJ for 2020 is defined. This target corresponds to a stabilization of the current final energy consumption. With respect to the final energy consumption for space heating and cooling, the document foresees a reduction from 337 PJ in 2005 to 303 PJ in 2020 (-10%).

In Austria, the EPBD (recast) is implemented in various documents. The Austrian Institute of Construction Engineering[8], for example, has released an important document

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[7] Translates to: “Austrian Energy Strategy“.

[8] In German: “Österreichisches Institut für Bautechnik“ (OIB).

defining nearly zero energy buildings and intermediate targets in a “national plan”[9] (OIB, 2012a) for a path towards minimum standard of new and comprehensively renovated buildings until 2020. With some exemptions this document has already been adopted by the Austrian federal states. In April 2014, an updated version (OIB, 2014), which also contains targets for non-residential buildings was submitted to the European Commission. Moreover, cost-optimality calculations are carried out to compare the current and different future building codes with respect to their cost-optimality. The Austrian national renewable energy action plan (NREAP-AT, BMWFI, 2010) indicates sectoral targets for renewable energy, including the heating and cooling sector. The document does not distinguish between space heating and process heat, therefore specific targets for the space heating and domestic hot water energy end-use sector cannot be derived. After several elaborated legislative proposals, the energy efficiency act implementing the energy efficiency directive was adopted in Austria by June, 2014 (BGBl, 2014).

1.5 Definition of applied energy terms

In literature a large number of different terms are used to describe the energy demand and energy consumption[10] in buildings. However, the commonly used terminology for energy flows in buildings and associated system boundaries is different in various scientific disciplines and contexts, in particular in the disciplines of energy economics and civil engineering. In the discourses of energy economists, a community this work addresses, terms like “*useful energy demand*” or “*final energy demand*”[11] are often used, probably triggered by their widely usage in the context of energy balances. However, these terms only refer partly to the wording “*energy need*” and “*delivered energy*” as defined by the EN15603:2008, which is well known in the building physics and civil engineering communities. While the term “*final energy demand*” departs from the term “*energy use*” depending on whether local renewable energy carriers are taken into account or not, the differences between “*energy need*” and “*useful energy demand*” are not always as clearly drawn. The German and Austrian energy calculation standards refer to the expression “*Nutzenergiebedarf*”, which, if it is

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[9] German title: “Dokument zur Definition des Niedrigstenergiegebäudes und zur Festlegung von Zwischenzielen in einem ‚Nationalen Plan‘“.

[10] *Energy consumption* refers to the utilization of energy carriers.

[11] Instead of “energy demand”, also the terms “energy consumption” or “energy use” are used.

directly translated means "*useful energy demand*". This "*Nutzenergiebedarf*" corresponds to the expression "*energy need*" as defined by the EN 15603. However, a technical definition of the term "*useful energy*", especially related to energy flows in buildings, is not given. The glossary of the "Europe's Energy Portal" (EU BCN) defines "useful energy" as "*the energy drawn by consumers from their own appliances after its final conversion, i.e. in its final utilization*". Andersen (2007), on the other hand, defines "useful energy demand" as "*the demand for energy services such as heating and lighting*", also referred to as "*energy-service demand*". Furthermore he states that:

> "*Useful energy demand may be the desire to have for example 20°C in-doors or a demand expressed in tons of paper production. This means that useful energy demand does not necessarily have to be expressed in energy terms. However, in an energy systems model, such as the ones used here*[12]*, useful energy demand is generally expressed in energy units. The demand for 20°C may be expressed in, for example W/m² given the insulation for a specific type of building.*"

The following section aims to clarify the system boundaries and meanings of the different energy related terms, which are then consistently applied in this thesis. However, when referring to work carried out by other authors (especially in chapter 2), the terminology used in their publications is applied in this thesis, even though the actual system boundaries remain unclear and inconsistent. Whenever an unspecific energy flow is addressed in this work, either the expression "*energy demand*" or "*energy consumption*" is used. In this work these terms are meant to describe energy flows with loosely and flexibly defined system boundaries, somewhere in-between the terms "*energy need*", "*final energy demand*", "*energy use*" and "*delivered energy*". The term "*energy demand*" is used in a context where a calculated energy flow is addressed, while "*energy consumption*" rather refers to measured energy flows.

In this work I focus on the definitions and system boundaries as defined in the EN 15603 and EN ISO 13790 standards. Although these terms defined in these norms are well-known in the building physics and civil engineering community, they are (or used to be) widely unknown in the energy economics community. Thus, using these terms often leads to confusion when discussing the results with representatives of the latter group. On the other

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[12] MARKAL models are meant.

hand, the cited standards do not specify the expression "*final energy demand*", a term defined by the European directive 2009/28/EC and thus very important to the energy economics community. For clarification, the Figure 1.1 defines the boundaries for different energy related terms in this work.

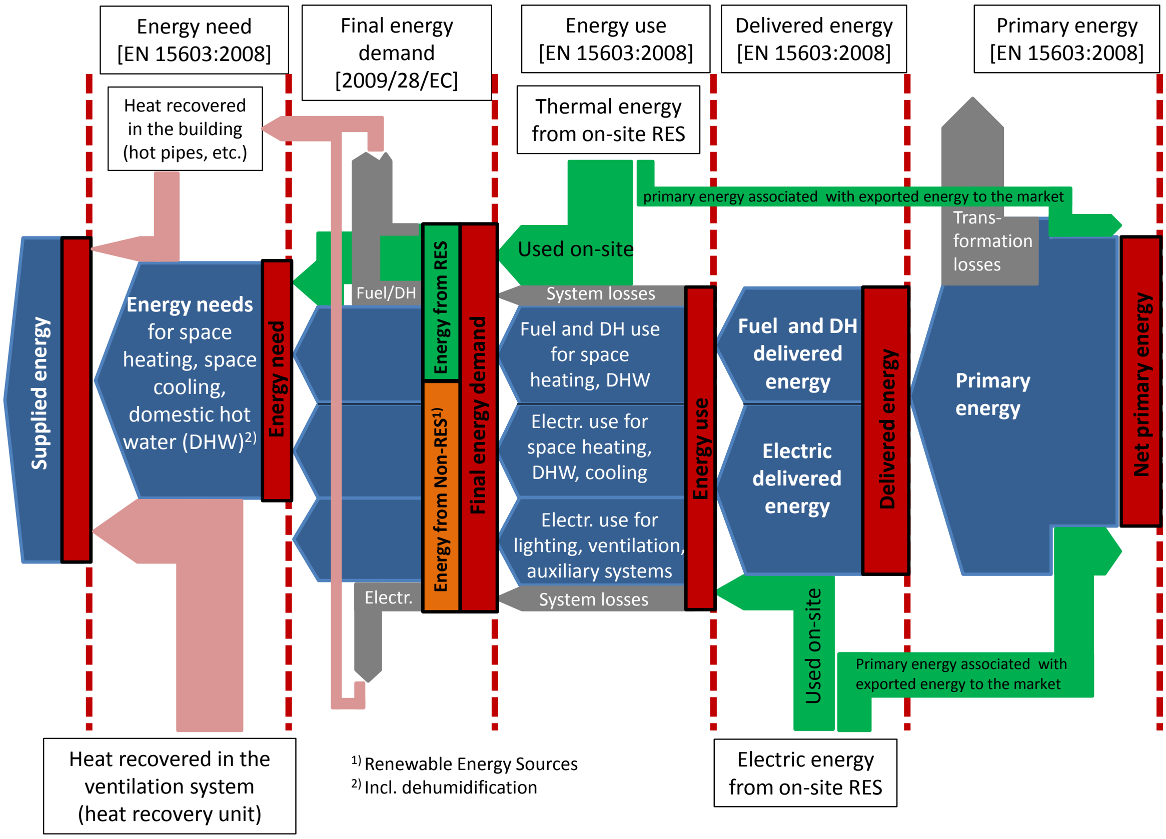

Figure 1.1 – System boundaries for different types of energy terms used.

A second dimension of the heating and cooling-related energy usage in buildings is not depicted in this figure, but has to be kept in mind: the difference between measured and calculated (standard or tailored energy need calculation) energy need or energy use. The *final energy demand*, as defined by the Directive 2009/28/EC refers to physical flows (measured data on a national level). One the other side of the spectrum lies the energy need based on the standard calculation approach, which does not incorporate site-specific parameters such as the local climate or the actual 24/7 usage of the building. The tailored energy need calculation incorporates such factors and lies somewhere in-between. This calculation method aims to decrease the deviation between the measured energy use or delivered energy and the calculated equivalents.

The developed Invert/EE-Lab model addresses both approaches: the standard and the tailored energy demands. The energy needs are calculated based on the standard calculation method and a tailored approach, which considers, based on various statistical bottom-up and top-down parameters, systematic behavioral aspects such as the dependency of the energy consumption on the thermal quality of the building envelope, the dwelling specific conditioned floor area, and the energy costs.

The expression *energy needs* used in the following chapters refers to the standard energy need calculation approach. Whenever the energy needs based on the tailored approach are addressed, the expression *energy needs considering user behavior* is applied. The final energy demand shown in this work is, if not explicitly stated otherwise, calculated based on the tailored approach.

1.6 Structure of this thesis

The remainder of this thesis is structured as followed:

Chapter 2 starts with a classification of different modeling approaches. It briefly discusses the strengths, weaknesses and typical scope of the different methodologies. Based on this typology, an overview of existing building-related energy models found in literature and their applications is given. Finally, it classifies the model developed in the course of this thesis based on the discussed modeling approaches and describes how it departs from existing models.

Chapter 3 describes the current Austrian building stock, the applied technologies for heat generation and their observed market trends. It outlines the methodology of how the spatial distribution of buildings and the applicability of energy carriers is determined. Based on these data, the calibration of the final energy demand for space heating and domestic hot water preparation is shown.

Chapter 4 is devoted to the developed model, the Invert/EE-Lab model. It describes the applied approach and the three calculation modules: the energy calculation module, the lifetime module and the investment decision module. For each module, the most important implemented equations are given and discussed.

Chapter 5 analyses the uncertainties of results deriving from the actual implementation of the model and uncertainties with respect to the decision criteria and unobserved parameters.

Chapters 6 and **7** describe the scenarios for the Austrian built environment and the development of its energy demand for space heating. Chapter 6 outlines the assumptions for the main input variables used to derive the policy scenarios. Chapter 7 reports and depicts the scenario results.

Chapter 8 summarizes the key findings and draws conclusions derived from the results of the former chapters.

2 Existing building-related energy models and their approaches

This chapter briefly presents existing approaches to model the energy demand and energy consumption of buildings. Such overviews and comparisons have already been given extensively by other researchers, either on a detailed model-by-model-based analysis or already on a meta level (e.g. Huntington and Weyant, 2002; Nakata, 2004; Böhringer and Rutherford, 2008, 2009; Strachan and Kannan, 2008; Swan and Ugursal, 2009; Tuladhar et al., 2009; Kavgic et al., 2010; Suganthia and Samuel, 2011; Keirstead et al., 2012; Olofsson and Mahlia, 2012; Kialashaki and Reisel, 2013 or Pfenninger et al., 2014[13]).

Models can be categorized in several ways. Hourcade et al. (1996) use three characteristics to classify models: (1) the purpose of the model, (2) the model structure and (3) their exogenously defined input assumptions. Grub et al. (1993), on the other hand, define six categories to distinguish (energy) models: (1) top-down versus bottom-up, (2) time horizon, (3) sectoral coverage, (4) optimization versus simulation techniques, (5) level of aggregation, and (6) geographic coverage, trade, and leakage. Van Beeck (1999) defines[14] 9 dimensions according to which models can be classified and describes each of these approaches in her paper:

1. General and specific purposes of energy models
2. The model structure: internal & external assumptions
3. The analytical approach: top-down vs. bottom-up
4. The underlying methodology
5. The mathematical approach

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[13] They performed a (meta) review of another 10 meta reviews.

[14] Based on Vogely (1974), Meier (1984), APDC (1985), Munasinghe (1988), Kleinpeter (1989), World Bank (1991), Grubb et.al. (1993), IIASA (1995), Kleinpeter (1995), Hourcade et. al. (1996) and Environmental Manual (1999).

6. Geographical coverage: global, regional, national, local, or project
7. Sectoral coverage
8. The time horizon: short-, medium-, and long-term
9. Data requirements

In the following sections, I will first briefly describe the underlying methodology (4) and then focus on the analytical approach (3).

2.1 Classification based on the underlying methodology

The fourth dimension of Van Beeck's classification, the **underlying methodology**, considers the way the model is driven towards its solution. She defines 8 commonly used methodologies: (1) econometric, (2) macro-economic, (3) economic equilibrium, (4) optimization, (5) simulation, (6) spreadsheet, (7) backcasting, and (8) multi-criteria, although these distinctions are, in practice, not always very conclusive. According to her research, literature distinguishes between simulation, optimization and spreadsheet models only with respect to bottom-up models, even though these techniques are applied by top-down models.

The optimization approach

An optimization approach aims for the minimization (e.g. costs, CO_2-emissions) or maximization (e.g. profits) of an objective function. The results of such models are solutions found by the algorithm which are considered as optimal (or close to the optimum) with respect to the objective (or target) function. Therefore optimization models are prescriptive rather than descriptive. This means that this approach can rather be used for "*how to*" instead of "*what if*" research questions (Ravindranath et al., 2007). Van Beeck's fifth dimension, the **mathematical approach,** defines how optimization models solve the problem. Most energy-related optimization models use common mathematical methods such as Linear Programming (LP), Mixed Integer Linear Programming (MILP), Multi-Objective Linear Programming (MOLP) and Dynamic Programming (DP) to derive their solutions. Only some energy models use more advanced methods such as Non-Linear Programming (NLP), Mixed Integer Non-Linear Programming (MINLP), and (Multi-Objective) Fuzzy (Linear) Programming ((MO)F(L)P).

Jebaraj and Iniyan (2006) give an overview of 30 optimization models. Ravindranath et al. (2007) describe and assess another 16 publications related to decentralized energy planning using an optimization approach. While the optimal allocation of different energy carriers or the optimal GHG emission reduction targets between different economic sectors are often analyzed, none of these publications or optimization models focus on emission or energy reduction strategies within the building sectors. This supports the commonly held position that conventional optimization techniques, which tend to show "penny switching behavior"[15], are not particularly suitable to analyze systems where many individual decision-makers decide on many rather small subjects. The Fuzzy Logic approach (or Fuzzy Programming, FP) constitutes an improvement with respect to such model behavior. Similar (in a non-mathematical definition) to the logit model and other probability approaches commonly used in discrete choice analysis, Fuzzy Logic allows that a variable is "partly true" and defines "*how much*" a variable is a member of a set. Thus, Fuzzy Logic approaches are more suitable to find realistic solutions for decentralised optimization problems with a medium or high degree of uncertainty than conventional approaches (Zimmermann, 1978; Jana and Chattopadhyay, 2004).

The MARKAL (*MARKet ALlocation*) model, the TIMES (*The Integrated MARKAL-EFOM System*) model, the MESSAGE model (*Model for Energy Supply Systems And their General Environmental impact*), and the OSeMOSYS (*Open Source Energy* Modeling *System*) are well-known and widely applied energy system optimization models (Pfenninger et al., 2014).

The simulation approach

The simulation approach does not consider inherently the optimality of a solution but just aims to explore a solution based on a set of input (decision) data. The optimality of such a resulting state can be assessed by comparing different solutions, yet this is not within the scope of the simulation algorithm. Lacking an inherently systematic approach to evaluate the optimality of derived solutions is considered to be the main disadvantage of the simulation approach. The benefit of the method is that models do not need to be as restricted and simplified as they need to for optimization approaches in order to find a solution that is sufficiently close to the optimum.

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[15] The utilization of a technology option depends only on restrictions of superior technologies options and its own restrictions. It is independent from inferior technology options.

Three widely acknowledged and applied energy system simulation models are the LEAP (Long range Energy Alternatives Planning System) model, NEMS (*National Energy Modeling System*) model and the PRIMES Energy System model (Pfenninger et al., 2014).

2.2 Classification based on the analytical approach: top-down vs. bottom-up

Another aspect of classifying models is the analytical approach. Literature (see Kavgic et al.; Nakata, 2004; IEA 1998; or IPCC, 2001) suggests that there are two main approaches to developing scenarios for the future state of a specific system: bottom-up models and top-down models. The principal idea and philosophy behind top-down and bottom-up models based on IEA (1998) is displayed in Figure 2.1. Broadly speaking, top-down models, on the one hand, tackle the research question from an aggregate perspective based on aggregated economic variables. On the other hand, bottom-up models start with different technological options which can be used to supply a specifically desired energy service level.

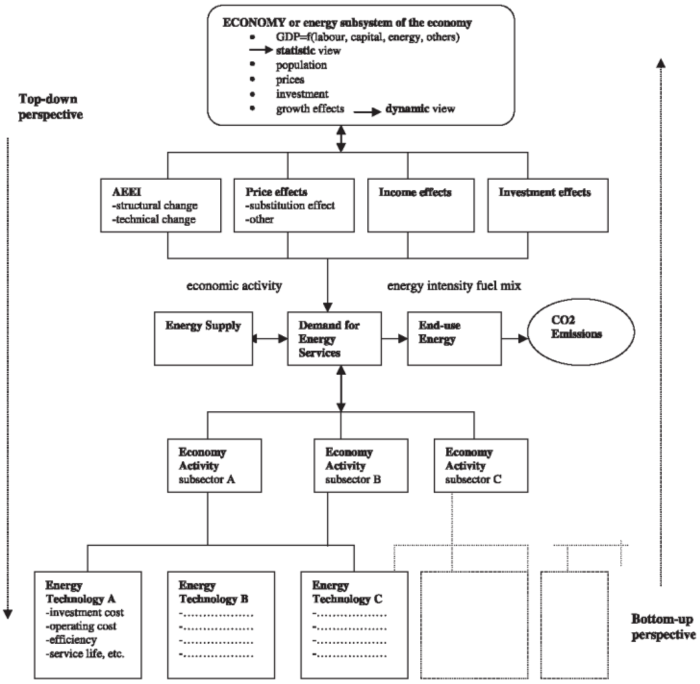

Figure 2.1 – Top-down and bottom-up modeling approaches. Source: Kavgic et al., 2010, based on IEA, 1998.

In general, top-down as well as bottom-up approaches tend to derive solutions which are oppositely biased. The main characteristics, advantages and limitations of top-down and bottom-up models are summarized in Table 2.1.

Table 2.1 – Main characteristics, advantages and drawbacks of tow-down and (technical) bottom-up models. Source: van Beeck, 1999; Nakata, 2004; Kavgic et al., 2010

Top-down models	**Bottom-up models**
Main Characteristics	
Build on an economic approach	Build on an engineering approach
Determine energy demand based on aggregate economic indices such as GDP and (price) elasticities	Derive the energy supply (structure) on a disaggregated level based on technological properties
Define most efficient technologies by production frontier set by markets, without representing technologies explicitly	Define most efficient technologies based on technological description, without considering economic production frontier
Based on observed market behavior	Independent of observed market behavior
Reflect potential adopted by the market	Reflect technical potential
Give a pessimistic estimates on “best” performance	Give an optimistic estimates on “best” performance
Benefits	
Reflect technologies adopted by the market	Reflect technical potential
Endogenously incorporate behavioral relationships	Assess (direct) costs of technological options directly
Consider relationship between the energy sector and the broader economy	Cover current and emerging technologies in detail
Capable of modeling the interaction between economic variables and energy demand	Use physically measurable data
Do not need detailed technology descriptions	Enable policies to be more effectively targeted
Able to assess the social-cost-benefit of energy and emission policies measures	Assess the effects of different combination of technologies
Able to build in aggregated economic data only	Able to estimate the least-cost combination of technical measures to meet given demand
Limitations	
Neglect the technically most efficient technologies, thus underestimate potential for efficiency improvements	Neglect market thresholds, hidden costs and other constraints, thus overestimate the potential for efficiency improvements
Are inflexible in addressing different energy supply structures	Are inflexible in addressing different energy service demand structures
Assume no discontinuities in historical trends	Describe interactions between energy sector and other sectors based on external assumptions
Often build on assumption of markets without efficiency gaps	Describe market interactions poorly
Are less suited for assessing technology-specific policies	Do not consider the connection between energy use and macroeconomic activity
Lack technological details	Require many technological data

More advanced models are often implemented as hybrid models (Kavgic et al., 2010; Nakata, 2004), yet still have set the main focus on one of the two approaches. Bottom-up and top-down models consider the inertia behavior of the analyzed systems differently and thus respond differently to changing input factors. The relationships of aggregated variables used in top-down models are usually more stable than those of disaggregated entities. Thus, by introducing some top-down constrains to bottom-up models, their results become less unrealistic and unstable to short-term effects.

2.2.1 Top-down modeling approaches

Top-down models approach the research question from an aggregated level. According to Nakata (2004), the terminology "*top-down*" refers to the approach

- of how the relationship between supply and demand is applied based on macroeconomic theory,
- of how the current economy is depicted using input-output matrices,
- of how the role of prices and costs for production factors such as energy, labor, capital (and land) are used,
- and of how econometric and other statistical methods are used to derive estimated elasticities and associated production functions (e.g. the unlimited non-linear Cobb-Douglas or the linear-limitational Leontief).

Top-down approaches do not directly consider interrelationships between input and output variables in detail. They rather treat them as some "black box" and describe the interactions of the output on the input based on dependencies derived from observed historical data. Therefore these models typically cover the status-quo or historical status of the economy and/or energy sector broadly and are well-suited to estimate the near term system behavior under the precondition that no structural changes occur, which would ultimately alter observed trends. In reality, these approaches are often applied to analyze the interactions of the energy sector with the overall economy.

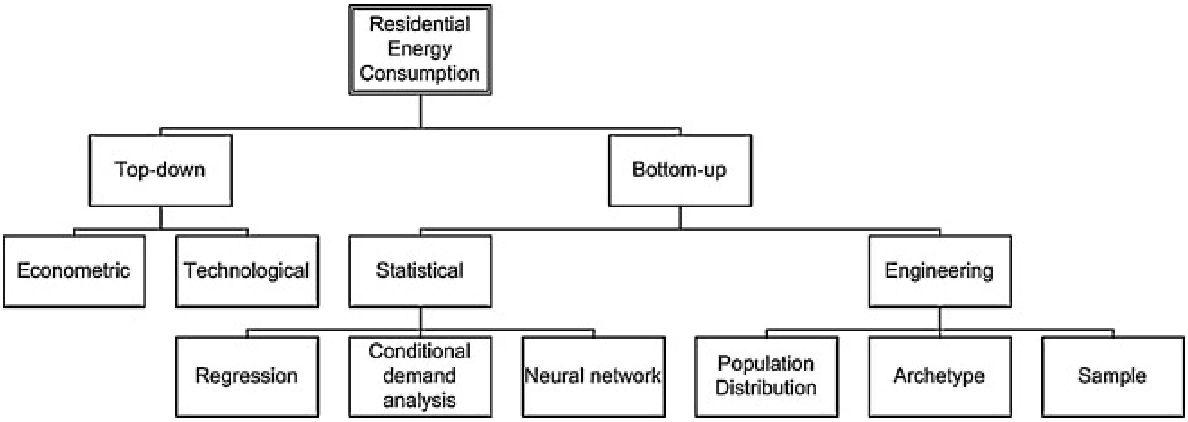

Figure 2.2 – Top-down and bottom-up modeling techniques for estimating the regional or national residential energy consumption. Source: Swan and Ugursal, 2009

Top-down models can be further classified into econometric and technological top-down models (Kavgic et al., 2010; Swan and Ugursal, 2009, see Figure 2.2). Technological top-down models extend the econometrical models by incorporating effects such as technology saturation (Bento, 2012a; Bento, 2012b; Grübler and Nakicenovic, 1991) or structural changes within the economy without explicitly describing them within the model.

Two commonly applied types of how top-down models find their solutions (Nakata, 2004) are the equilibrium models and the (partial equilibrium) optimization models. The equilibrium models (computable general equilibrium (CGE) models) find their solution based on microeconomics (IPCC, 2001). These models contain equations which define supply and demand based on production functions for production factors such as raw materials and labor and their associated prices and wages. The model-solver algorithms then search for solutions for which the depicted economy is in equilibrium. (Partial equilibrium) Optimization models, on the other hand, allow that the year-by-year solutions differ to some extent from the economic equilibrium state. These types of models search for solutions, which minimize or maximize a specific objective function (e.g. cost, revenues) within or after a given time horizon.

A comprehensive overview of top-down model approaches, developed/implemented models and their applications is given by Bourdic and Salat (2012), Firth et al. (2010), Uihlein and Eder (2019), Grigorova (2012), Ratti et al. (2005) or Pérez-Lombard et al. (2008).

A top-down model for the Austrian mobility and heating sector with focus on sustainable consumption patterns is presented by Kletzan et al. (2006). They develop a top-down econometric model, which incorporates three main components: (1) production functions for energy service, (2) capital accumulation functions, and (3) demand functions for energy services. Contrary to the neo-classical approach, demand functions for market goods are not defined purely based on relative prices, but are adjusted by the capital stock in investment goods (infrastructure). They also implement several household types, distinguished by their “consumption sustainability” patterns, derived from Austrian consumer survey data. The energy demand for heating (non-electrical energy) is described by the capital stock with an elasticity of -0.783[16], and the heating degree days (HDD) with an elasticity of +0.693. The residential electricity demand, which includes also some energy for space heating and domestic hot water (DHW), is defined by the independent variables HDD, the

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[16] The energy demand decreases with additional investments in the building stock.

electricity-to-non-electricity price ratio and a trend. Two scenarios for the energy service “heating” are defined: (1) “Building regulations” with focus on minimum energy performance indicator standards and (2) “Demand shifts”, which analyse a shift from “normal” households towards “sustainable” households and the effects on the energy consumption assessed.

2.2.2 Bottom-up modeling approaches

In bottom-up models the analyzed (complex) systems emerge from piecing-together sub-systems, often described in an engineering-based way. The interrelationships between input and output data are explicitly modeled based on actual processes. Compared to top-down approaches, the analyzed systems in bottom-up models are modeled on a highly disaggregated level. Therefore additional technological (and statistical) data and/or expert estimates are needed to describe the technical behaviors and effects on the output variables of each sub-system (Shorrock and Dunster, 1997). Bottom-up models can be classified further in statistical and engineering-based models (Swan and Uqursal, 2009, see Figure 2.2).

Bottom-up statistical building stock energy models

Swan and Uqursal (2009) give a comprehensive review of statistical bottom-up models of the building sector. This model type uses statistical methods, mostly regression techniques, to determine the inter-relationship between energy demand and different input factors.

Statistical bottom-up models are often used to assess the energy consumption of a building stock as a function of macroeconomic variables such as household income or GDP, energy price or technological variables such as climate conditions, household size, building type or efficiency of buildings (e.g. Halvorsen, 1975; Biermayr, 1998; Summerfield et al., 2010). They can either be formulated as aggregated time series models (Haas and Schipper, 1998; Lin and Liu, 2015, Kialashaki and Reisel, 2013), as cross-sectional models (e.g. Biermayr, 1998; Haas et al., 1998; Aksoezen and Hassler et al., 2015) or as combination of both approaches (Halvorsen, 1975). Most bottom-up statistical models apply common regression techniques to find the model solution. The application of conditional demand analysis (CDA) and neural network (NN) statistical bottom-up model approaches are described by Aydinalp et al. (2002, 2003, and 2004). Aydinalp-Koksal and Ugursal (2008) compare their applicability for analyzing the end-use energy consumption in the residential sector with engineering approaches.

Mastrucci et al. (2014) develop a statistical bottom-up model based on a segregated multiple linear regression model at city scale. With the developed model they analyze the energy saving potentials of the residential building stock in the Dutch city of Rotterdam.

Newsham and Donnelly (2013) present a statistical bottom-up model for Canadian households. Using a set of close to 9800 survey data on the total household energy use and appliance ownership accompanied by heating- and cooling-degree-days, a conditional demand analysis is applied to estimate the energy consumption of different energy carriers and end-use appliances. By comparing the average energy consumption of different end-use categories with those of efficient appliances, estimates to identify cost-efficient energy savings potentials are provided.

Aksoezen and Hassler et al. (2015) develop a statistical bottom-up model and apply it on a vintage building stock model of the Swiss city Basel. Their model describes the energy consumption of buildings through correlations of specific building characteristics including parameters such as building compactness, construction age, exposed surface area, number of people, or exposed elevation area. The influence of the explanatory variables is quantified by applying the Chi-Square Automatic Interaction Detector (CHAID) method.

Kialashaki and Reisel (2013) present two statistical bottom-up model approaches: regression models and three neural networks models, which do not rely on isoelastic dependencies. The energy demand of the residential sector in the United States is evaluated using a set of six different model formulations (three regression models and three neural network models. The input factors for their model are time series from 1984 to 2010 for population, GDP, household size, the median household income and the costs of electricity, gas and heating oil as well as efficiency variables for the heating system and the useful energy intensity. An application of a (hybrid) neural network model, the CHREM (Canadian Residential Energy End-use Model) is presented in Svan et al. (2013).

Common to all bottom-up statistical models is that they derive the effect of the independent variables (e.g. price, GDP, HDD, etc.) on the dependent variable (e.g. energy consumption) from historical data and do not cover the analyzed system in much detail. Structural changes such as discontinuous introduction of new technologies or behavioral changes and changing social norms (increasing awareness about climate change and GHG mitigation) are outside of the scope of these models (Kavgic et al., 2010). Therefore their ability to evaluate the impact of a wide range of future scenarios is restricted.

Bottom-up engineering-based energy models

A considerable list of studies, literature and models exists with respect to the description of the building's energy demand using engineering-based bottom-up models. Swan and Ugursal (2009) identify three different categories: population distributed, archetype and sample-based approaches (Figure 2.2). Another dimension, not shown in Figure 2.2, is whether the scope is set on a predefined static building (stock), possibly considering dynamic environmental conditions (static model), or whether the focus of the model and the objective of the analysis is set on a changing building environment und constant or dynamic environmental conditions (dynamic model).

Energy models based on the building physics calculate energy needs, final energy demand, and/or delivered energy based on thermodynamic calculation methods. Buildings are described to such a technical degree that it allows to cover all relevant input and output energy flows. Therefore quantitative data need to be available on the building geometry and the thermodynamic characteristics of boundary layers (e.g. walls, roof, and windows), the efficiencies related to heat supply and distribution systems, as well as on the utilization of the building (e.g. indoor temperatures, ventilation rates and internal gains through occupants and energy consuming appliances) and on the environmental conditions (e.g. outdoor temperature and solar radiation). The actual degree of detail in the description of the building depends on the core energy-calculation engine (Kavgic et al., 2010). With respect to the primary aim of the analysis and the availability of data, a model or model category is chosen.

A severe shortcoming of pure non-statistical engineering-based bottom-up models (building physics bottom-up model) is that the occupant's behavior is not taken into account appropriately (see Heeren et al., 2013). Numerous studies have shown that the occupants have a significant influence on the building related energy consumption (e.g. Biermayr, 1998; Majcen et al., 2013; Holzmann et al., 2013; Loomans et al., 2008; Steemers and Yung, 2009; Schweiker and Shukuya, 2010). Therefore adding statistical bottom-up elements to the basic technical bottom-up model significantly improves the forecast results.

Sample based models are applied to analyze the energetic behavior (e.g. energy need, energy use, delivered energy) and eventually associated environmental impacts (e.g. primary energy consumption or CO_2 emissions) in detail for individual buildings (Figure 2.2, "Sample" based engineering bottom-up-models). These models often demand (for such a purpose) a very detailed description of the analyzed building and its usage and allow multiple thermal zones within the building and complex building geometries. They usually belong to the category of static models with respect to the building stock. The energy flows are either calculated using a semi-static monthly approach (e.g. the SBEM (Simplified Building Energy Model)[17], the “IBP:18599” software tool developed by Fraunhofer IBP[18], or the spread-sheet models developed by the Austrian institute of construction engineering (OIB)[19]), a simple hourly dynamic (see spread-sheet model applied by Zangheri et al., 2014) or a detailed dynamic simulation approach on a sub-daily resolution (typically hourly or sub-hourly). Representatives of the later model family are TRNSYS (TRNSYS, 2013), EnergyPlus (Crawley, 2001) or the eQuest[20] tool (which is based on the DOE-2[21] calculation engine).

Archetype engineering-based bottom-up models (see Figure 2.2) aim to divide a larger set of buildings (a building stock; either regional, national or international) into clusters of typical buildings. Each cluster (or cohort) represents buildings with similar characteristics such as primary building usage, construction period, building size, efficiency classes, and eventually the existing heating system and climate zones or other parameters. The energy demand of the building stock is then assessed based on a defined set of reference buildings. The available statistical data for a larger building stock are usually limited. Therefore these analyses typically deploy a less detailed calculation method (compared to the model class described above), as the uncertainties related to input data are larger than those associated with simplified energy calculation methods. These types of models are either used to define a static building environment (e.g. in the project: TABULA (Amtmann and Groß, 2011) or in its predecessor, the project EPISCOPE[22]), to analyze the energy demand of a static building stock in a dynamic environment (e.g. Fung, 2003) or to evaluate the development of a dynamic built environment and the associated trajectories for energy demand and energy consumption.

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[17] http://www.bre.co.uk/page.jsp?id=706.

[18] Fraunhofer Institut für Bauphysik: Software “IBP: 18599”, www.ibp18599.de.

[19] http://www.oib.or.at/sites/default/files/ea-wge-2012-01-01-v10b2.xls ; http://www.oib.or.at/sites/default/files/ea-wgv-2012-01-01-v10b2.xls.

[20] The Quick Energy Simulation Tool (2014) http://doe2.com/equest.

[21] DOE-2, Building Energy Use and Cost Analysis Tool. (2014) http://doe2.com/DOE2.

[22] http://episcope.eu/.

(Dynamic) bottom-up approaches with exogenous decision-making algorithms

In their paper Mattinen et al. (2014) present the engineering-based bottom-up model EKOREM. The model applies an energy calculation method in accordance with the EN ISO 13790 augmented by empirically derived utilization factors. The effects of different energy efficiency measures and changes in the utilization behavior are shown for the Kaukajärvi district located in the city Tampere, Finland. The variable time is not explicitly addressed in the model; thus, the model rather belongs to the category of static than dynamic models.

Mata et al. (2013a) presents a similar analysis done for Swedish residential building stock. They apply the engineering-based bottom-up model ECCABS (Energy, Carbon and Costs Assessment for Building Stocks, Mata et al., 2013b) on the Swedish building environment. The ECCABS model is a Matlab/Simulink (MathWorks, 2010) implementation of the EN ISO 13790:2008 quasi-steady state energy balance calculation standard[23]. In their paper, the Swedish residential building stock is represented by 1400 reference buildings; 12 energy saving measures and their associated costs are defined. The effects of the (a) full application (technical potential) or (b) the application of only the economic potentials on the final energy demand and CO_2-emissions are then evaluated and discussed. Behavioral effects and other rebound effects are not considered in their study. The estimate of the applicability of refurbishment measures does not directly considered the variable “time”. Therefore there model framework also represents a static approach.

A dynamic method is used by Sartori et al. (2009) for the Norwegian building sector. They describe a developed archetype-based bottom-up model and perform a scenario-based analysis for the energy demand. The specific energy needs of the building stock are based on different sources, and are not calculated within the model. The allowed energy needs of the Norwegian energy classes (energy performance indicators) define the different refurbishment options. The efficiencies of the different heating systems are defined by the overall efficiency of the technical building systems. Construction, demolition and renovation activities, as well as the chosen refurbishment and heating system options are explicitly defined and not within the scope of the model. Six different scenario settings—reference scenarios and two settings with different assumptions on newly installed heating systems (thermal energy carriers versus

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[23] Although the energy need calculation is performed on an hourly resolution, it is assumed that the indoor air temperature and the temperature of all internal layers are identical. This implies that no R-C model (see section4.4.2) is applied.

heat pumps, each with and without energy conservation measures—are drawn up and the results for the delivered energy are compared.

A similar analysis is performed by Broin et al. (2013). In their paper they apply a bottom-up model to analyze potential energy savings of the building stock in the EU-27 countries. They describe the model as a “bottom-up engineering variant” based on the definitions set by the World Bank (2009), Sorrel (2004) and Chateau and Lapillonne (1978). The energy needs and the energy consumption are defined based on top-down indicators and not calculated endogenously by applying an integrated building physics model. In their model, the incremental change of the energy demand of the building stocks is defined by six exogenously defined factors: the annual construction rate (C), the demolition rate (D), the increase in living standard (S), the continuous improvement in efficiency measures (F1), once-off efficiency measures (F2), and finally, renovation cycle efficiency measures (F3). Trajectories of the energy demand and related CO_2-emissions until 2050 are shown and discussed in three scenarios: a “Baseline Scenario”, a “Market Scenario”, and a “Policy Scenario”.

In his thesis Cost (2006) develops a dynamic bottom-up model for the Swiss vintage building stock, which considers the energy demand for heating and domestic hot water preparation. In his model, the area specific energy needs are not endogenously calculated using a building physics model, but are derived on a top-down basis. Also, other important scenario parameters such as the realized energy savings due to energy efficiency measures and the type of heating systems installed are defined exogenously based on expert judgment. These assumptions are altered in different scenarios, and the effect is assessed and discussed on an aggregated level.

The methodology presented by Tuominen et al. (2014) extents the dynamic approaches discussed above by incorporating an engineering based building-physics model to calculation framework. By applying their archetype-based bottom-up model they draw scenarios for the heating energy consumption and the associated CO_2-emissions of the Finnish building stock until 2050. The described approach uses two tools. The first, a dynamic simulation tool (IDA-ICE software package), derives the energy demand of buildings. This tool is applied to the developed set of representative buildings. The second tool used in their analysis is the developed REMA spreadsheet modeling tool. The REMA model is described as a light, simple and flexible tool that allows analyzing the effects of changing the scenario input parameter instantaneously. The REMA model does not incorporate any dynamic modeling but assumes a linear development instead. The economicality of technology options are not directly considered and the scenarios are mainly based on exogenously defined input parameters such as estimated rates of construction, renovation and demolition as well as refurbishment standards.

A similar engineering-based building stock bottom-up model is presented by Olonscheck et al. (2011) and applied to the German building stock. The buildings physics model deploys the concept of heating and cooling degree days and is based on the German industrial standard DIN 4108-6 (DIN 4108-6:2004). By applying different assumptions for renovation rates (1%, 2% and 3%), temperature increase triggered by climate change until 2060 (1 °C, 2 °C and 3 °C), increasing heated building stock area and the saturation level of cooling devices (13%, 2.5% and 1%), the effects on the heating and cooling energy demand and GHG gas emissions are evaluated in three scenarios.

The innovative aspect of the model presented by Heeren et al. (2013) results from introducing the concept of technological diffusion. They develop a dynamic engineering-based model, applied to the Swiss building stock. Retrofitting rates and demolition and construction rates are defined exogenously based on data taken from literature (Jakob and Jochem, 2003). In their work a reference scenario for 2050 is compared to two efficiency scenarios. The diffusion process is modeled based on the Bass model (Bass, 1969) and limits the penetration speed of energy-conservation technologies. The diffusion parameters for heating and ventilation systems are based on Usha Rao and Kishore (2010). Based on an iterative expert discussion process, the main parameters for three scenarios, typical business-as-usual scenario (R1) and two efficiency scenarios (E1 and E2), are defined exogenously and the evolution of the ecological impact based on a life cycle analysis are determined.

Another step towards a higher degree of endogenously defined variables is applied by McKenna et al. (2013). They present a building-stock-model-based analysis, which is used to determine whether or not Germany’s energy saving goals defined for the residential stock, are realistic and can be reached by 2050. They differentiate between various building types, and between building size, age, location (old and new federal states) and specific energy demand levels. In addition to publications discussed above, refurbishment rates are endogenously modeled by using data form ARGE Kiel (Walberg et al., 2011). Demolition is still defined exogenously and the specific energy demand is taken from Ebel et al. (2000) and not calculated endogenously. Conclusions are drawn on the basis of the results of five different scenario settings.

Uihlein and Eder (2010) define additional variables endogenously. They assess possible energy savings and GHG emission reduction potentials and associated costs for the EU-27 building stock up to 2060. The applied model represents a technical building stock model. In addition to the publications discussed above, the model framework endogenously calculates the building construction, demolition, and renovation rates as well as energy demand for space heating. However, the decision on the energy efficiency level of the applied renovation measure is still defined exogenously and remains outside the scope of the model.

A similar approach is chosen by Hansen (2009). In his thesis he develops a bottom-up model to analyze the energy saving potential through thermal building refurbishments of residential buildings in the EU-15 countries. In a later publication, his database is extended to the EU-27 countries (Hansen , 2011). In the presented model the buildings of the national building stocks are distinguished according to building size, expressed in households per building (2 clusters: buildings with less than 3 households per building and buildings with 3 or more households per building) and the construction period (6 construction periods). In the model the energy needs of the building stock are calculated using the conditioned floor area, transmission and ventilation energy losses per cohorts, the internal and solar gains as well as heating degree days per country. The refurbishment options implemented in the model include measures related to the building envelope as well as to the heat production and distribution inside the buildings. The potential energy savings are evaluated based on the potential specific energy savings (kWh/m^{2}a) per cohort cluster and the future refurbishment rate derived from applying a statistical service lifetime-based approach. Concerning the reference energy demand of thermally refurbished buildings, the regulatory demanded energy needs of newly constructed buildings are taken as reference. In the model the product of specific energy savings and the derived renovation rate constitutes the energy saving potential. This saving potential is compared to realized energy savings per country for the period between 1990 and 2001. The ratio of realized energy savings and derived energy saving potential for the same period (1990 – 2001) constitutes the degree of the historically observed *refurbishment potential exploitation* PA. According to his analysis, this factor varies for the EU-15 countries between 0% (Luxembourg) and 99% (Sweden). The Austrian PA index of 16% constitutes the (more or less) median value of 16.5%. While the refurbishment rate is endogenously calculated in this model, the developed scenarios imply exogenously defined *refurbishment potential exploitation* PA parameters and exogenously defined shares of types of newly installed heating systems. Thus, the evaluation of non-regulatory instruments such as financial instruments is not within the scope of this model.

Dynamic bottom-up approaches with endogenous decision-making algorithm

The bottom-up approaches shown above set their scenarios mainly on exogenous defined input parameters concerning the future development of the built environment and its stock of heat supply systems. So far, only a few models have also calculated the decision-making processes endogenously and have been capable of endogenously deriving the development of technology and the energy carrier mix of heating, cooling and hot water systems based on economic factors.

The National Energy Modeling System (NEMS), according to Wilkerson et al. (2013), is one of the most influential energy models in the United States of America and the flagship model of the U.S. Energy Information Administration (EIA). This model is used to derive the official forecasts for energy supply and energy demand, technology adoption, and prices. Furthermore, the EIA uses the NEMS modeling framework to analyze environmental and energy policies or to derive the numerical basis for the EIA's Annual Energy Outlook series. The NEMS framework consists of 13 sub modules, of which two are the Residential Demand Module (RDM) and the Commercial Sector Demand Module (CSDM). These modules are bottom-up building and appliance stock models, although they do not explicitly incorporate a building physics model. The approach of these modules extends that of the reviewed bottom-up models described above by introducing an endogenous decision module. While the CSDM applies a segmented least-cost-approach (considering some behavior rules), the RDM applies a logit-approach for ten major end-use services (Wilkerson et al., 2013; EIA, 2014) to determine the market shares of competitive technology options. The decision criteria used by the logit approach are capital costs and operating costs. A consumer preference is defined to weight these two parameters and derive a single decision parameter per technology option. In their paper, Wilkerson et al. conclude that the model responds robustly with respect to the consumer preference parameters, as "*a reasonable adjustment of the modestly impact the final energy demand of the building sector*". The lifetime of appliances is calculated using a Weibull distribution, and existing households (= existing buildings) are removed from the stock at a constant rate over time.

A similar approach to forecast the energy demand of the building sector is implemented in the Buildings Module (DeForest et al., 2010)—the Stochastic Buildings Energy and Adoption Model (SBEAM)—of the Stochastic Energy Deployment System (SEDS). The SBEAM is an *"engineering-economic"* model with technology adoption decisions based on cost and energy performance characteristics of competing technologies; again a building physics model is not directly implemented. SEDS focuses on modeling the economy-wide energy costs and consumption with minimal user effort or expertise (Marnay et al., 2008). Thus, the SEDS design (and SBEAM) favors simplicity over detail, unlike the NEMS and RDM. The lifetime of building elements and appliances is calculated using a logistic decay function.

A hybrid model, the Global Change Assessment Model (GCAM), is presented by Zhou et al. (2014). It embeds a bottom-up service-based building stock energy model for the US in an integrated assessment top-down modeling framework and belongs therefore to the group of hybrid models. In this model, the investment decisions process with respect to heating systems is endogenously defined, for which a two-level nested logit approach is used. On the top level, the decision about the main energy carrier is defined; the second level defines the efficiency class. The main decision criteria are the relative cost of each technology option compared to competing technologies.

Henkel (2012) develops a statistical vintage stock bottom-up model, which is used to analyze possible futures for the energy demand of the German building stock. The heating-systems-related investor decisions are endogenously modeled. The decision algorithm is based on a multinomial logistic regression model, for which the coefficients are estimated based on an online survey conducted in the course of his work (233 samples are used for model estimation).

A similar approach for the German residential building sector is chosen by Bauermann (2013). He develops a building stock model for the German residential sector. The model presented distinguishes 75 building categories (5 different building types, from single-family houses to tower blocks, and 18 age classes from before 1918 and until 2050). While the refurbishment rates are defined exogenously, the replacement cycle of heating systems are calculated endogenously. The decision process of households with respect to new heating systems is also modeled endogenously. Like in the GCAM, a nested logit model is used. The main decision parameters are the full annual heating costs, augmented by factors of investor preference and technology diffusion.

The FORECAST model[24] constitutes another model framework, which can be used to develop medium- to long-term scenarios for different regions based on a bottom-up simulation approach. With its four individual modules: industry, service/tertiary, residential and others (agriculture and transport), it is able to cover the whole economy. Investment decisions are modeled endogenously by applying *"whenever possible"* a logit-approach. The main decision variable constitutes the total costs of ownership. The model framework furthermore considers technology diffusion and endogenously defined replacement rates.

The Invert/EE-Lab model: endogenously and exogenously defined parameters

The developed Invert/EE-Lab differs from the models discussed above by its high degree of endogenously defined variables and can be added to the group of

- dynamic,
- (building physics) engineering-based archetypes
- hybrid bottom-up models
    - augmented by statistical bottom-up elements (user behavior) or income and price elasticities
    - and statistical top-down elements such as cost-resource curves for energy carriers and market diffusion effects
- with endogenously modeled construction, renovation and demolition activities
- and endogenously modeled investment-decision-making for renovation measures and heating systems replacement, applying a nested logit approach
    - considering different types diffusion restrictions.

A list of important endogenously and exogenously defined input parameter is given in the following table.

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[24] http://www.forecast-model.eu.

Table 2.2 – Endogenously and exogenously defined central input parameters.

Endogenously calculated	**Exogenously defined**
• Building demolition and construction rates • Renovation rates and replacement rates of heating system • Energy need and final energy consumption • User behavior • Share of competing refurbishment options • Share of competing heat supply options • Partly energy price by employing the concept of cost- resource-potential-curves	• Geometry of buildings • Usage of building • Existing building stock • Energetic properties of components of existing building stock • Reference energy prices and cost-resource-potential-curves • Development of number of buildings per building category, climate region and energy carrier region • Available technologies, their energetic properties and costs • Income and sectorial value added • Climate conditions • Availability of energy carriers per region • Investor preferences • Policy measures: Financial and regulatory instruments

3 The Austrian building stock and its energy demand for space heating and DHW preparation

This chapter intends to give an overview of the present building stock in Austria and its energy consumption for space heating and domestic hot water preparation. A focus is set on the regional disaggregation of the building stock and the applicability of different energy carriers. Furthermore, the applied energy carriers and their installation rates as well as the renovation activities of the last two decades are discussed.

3.1 The existing Austrian building stock

The developed input dataset describing the current Austrian building stock is implemented based on sources mainly from the national statistical bureau. On a municipal ("Gemeinde") level (2380 municipals) the following publications are used: "Gebäude- und Wohnungszählung 2001"[25] (Statistic Austria, 2009a), "Arbeitsstättenzählung 2001"[26] (Statistic Austria, 2009b), "Fertig gestellte Gebäude mit Wohnungen"[27] (Statistic Austria 2009c). On the level of federal states ("Bundesländer") the results from the annual publication series "Wohnen 2002, Ergebnisse der Wohnungserhebung im Mikrozensus Jahresdurchschnitt 2002"[28] until "Wohnen 2012, Ergebnisse der Wohnungserhebung im Mikrozensus Jahresdurchschnitt 2012"; (Statistik Austria, 2003, 2005-2012) are used. The thermal quality of the buildings is calibrated using Pech et al (2007), Amtmann and Groß (2011) and Schriefl (2007). The data are also cross-checked with Hansen (2009).

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[25] Translates to: "Housing (buildings and dwellings) Census 2001".

[26] Translates to: "Census of Enterprises and their Local Units of Employment 2001".

[27] Translates to: "Completed new buildings with dwellings".

[28] Translates to: "Housing 2002, results from the Microcensus 2002".

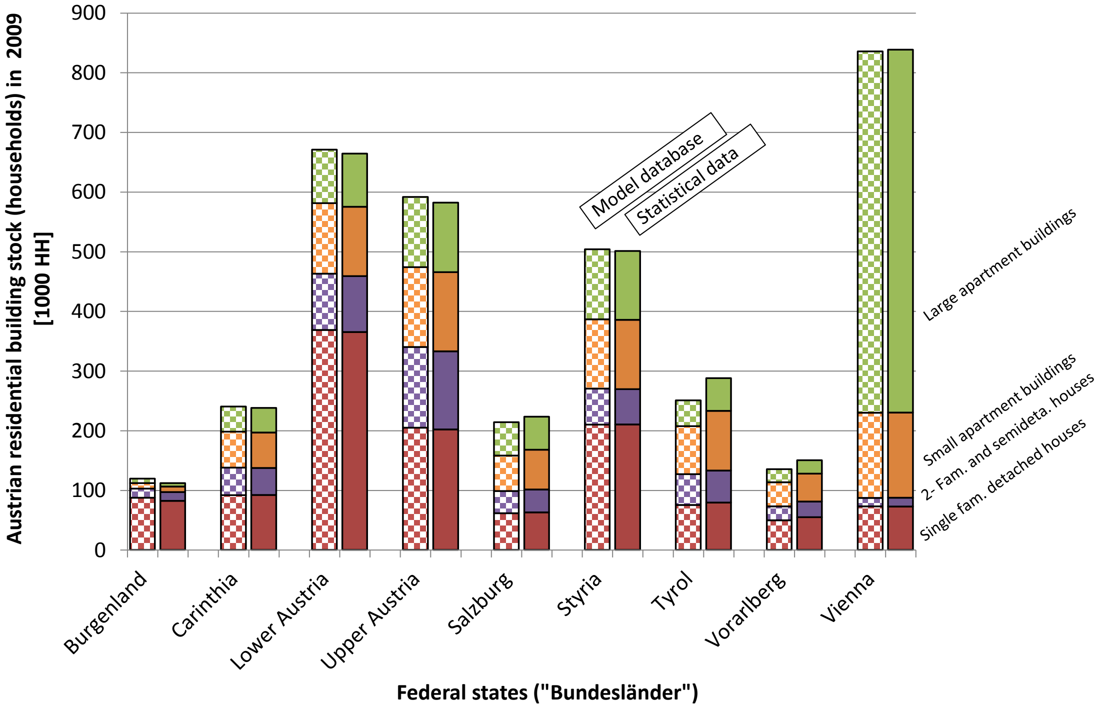

Figure 3.1 – Number of dwellings per federal state and residential building category.

The subsequently discussed analysis of climate conditions is performed on the level of municipalities[29]. Furthermore, the regional applicability of energy carriers is assessed on a sub-municipality level. For the calculation of the buildings stock's energy demand data on a municipal level are used, which are then clustered into different (not necessarily contiguous) regional zones, according to their site-specific conditions. At the time this analysis was done, data on this regional level were only available (for free) for the reference year 2001[30]. For the extrapolation to 2008 (and up to 2050 in the scenarios), data on the historical development of the population in each municipal region (Statistic Austria, 2012j), the regional dwelling forecast for 124 regions (Hanika, 2011, Hanika et al., 2011), and the population forecast per population density (inhabitants/km²: >1750; 1750-1250; 1250-900; <900; not within settlement clusters) for 118 regions (Müller et al., 2012) is used.

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[29] This task was performed by the Department of Metrology of the University of Life science in the course of the project PRESENCE (Kranzl et al., 2014a).

[30] In 2014, the data of the new register-based census performed in 2011 were published: http://www.statistik.at/blickgem.

3.2 Regional disaggregation of the energy demand for space conditioning and DHW and available energy carriers

3.2.1 Climate regions

The parameter guidelines for the calculation of the energy performance certificate (ÖNORM B 8110-2) define 7 reference climate zones for Austrian. Based on a three-contour-layer model (altitude below 750 m, 750 – 1500 m and above 1500 m) the site specific climate conditions are calculated applying a linear regression model using the site specific altitude.

In this work I use an alternative cluster approach, derived within the Presence project (Kranzl et al., 2014a) by the Department of Metrology of the University of Life science (Schicker and Formayer, 2012). In the course of this project, the population weighted climate conditions of each Austrian municipality is clustered by the average summer temperature, winter temperature, as well as the summer and winter solar radiation. This approach results in 16 climate clusters. Since the applied methodology defines the threshold values for the temperatures and solar radiation in the beginning, the number of inhabitants and thus the energy needs for heating of the derived climate zones varies in a wide range. Thus, in a subsequent step, some clusters are aggregated. This results in a set of 10 climate clusters populated by a comparable number of inhabitants which is used in this work (see Figure 6.8).

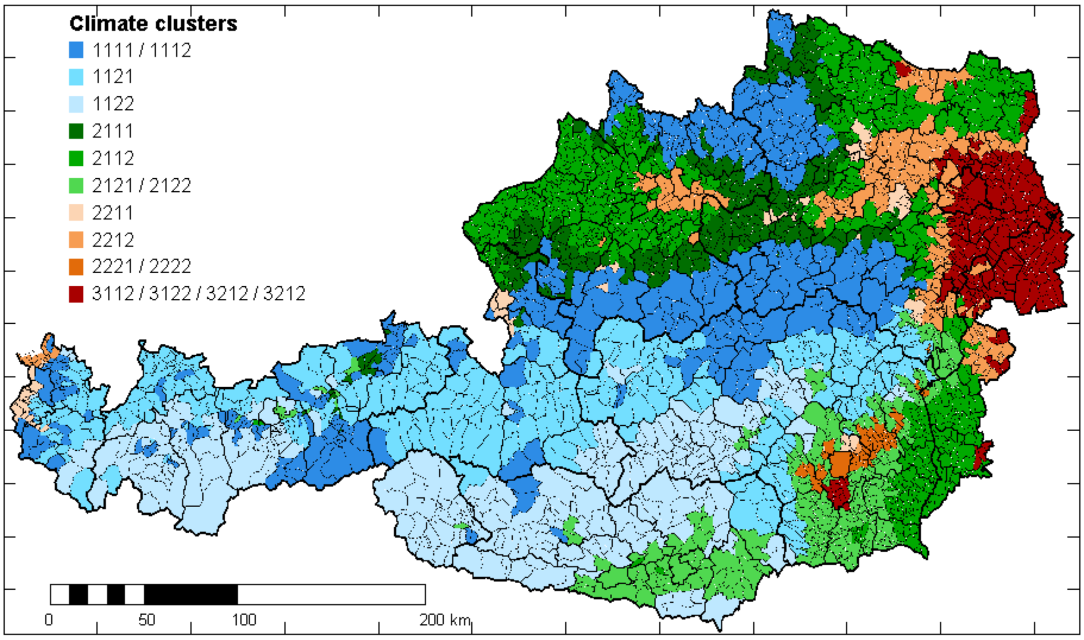
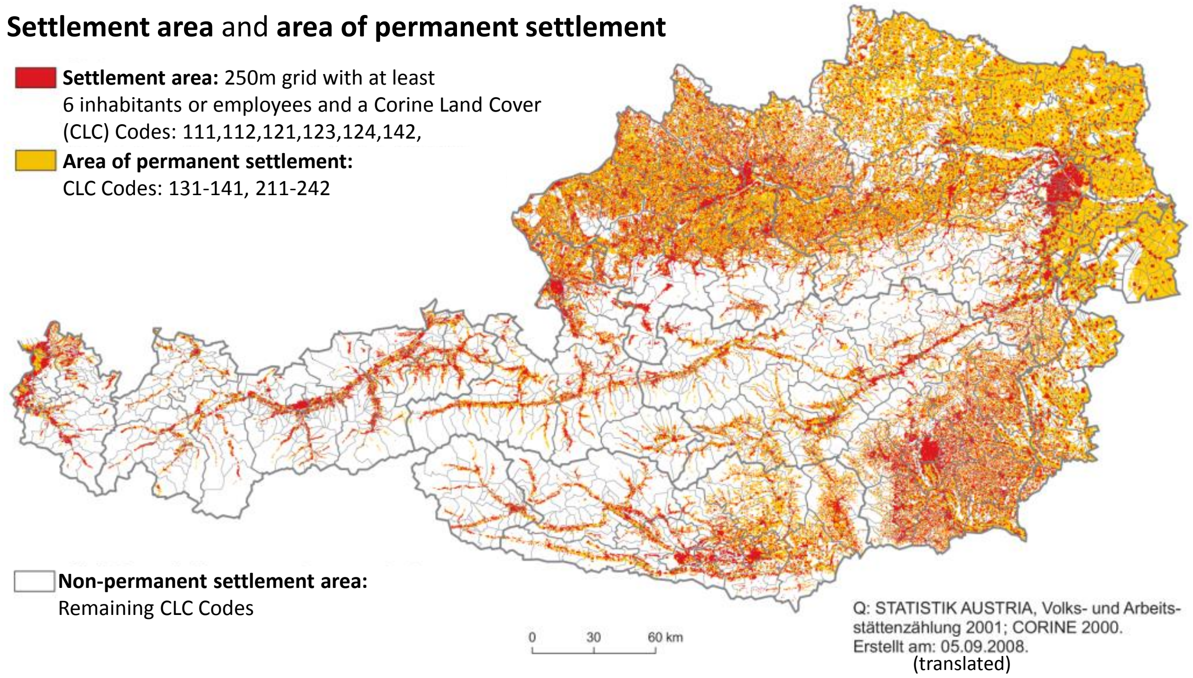


Figure 3.2 – Climate regions used in this work.

3.2.2 Estimate of the regional heat demand density

A further regional disaggregation of the Austrian building stock is done in this work. The starting point are regional Corine Data on a 250x250 m raster that defines a pixel as settlement areas, if at least 6 people live or work in this area (based on the Housing Census 2001, Statistik Austria, 2008).


Settlement area and **area of permanent settlement**

Q: STATISTIK AUSTRIA, Volks- und Arbeitsstättenzählung 2001; CORINE 2000.
Erstellt am: 05.09.2008.
(translated)

Figure 3.3 – Settlement areas in Austria. Source: Statistik Austria, 2008, my translation

This information is merged with the number of inhabitants on 1x1 km level (Statistik Austria, 2006). Using this data, a population density function is estimated (tangent-plane-based for 50x50m grid). It is assumed that the energy density of residential buildings correlates with the derived population density function, but this is corrected by the density of surrounding areas, leading to higher energy demand densities in the centers of settlement areas, and lower energy demands in the outer zones. For non-residential buildings, a uniform distribution over settlement areas is given a weight of 30%, while 70% correlates with the density function of residential buildings. The number of buildings and dwellings per building type and construction period on the regional level of 2380 municipalities ("Gemeinden") for the year 2001 are taken from the Housing Census 2001 (Statistik Austria 2004a-i) and the

Census of Enterprises and their Local Units of Employment [31] 2001 (Statistik Austria 2009b). The development of the built environment between 2001 and 2010 is estimated using the number of households per energy carriers used for heating and construction period (2002-2012) based on the annual Mircocensus surveys (Statistik Austria, 2003, 2005-2013). The number of residents, dwellings, buildings and working place is considered on a local level of settlements[32] (~17,000 settlements). The Invert/EE-Lab Model is used to calculate the energy density for heating and domestic hot water.

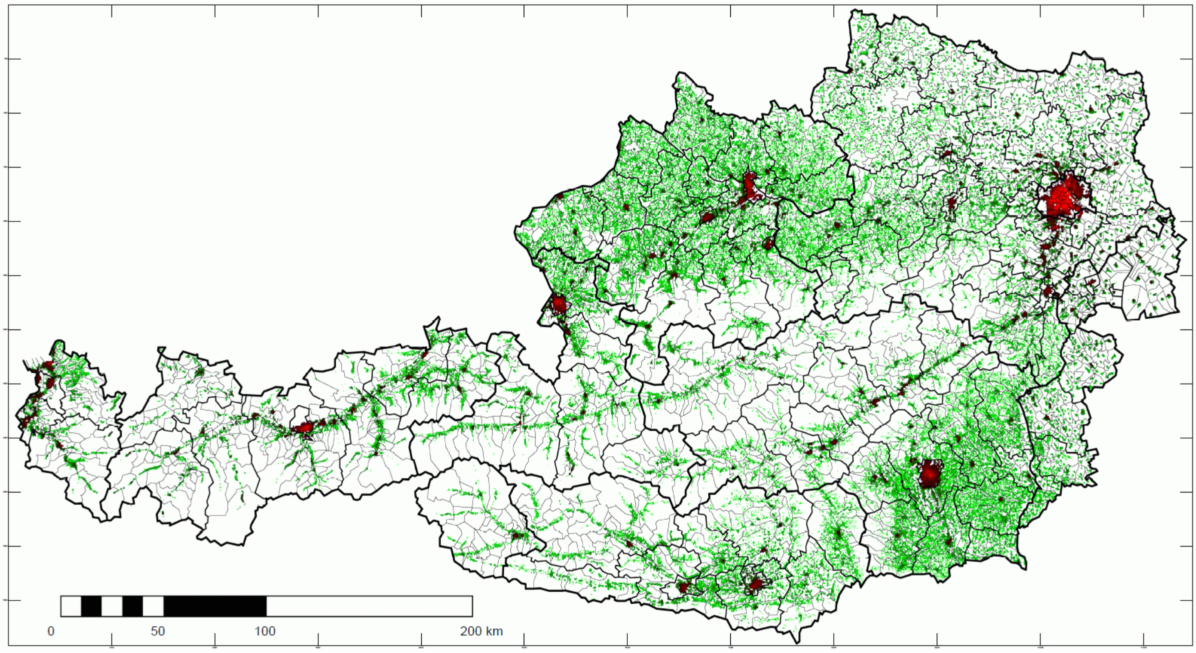


Figure 3.4 – Calculated energy needs for heating density in Austria.

3.2.3 Estimate of the regional availability of district heating

Existing district heating networks

Currently, about 30% of the total Austrian district heating sales occur in Vienna, another 20% in 8 cities: Graz, Linz, Salzburg, Klagenfurt, St. Pölten, Wels, Villach and Lienz. Besides these (and some other relatively large heating grids, e.g. Kufstein) an estimated number of more than 1100 rather small, biomass-fueled district heating networks existed in 2008 (LEV, 2008a, 2008b).

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[31] German title: “Arbeitsstätten und Beschäftige nach Betriebsgröße und Abteilungen der ÖNACE“.

[32] In German: “Ortschaften”.

(Small-scale) District heating operating companies have to undergo an external quality control management (“qm-heizwerke”) if they apply for investment subsidies. The data collected in this assessment process are stored centrally in a database, which, until recently, was administrated by LEV Steiermark[33]. In 2012, the database held information of about 800 biomass district heating nets with a size of more than 500 kW. These data were used by LEV Steiermark within the course of the project Solargrids (Müller et al., 2014c) to perform an anonymized statistical evaluation of 607 biomass-fueled district heating networks with respect to the average size of the (contracted) heating load connected to the DH. The district heating networks are clustered in 8 size categories (Table 3.1). The first 6 clusters contain about 100 networks each, the cluster containing the DH grids with a contracted load in the range of 25-65 MW contains 19 datasets, the cluster with larger networks is composed of only two (2) networks.

Table 3.1 – Distribution of contracted load connected to biomass fueled district heating networks in Austria. Data source: LEV Steiermark, 2012

	Number of district heating network per cluster	**Contracted thermal load, connected to the district heating network [MW]**	
		Mean value	**Median**
0 - 1 MW	109	0.8	0.8
1 - 1.5 MW	84	1.2	1.2
1.5 - 2.5 MW	107	1.9	1.9
2.5 - 4 MW	89	3.1	3.0
4 - 7 MW	96	5.3	5.3
7 - 25 MW	101	11	10
25 - 65 MW	19	41	38
more than 65 MW	2	110	110

Estimate of the future availability of district heating

The estimation of the near- to mid-term availability of district heating is done based on existing district heating grids and the share of dwellings supplied with DH on the regional level of municipalities (“Gemeinden”) according to the Housing Census 2001 (Statistik Austria 2004a-i) and the existence of a DH net according to LEV (2008a, 2008b). A mid- to long-term potential is derived by considering the calculated density function for space heating and DHW (section above, see also Müller et al., 2014c). This heat demand density function is used to identify the share of heat demand per municipalities and energy density clusters in (GWh / km²). The results of this analysis are depicted in Figure 3.5

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[33] Translates to: “Styrian Energy Agency”.

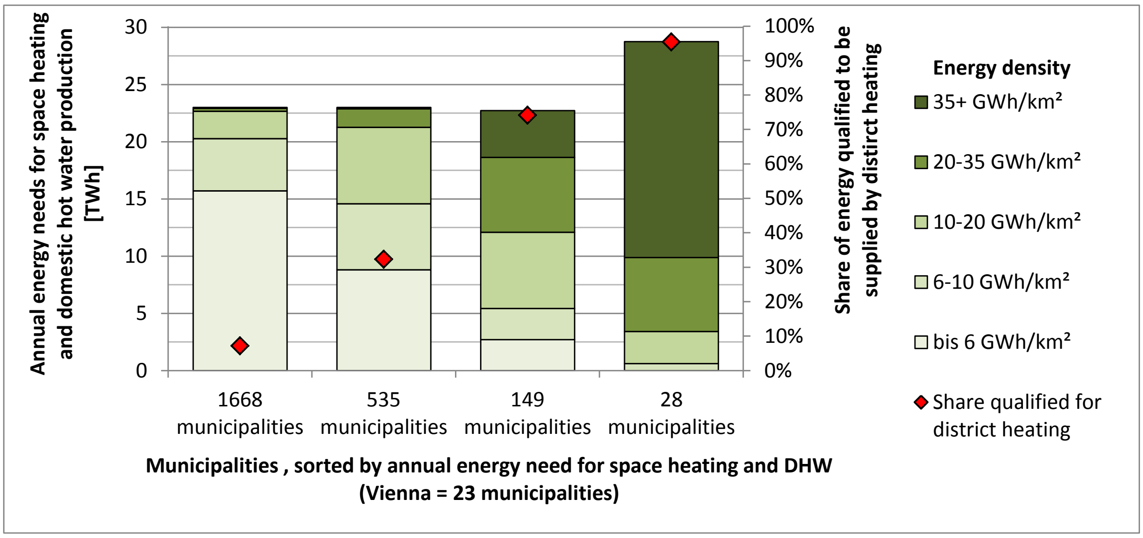

Figure 3.5 – Calculated energy needs for heating and domestic hot water divided into energy density clusters for the Austrians municipalities, sorted by their total energy needs for this energy end-use category. Source: Müller et al., 2014

3.2.4 Estimate of natural gas availability

The number of buildings and dwellings by fuel type used for heating on a municipality level are given by the Housing Census 2001 (Statistik Austria 2004a-i). This data can be used as a first estimate for the availability of natural gas on a local level. However, they appear to be not very accurate, as there are many municipalities, which have, according to this census survey, buildings using natural gas for heating, although the region is not close to the natural gas grid. Furthermore, the number of buildings using natural gas in 2001 is a static indicator and it might be insufficient or misleading if long-term scenarios are drawn. Therefore, a different approach is chosen to estimate the mid- to long-term regional availability of natural gas. Based on the regional buildings distribution and position of the high pressure natural gas grid, the regional (mid-term) availability of natural gas is estimated.

Spatial data on the natural gas transportation grid (e-control, 2008) are used to calculate the distance of the (calculated) spatially distributed building stock to the closest (high pressure) natural gas grid. The defined availability functions and the subsequently derived distribution of the natural gas availability are shown in Figure 3.6. Depending on the function used to estimate the availability, between 73% and 77% of the conditioned residential floor area can be supplied with natural gas.

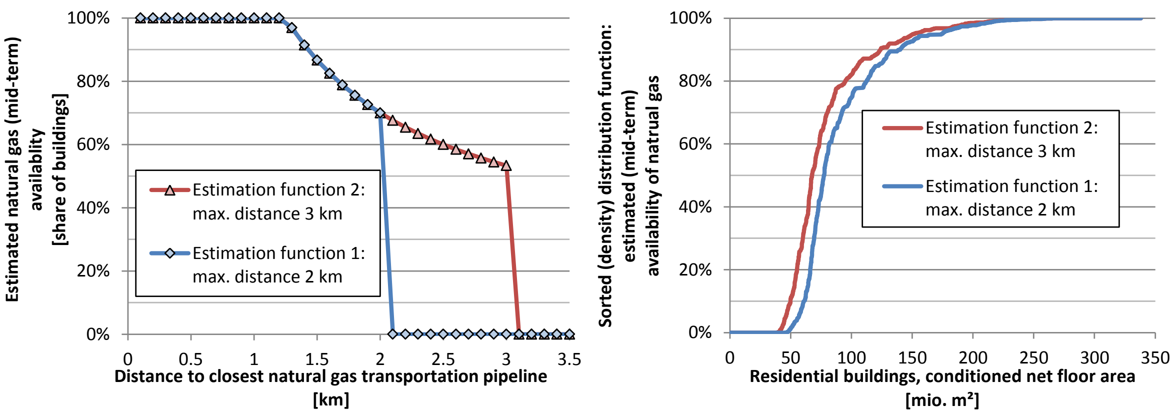

Figure 3.6 – Estimated natural gas availability in buildings for Austria.

In this work, the natural gas availability per municipality is based on estimation function 1, assuming an upper limit for distance between the building site and the natural gas transportation pipeline of 2 km.

3.2.5 Estimate of the energy demand for heating and DHW in air-immission protection law regions

Furthermore, the shares of buildings which are located in an air-immission protection law region[34] (IG-L region) are estimated. In these regions a particular focus is set on air pollution, an aspect that has implications on the type of heating system (and energy carriers used). The data for the share of land area and population that lives in these special regions are taken from Müller and Kranzl (2013) on a municipality level. On the national level, about 51% of the population and 21% of the Austrian land area are declared as such a region.

The number of buildings per building type and the existing heating systems located within these regions are estimated under the assumption that their share corresponds to the population share living in this regions on a municipality level. The resulting share per federal state and heat demand density type is shown in Table 3.2.

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[34] In German: “Immissionsschutzgesetz – Luft (IG-L) Sanierungsgebiet“ based on BGBl 115/1997.

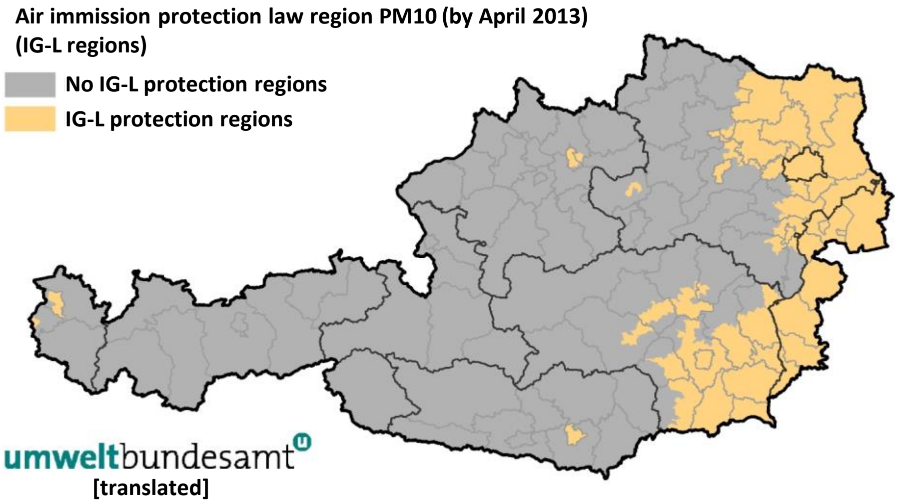

Figure 3.7 – Air-immission protection law regions in Austria. Source: UBA, 2014, my translation

3.3 Regional clusters used in this work

The analyses performed in this work, not the most disaggregated development of the building stock is necessary. In order to develop national energy demand scenarios, the number of buildings and the associated conditioned floor area per building category, construction period and heating system for the starting period as well as the evolution of the total number of buildings per building category until 2055 are grouped considering the following criteria:

- Climate zones: 10 climate regions as described in chapter 6.5 and 3.2.1 are used. Six of these climate clusters incorporate 170 to 260 tds. Dwellings. To the remaining 4 cluster 340 tds, 460 tds., 550 tds. and 940 tds. dwellings are assigned.
- 9 federal states regions: These regions are the lowest level for which consistent energy consumption data are available and are used to calibrate the final energy consumption of the assessed energy end-use sectors.
- Applicability of specific energy carriers with special focus on district heating: In order to enable a sound basis for the ultimate penetration of district heat, the regions are subdivided into three different types of settlement structure using the current energy density for heating per area as indicator. Based on a developed model (Müller et al., 2014a, see section above), building stock data are summarized for regions with an energy density of less than 8 GWh/km², more than 16 GWh/km² and in-between these levels. The

natural gas availability is estimated for each of the clusters using the model described in section 3.2.4.

In total, these criteria lead to a set of 73 regions in Austria. The number of climate clusters per federal region, the share of energy demand per energy density region and the population share living in IG-L regions are shown in Table 3.2.

Table 3.2 – Number of climate clusters per federal state and share of final energy demand per energy demand density.

	Number of Climate Clusters	**Share of energy demand in region with**			**Share of population in IG-L region with**		
		> 16 GWh/km²	**8 - 16 GWh/km²**	**< 8 GWh/km²**	**> 16 GWh/km²**	**8 - 16 GWh/km²**	**< 8 GWh/km²**
Burgenland	3	18%	34%	48%	100%	100%	100%
Carinthia	3	30%	17%	54%	49%	15%	4%
Lower Austria	6	30%	25%	45%	87%	65%	39%
Upper Austria	4	34%	16%	50%	41%	4%	1%
Salzburg	4	54%	0%	46%	0%	-	0%
Styria	5	35%	16%	49%	90%	71%	69%
Tyrol	4	38%	24%	38%	0%	0%	0%
Vorarlberg	4	60%	9%	31%	35%	12%	6%
Vienna	2	98%	2%	0%	100%	100%	-

3.4 Building renovation activities

To the author's knowledge, no consistent and comprehensive data on the historical renovation activities for the Austrian built environment exist for the last decades. For the period of 1991 to 2000, data on measures done on the façade or replacing windows are given by the Housing Census 2001 (Statistik Austria 2004a-i). According to these data, the annual replacement rate of windows in the residential sector was about 1.9%. The annual measurement rate concerning the façade of residential buildings was 1.8%, and about 60% of these measures included some sort of thermal insulation. Broken down to building size (buildings with 1 or 2 apartments and buildings with more than 2 apartments) these data show that the measurement rates in the cluster with larger buildings are higher (+30% to 45%) than those for small residential buildings (Table 3.3).

Table 3.3 – Renovation activities in the Austrian residential building sector between 1991-2000. Source: Statistik Austria 2004a-i

	Windows	**Façades**	
		any measures	**thermal insulation**
	[tds. apartments]		
1-2 apartments per building	301.9	263.2	154.4
More than 2 apartments per building	419.3	411.2	238.5

On the level of federal states the replacement rate of windows (considering all residential buildings) varies between 1.5% (Tyrol and Vorarlberg) and 2.2% (Vienna). The rate of measurements involving the façade ranged between 1.5% (Lower Austria) and 2.0% (Upper Austria and Salzburg). In general, a strong correlation between the replacement rate of windows and the façade measurement rate can be observed.

More recent data are given by UBA (2012). Based on the analysis of Microcensus data, the annual windows replacement rate in dwellings for the period 1996-2006 is estimated to be 2.6% and 2.4% for the period 2000-2010. In contrast to the Housing (buildings and dwellings) census 2001 (Statistik Austria 2004a-i), these data are not based on full census, but on a sample of 22.500 dwellings. Therefore, the data contain a larger statistical uncertainty between surveys in different years. According to the same publication the thermal renovation rate of façade measures increased from about 1% (1991-2000, Statistik Austria 2004a-i) to 1.8% for the period 1996-2006 and 2000-2010. In addition, the annual rate of insulating the upper ceiling lies in the range of 1.5to 1.6%, thus it is about 0.25% below the renovation rate of façade measures.

Another evaluation of thermal renovation activities is given by IIBW (2013). Based on data provided by the funding bodies of the federal states and the Federal Ministry of Agriculture, Forestry, Environment and Water Management (BMLFUW), renovation activities are monitored for the years 2009, 2010 and 2011 on the level of federal states. In contrast to the publications discussed above, only major renovation[35] activities are considered, leaving measures concerning only one or two components out of scope. It concludes that the renovation rate of major renovations is in the range of 0.9 to 1.2% (2009 - 2011). Furthermore, it is stated that the renovation rate on a federal state level is highly

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[35] At least three out of five renovation measures (replacement of (1) windows (and doors), or (2) heat supply system (boiler), insulation of (3) façade, (4) ceiling or roof or (5) basement) must be taken at once.

discontinuous with large differences between the analyzed years 2009, 2010 and 2011, and also varies highly between the federal states (0.2/0.4% for Salzburg vs. 2.1/1.5% for Upper Austria). On a national level however, no statistically significant changes in the renovation rates between 2006, 2008 and 2010 on a 95% confidence interval is found.

3.5 Final energy demand for heating and DHW preparation and the distribution of energy carriers

3.5.1 Historic development of energy carriers used for space heating and domestic hot water preparation

More or less consistent energy usage data for Austria are available for the period since 1970 (Statistik Austria, 2014). Taking a historic perspective, solid energy carriers have been the most important energy carriers used for space condition in Austria. In 1970, biomass and coal together held a share of more than 40%. While biomass, which had an estimated market share of 18% was able to keep that level and has even increased its importance since the 1980s, the energy carrier coal could not. Holding a share of about 23% in 1970, the usage of coal products in households and the service sector has been declining steadily over the last 40 years. For several years now, the its usage for space heating and domestic hot water preparation has been well below the share of energy harvested by solar thermal solar collectors, ambient energy collected by heat pumps or biomass fractions such as pellets and wood chips.

Table 3.4 – Estimated historic development of the share of energy carriers used for space heating and domestic hot water supply of residential buildings and buildings of the tertiary sector. Data source: Statistik Austria, 2014, own calculations

	1970	**1980**	**1990**	**2000**	**2010**	**2012**
Coal	23%	18%	10%	3%	1%	1%
Heating oil	34%	38%	31%	28%	19%	17%
Natural gas	7%	11%	15%	24%	27%	28%
Biomass and other RES	18%	15%	23%	22%	25%	26%
District heat	2%	4%	8%	12%	20%	21%
Electricity[1)]	16%	15%	13%	10%	8%	8%

[1)] Estimated by the author

In 1970, liquid energy carriers (heating oil products) supplied about 1/3 of the energy consumption used for space heating and domestic hot water supply in Austria. The importance of oil products for this purpose rose during the following decade, leading to an all-time peak of almost 40% in 1978-1980. Although the share of has been declining since then, the absolute energy usage remained on a constant level of about 25 TWh for the period between 1982 and 2003. Since 2004, the energy usage of oil for heating purposes has been decreasing sharply (Figure 3.8). This may be coincident with the increase of the oil price share since 2004 compared to the price level before.

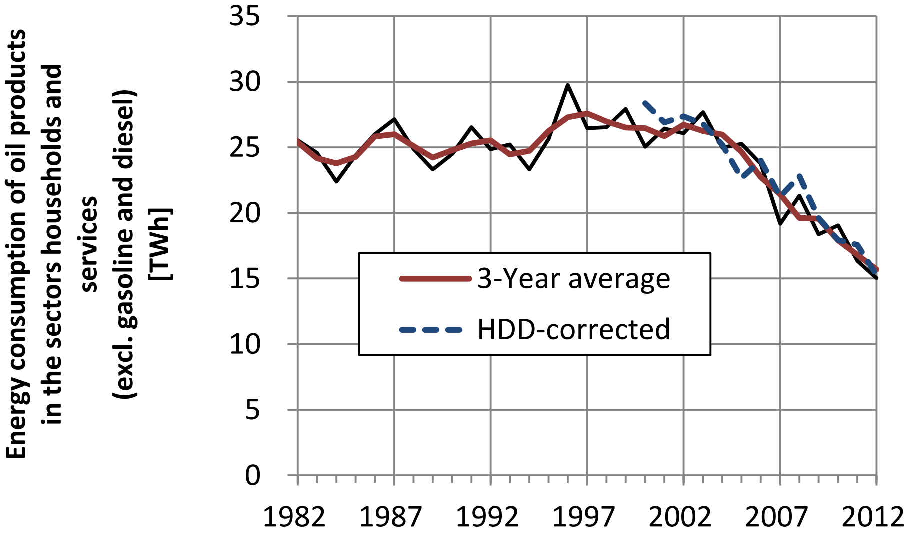

Figure 3.8 – Consumption of oil products excluding gasoline and diesel of the sectors households and services in Austria since 1982. Data source: Statistik Austria, 2014, own calculations

Annually installed oil- and natural-gas-based heating systems

The annual number of installations of heating systems is not consistently statistically covered. An indication of the installation rate can be found in the journal “unser wärme”[36] which is quarterly released by the Heizen mit Öl Gmbh. According to issue 2012-1 (Heizen mit Öl, 2012-1), 22,000 grant applications (20.000 shortly after the program had been running for 3 years) for the program “Heizen mit Öl Förderinitiative”[37] were submitted between 2009 and 2012. The same issue also states that during the 3 years between 2009 and 2012 14.000 new oil heating systems were installed. According to issue 2013-3 (Heizen mit Öl, 2013-3), within the first six months of 2013 2.317 applications for the subsided program were

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[36] Translates to “our heat/warmth”.

[37] Heffner et al. (2013): *“’Heizen mit Öl Förderinitiative’ is a program established by the Austrian heating oil industry to replace old boilers with new condensing boilers, thus improving efficiency by up to 40%. This voluntary program was established in 2009 in cooperation with the Ministry of Economic Affairs. All companies importing or distributing heating oil in Austria contribute to a fund, resulting in 100% market coverage.”*

submitted, which means that the total number of applications since 2009 had increased to more than 26.000. By March 2014 (Heizen mit Öl, 2014-2) the number of applications had increased to 30.000 for the 5-year period since 2009. Based on this data the number of installed oil heating systems in Austria is estimated to be about 6000 boilers per year.

Other data sources for historical installation rates of oil-based boilers are VÖK (2007, 2012 and 2014). According to their data, the number of annually installed oil-based heating systems peaked in 1996 at about 35 tds. boilers. Since then, the it dropped to about 4500 boilers in 2008, which was the last year before the introduction of the “Heizen mit Öl Förderinitiative” subsidy program. The average number of annually installed oil-based boilers for this period 2009 to 2013 is about 6.000 boilers per year, which is consistent with the estimations derived from the “Heizen mit Öl Journal” data.

Annual installation rates for natural gas-based heating systems in Austria are also given in VÖK (2007, 2012 and 2014). According to these data, annually sold natural-gas-based boilers are in the range of 45 to 55 tds. systems. This makes this technology by far the most sold systems in Austria. However, when it comes to new heating systems per dwellings, these numbers are difficult to compare with other heating systems, since in many cases a natural-gas-based boiler is installed per apartment, instead of house-central heating system, as it is mostly the case for other widely applied technologies. The data given by VÖK (2007, 2012 and 2014) do not indicate a significant change in the number of annually installation systems for the last 19 years.

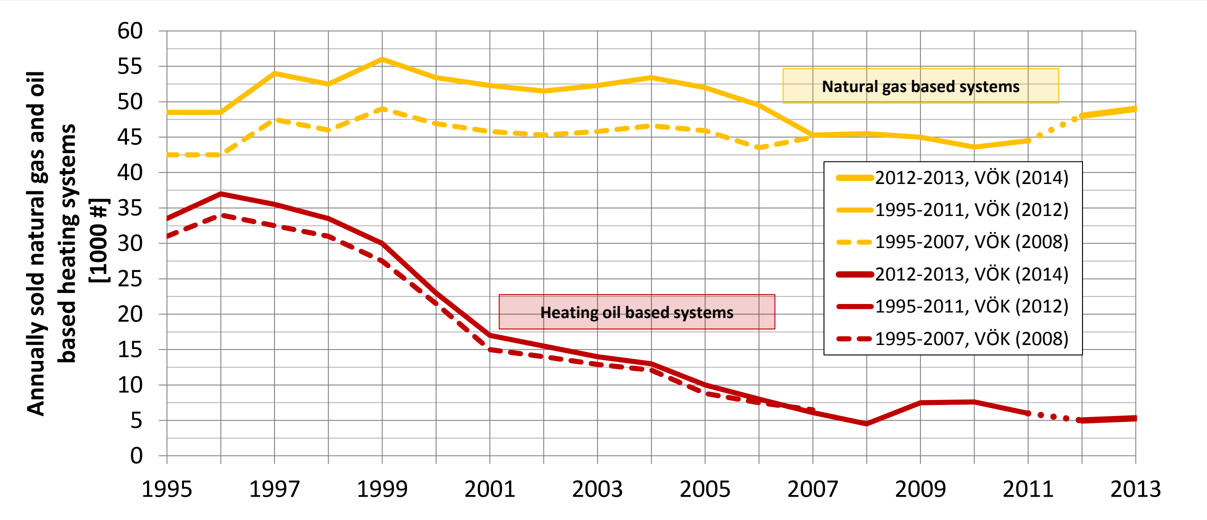

Figure 3.9 – Annually installed (or sold) natural gas (yellow) and heating oil (red) based heating systems in Austria.

Annually installed heating systems with renewable energy carriers

The probably most comprehensive overview of the installation rate of heating systems based on renewable energy carriers in Austria can be found in the annual publication series “Innovative Energietechnologien in Österreich Marktentwicklung”. The latest release covers the annual installation until 2013 of various biomass based heating systems (wood log, pellets, wood chips) for different nominal thermal capacities, solar thermal collectors, heat pumps as well as wind power and PV (Biermayr et al., 2014).

Wood pellets boilers started to gain increasing market shares in the late 90s of the previous century. Since 2005, the annually numbers have been in the range of about 10,000 systems per year. Wood log and wood chip boilers are grouped to “other biomass-based systems” in Figure 3.10. For the last 10 years their annually numbers of installed systems have been in the range of about 8 to 13 tds. boilers. Although no consistent data are available for the period before 2003, based on VÖK (2007 and 2012) the average number of installed systems for the period of 1995 to 2003 was estimated to be about 7 tds. systems per year.

The use of heat pumps for space heating has steadily increased within the last 20 years. Starting with about 2.000 annually installed systems in Austria in 1995, the installation rate has increased to almost 15.000 systems in 2012 and 2013. This means that heat pumps are currently the secondly most often installed decentral heat supply system.

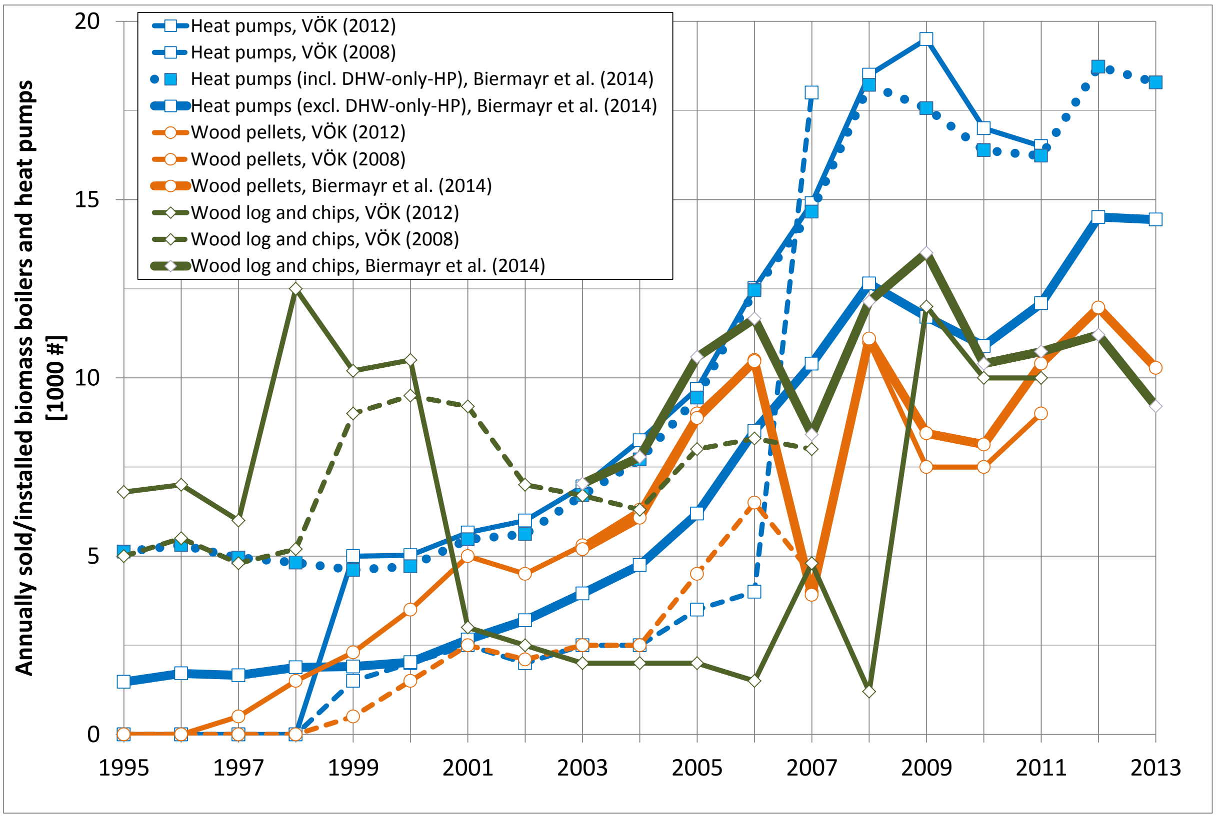

Figure 3.10 – Annually installed/sold heat pump, wood pellets and other biomass based heating systems in Austria.

Annual district heating connection rate

Connection rates of district heating networks are not directly available in existing literature for Austria. Therefore the author estimates them based on the total number of connected households (Microcensus data) and the energy consumption according to the national energy balance. Recent data for the number of households are given in the annual publication series “Wohnen” (Statistik Austria, 2003, 2005-2013), based on the results of the Microcensus “labour and dwellings statistics” and data derived from the Microcensus “energy consumption of households”[38]. The main difference between these two surveys comes from the obligation to provide information in the case of the “labour and dwellings statistics” census, while in the “energy consumption of households” census data are given voluntarily, following the “labour and dwellings statistics” questions. The response rate of the “energy consumption of households” census is in the range of 50%-65%. Furthermore, the “energy consumption of households” census is carried out every second year, while the “labour and

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[38] Results from the Housing Census 2001 (Statistik Austria, 2004a-i) are not consistent and cannot be used for the analysis.

dwellings statistics" census is carried out on a quarterly basis. In the following, data from the "labour and dwellings statistics" census (Statistik Austria, 2003, 2005-2013) are used to estimate the expansion of district heating during the last decade (2003-2012) on the level of federal states.

To get robust values for the number of dwellings connected to district heating in 2002 and 2012 per construction period and federal state, a linear trend function is derived from the annual census results. The development of the households connected to district heating is shown in Figure 3.11. The blue sections of the bars indicate the number of households supplied with heat from district heating networks in 2002. The red sections of the bars represent the number of households in buildings constructed before 2001 which were connected to district heating networks between 2002 and 2011. By comparing these numbers to the total number of dwellings in buildings with the same construction period, the average connection rate of existing buildings (buildings constructed before 2001) for the period from 2003 to 2012 is estimated. The highest connection rates of dwellings in buildings, constructed before 2001 for the period between 2002 and 2013 are found in Salzburg (~0.9%p.a.), followed by Vienna, Styria and Carinthia (~0.5%p.a). The other end of the spectrum marks Burgenland with an annual connection rate of less than 0.1%p.a. For the other four federal states, I derive annual connection rates of about 0.21% to 0.27%. This is in the range of 1/10th – 1/15th of estimated annual heating system exchange rate.

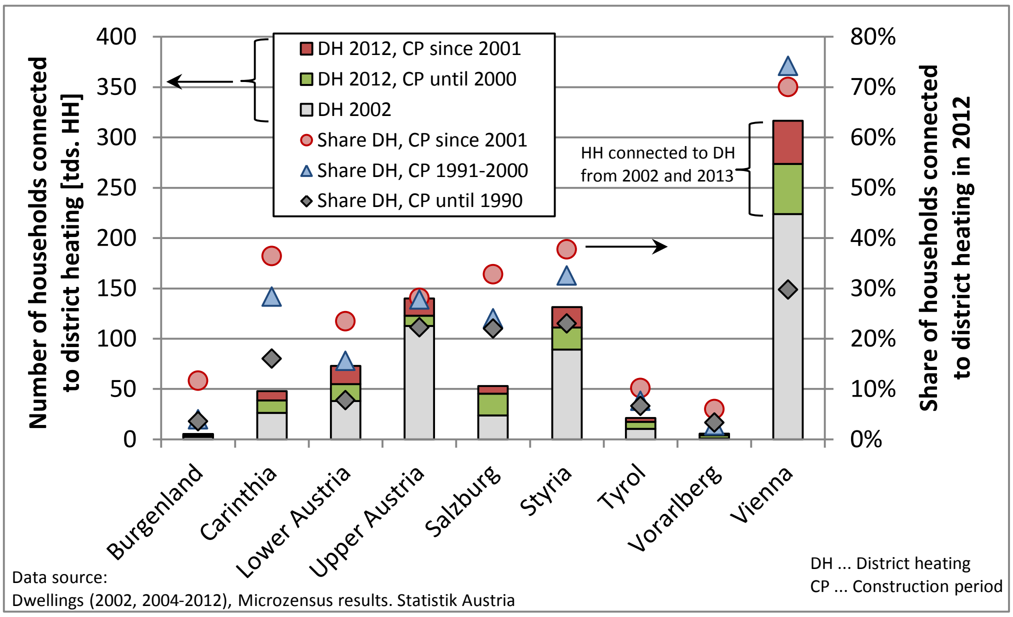

Figure 3.11 – District heating per federal state. Data source: Statistik Austria, 2003, 2005-2013

The green sections on top of the bars represent the number of dwellings in buildings that were constructed between 2000 and 2013, and were supplied with district heating in 2012. The red circles in Figure 3.11 give the market penetration of district heating in these buildings as of 2012. The district heating penetration of dwellings in buildings from the construction period between 1991 and 2000 is depicted by the blue triangles. The average DH penetration levels in households located in buildings constructed before 1990 per federal state are indicated by the grey diamonds. The lowest shares can be found in Vorarlberg, where about 6% of newly constructed buildings were connected to district heating networks. Vienna, on the other hand, has a connection rate of more than 70% of buildings constructed after 1990 and a total connection rate of about 37%. It can be seen that the share of new buildings connected to DH is above the average values. This is consistent with the gradual expansion of district heating networks which were not constructed in Austria before the early 70s. The generally lower energy needs of newer buildings is adverse to the economics of this particular heat supply system, as due to the rather high investment costs for the infrastructure, an higher energy need per supplied area reduces the total specific heating costs for the end users. However, this also implies that the energy needs of buildings currently connected to district heating networks will not decrease as much in the future as is expected for the total building stock.

These data lead to an annual number of new connected households of about 25 tds. dwellings per year, which is a rate of roughly 0.7% p.a. Again, this value cannot be directly compared to the data on installed boilers discussed above for three reasons: First, only the residential buildings are covered in the DH connection rate. Secondly, the data refer to households that are connected to district heating, while, at least for biomass and oil based heating systems, the annual installation rate refers to buildings rather than apartments. However, as mentioned above, this inconsistency also affects the comparability of the natural-gas-based systems with other technologies. Finally, in contrast to decentral heat supply systems, which need to be replaced after reaching their end of lifetime (25-40 years), the disconnection rate of district heating is virtually zero. This means that the district heating connection rate does not contain any district-heating-to-district-heating replacement rate, as it is the case for established decentral heating technologies such as natural gas, heating oil or word log (partly also wood chips) boilers.

As the number of dwellings connected to district heating rises, also the final energy consumption from district heating reported in the national energy balance increases.

However, the energy figures suggest a much faster penetration than the connection rates. While the number of connected households increased by about 47% between 2002 and 2013 (Statistik Austria, 2003, 2004-2013), the final energy consumption of district heating in the residential sector inclined by more than 70%, starting from 4.8 TWh in 2002 to 8.3 TWh in 2012 (Statistik Austria, 2014). The final energy consumption from district heating in the tertiary sector increased from 6.1 TWh in 2002 by 60% to 9.8 TWh in 2012.

Annually installed solar thermal collector areas

Historical data for annually installed/sold solar thermal collector areas in Austria are also given in Biermayr et al. (2014). Between 1995 and 2004, the annually installed solar thermal collector area ranged between 150 and 200 tds. m². By 2005, the number of installations started to increase, peaking at more than 350 tds. m² in the year 2009 (Figure 3.12). Since then (2009 – 2013), the annually installed area has been decreasing. For 2013, Biermayr gives an installed area of about 180 tds. m².

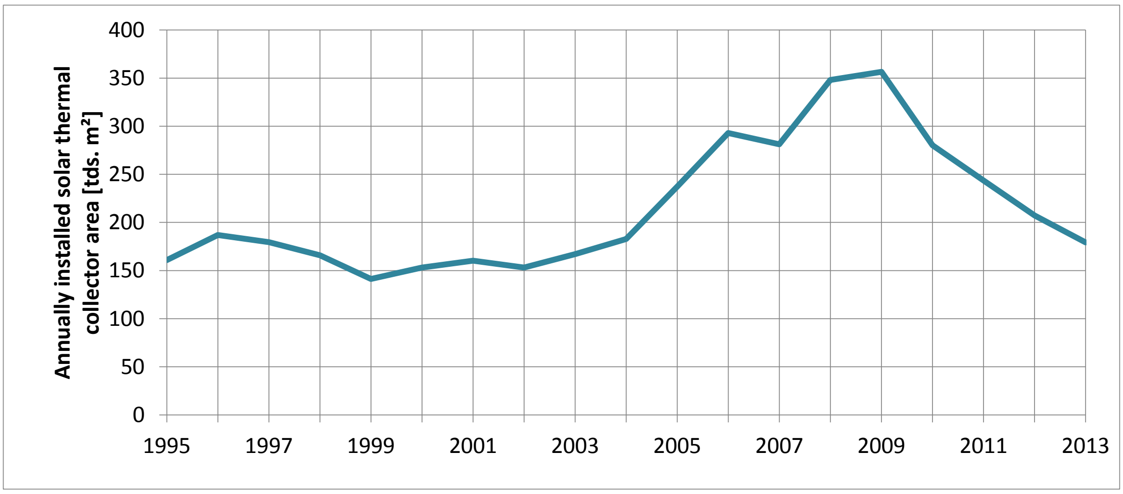

Figure 3.12 – Annually installed solar thermal collector area in Austria. Data source: Biermayr et al., 2014

3.5.2 Final energy demand for heating and DHW: base year 2008 calibration

A crucial issue is the calibration of the bottom-up tool to top-down statistical data regarding energy consumption. Previous projects and applications of the model have shown that differences between bottom-up calculated and top-down data usually are in the range of 10%-40%. By considering the user-behavior and comfort requirements (i.e. effective mean indoor temperature values, section 4.4.4), and adapting the efficiency of building structure and heating systems, within a small range of uncertainty it is possible to calibrate the bottom-up model results to top-down values. As a result, the results of the model are consistent with – climate corrected – energy consumption data (see e.g. Kranzl et al., 2011b; Müller et al., 2010; Müller and Kranzl, 2013a; Steinbach et al., 2011).

The following publications and data are used to calibrated the final energy consumption and energy consumption structure for the base year: Statistik Austria (2010a, 2010b, 2012a-i, 2013a, 2013b) and Wegscheider-Pichler, A. (2009).

Figure 3.13 compares the model outcome for the final energy consumption of residential buildings with the heating-degree-day-corrected energy consumption data provided by the energy balance divided according to the main energy carriers and federal states of Austria for the (model base) year 2008. As can be seen from these figures, the calibrated model is able to reproduce the heating degree day-corrected energy balance data fairly well.

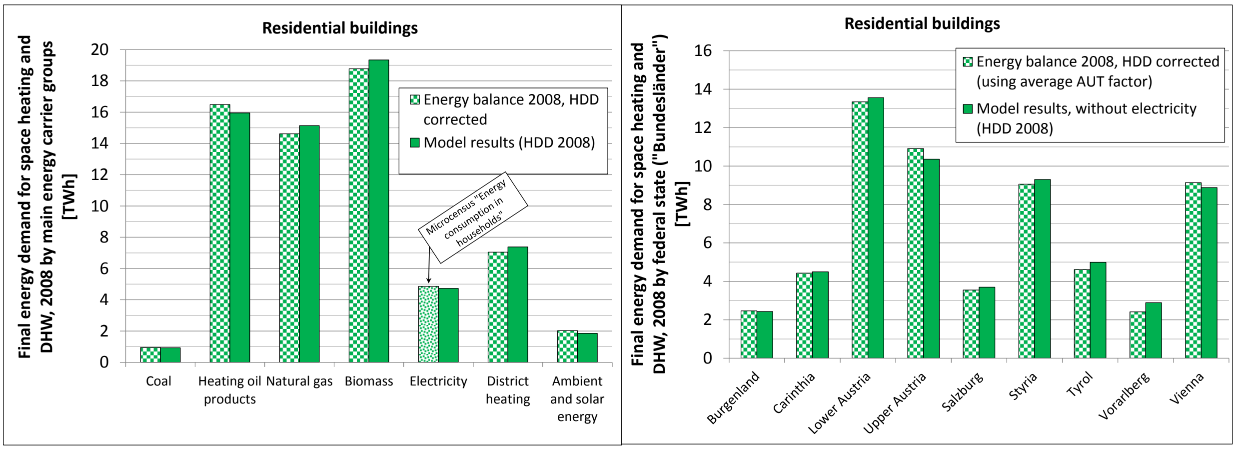

Figure 3.13 – Comparison of final energy consumption for space heating and domestic hot water in residential buildings: energy balance versus model results.

On the disaggregated level of energy carriers per federal state, the largest deviation between the model results and statistic energy data for the natural gas consumption are gotten in Viennese building. The gas consumption derived from the model is about 550 GWh lower than the actual statistical consumption, which results in an underestimation of the Viennese natural gas consumption (for space heating and DHW preparation) of about 10%.

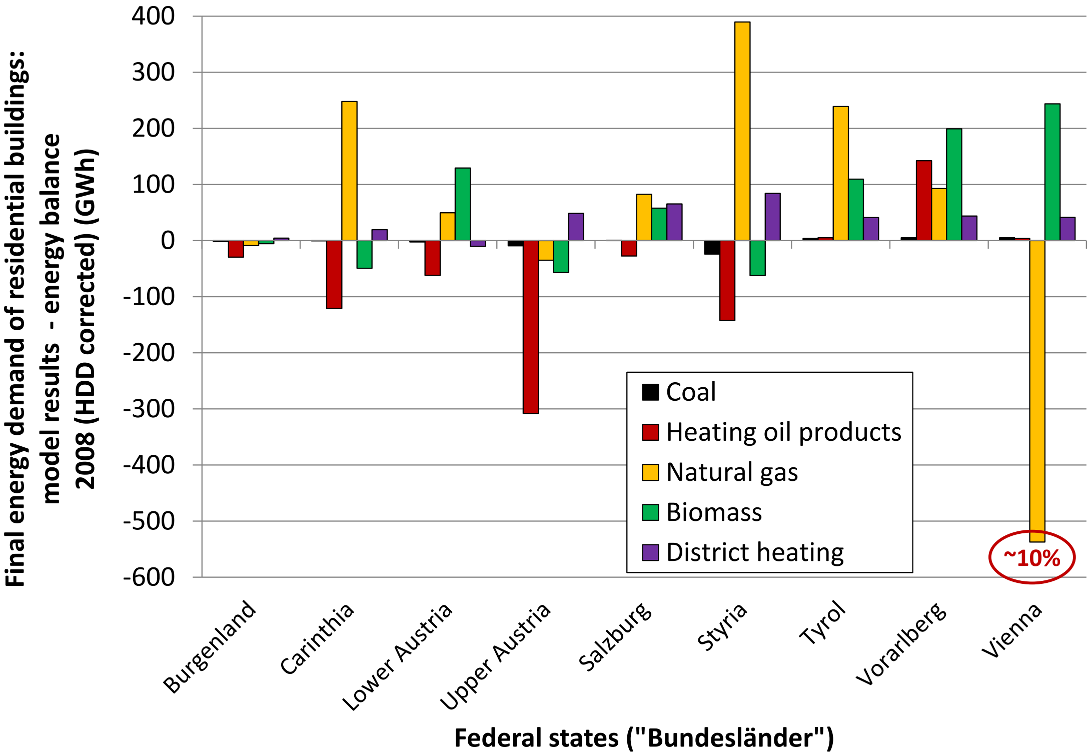

Figure 3.14 – Deviation between the final energy consumption according the energy balance and the model results.

The energy needs of the Austrian building stock

The next two figures depict the resulting specific energy needs for heating for different building categories and construction period clusters of Austria. In Figure 3.15 the specific energy needs for heating under site specific climate conditions (using the 10 specified climate zones), derived according to the ÖNORM B 8110-6 calculation standard, are shown. Since this calculation method does not consider the observable user behavior, the data are not consistent with those derived from a top-down, national or regional energy balance approach.

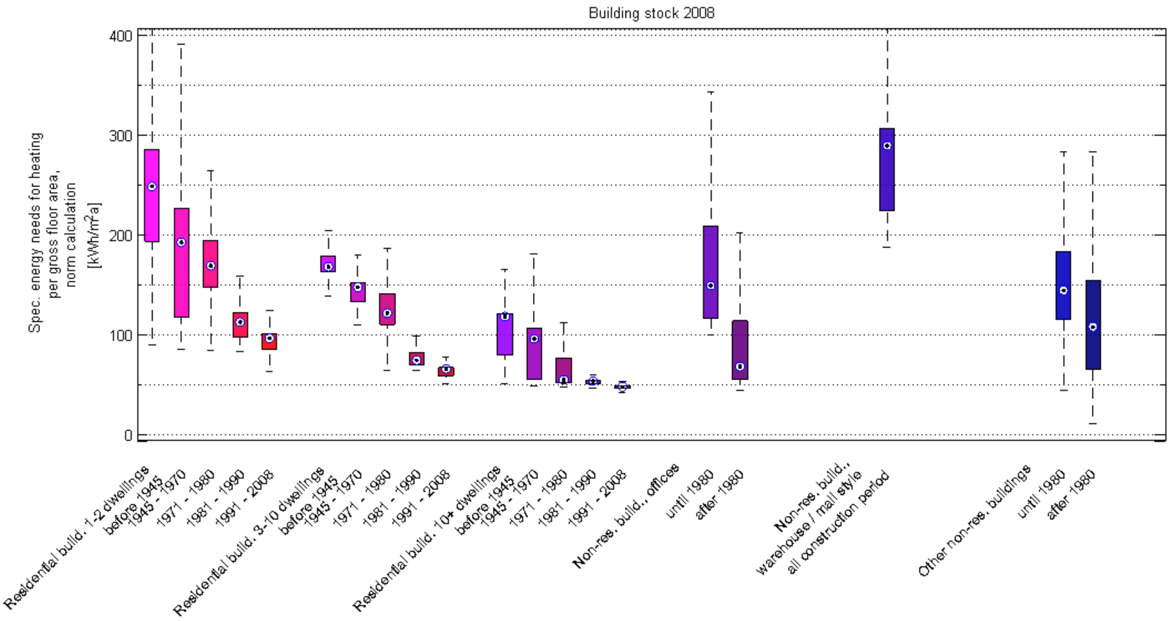

Figure 3.15 – Calculated energy needs for heating per gross floor area of the Austrian building stock under site specific climate condition according to ÖNORM B 8110-6 calculation standard.

As described in section 4.4.4, the user-behavioral effects lead to, generally speaking, lower final energy demand and subsequently lower energy needs in buildings with high energy-consumption-dependent annual costs and vice versa. For residential buildings, the quantification of this effect stands on a solid empirical basis. Reliant data on the scale of such effects in non-residential buildings are not available. Thus, the user behavior is included for residential buildings (see Figure 3.16) only; non-residential buildings are calculated according to the ÖNORM B 8110-5 settings.

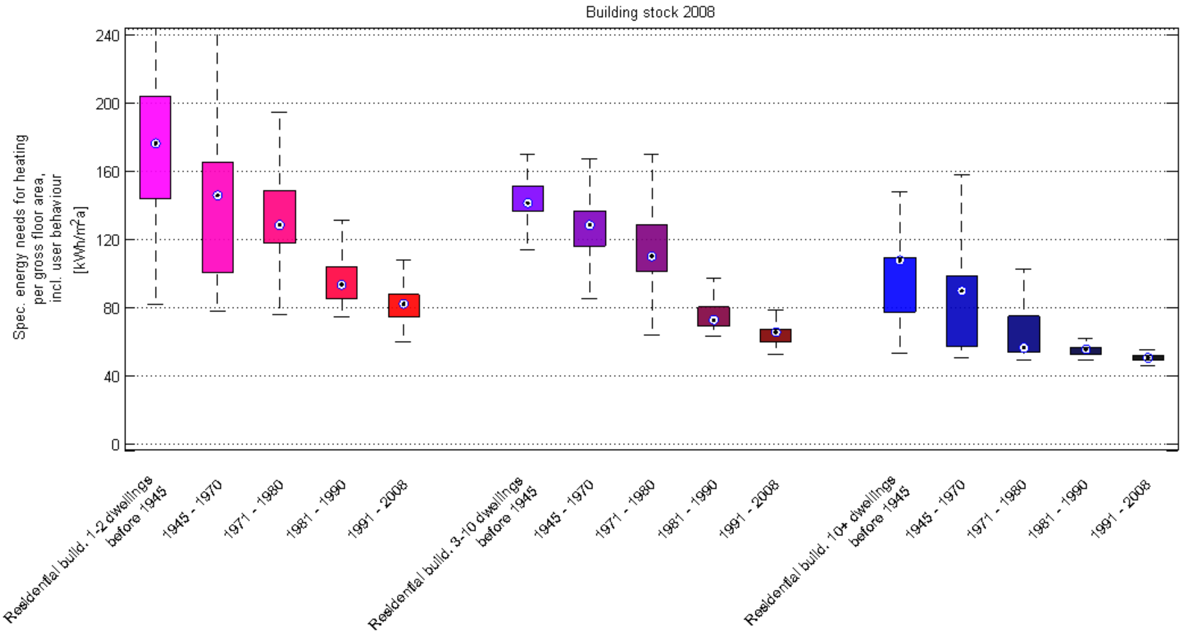

Figure 3.16 – Calculated energy needs for heating per gross floor area of the Austrian residential building stock under site specific climate condition considering user-behavioral effects.

Considering user-behavioral effects, the energy needs of residential buildings with a low thermal quality are lower compared to the reference calculations. The difference between these calculation methods is depicted by Figure 3.17. The average (median) energy reduction of residential buildings with less than three dwellings due to behavioral effects ranges between 15% for buildings constructed between 1990 and 2010 and almost 30% for buildings constructed before 1945. In apartment buildings the user effect is lower. The main reason is the typically smaller floor area of dwellings in these buildings. While in large apartment buildings constructed before 1945 the average energy needs according to the norm calculations using reference parameters are about 10% higher than those that include the user-behavior, the effect on the final energy consumption reverses for buildings constructed after 1970. In large apartment buildings constructed between 1991 and 2008, the energy needs for heating increased by about 5%, if the user behavior is considered.

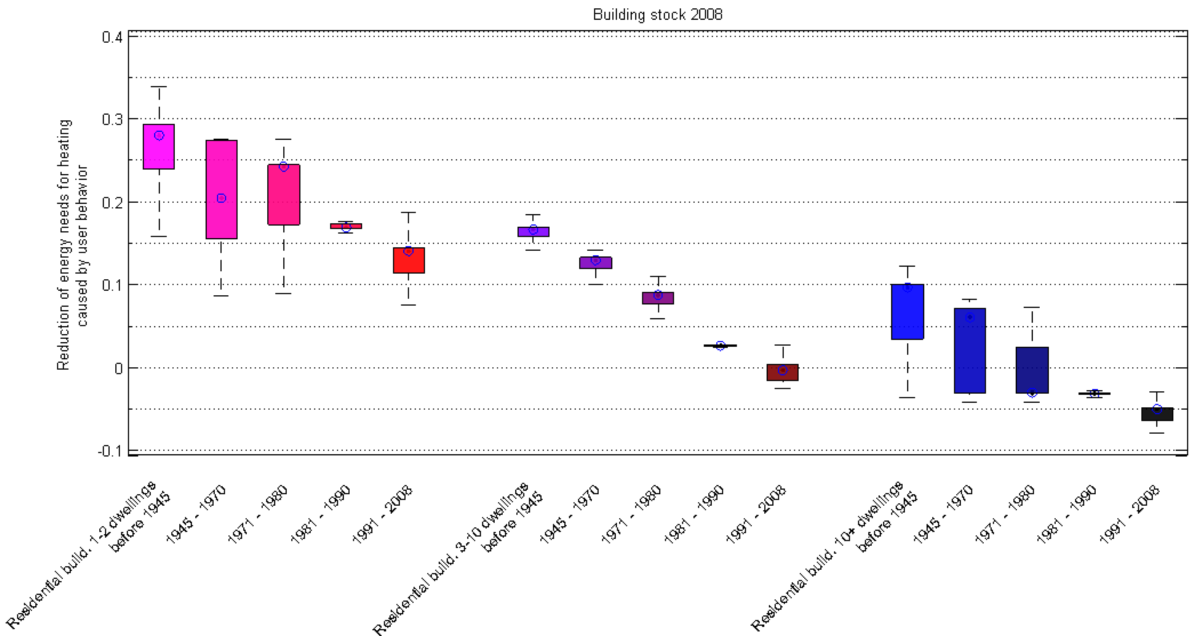

Figure 3.17 – Extent of the implemented user-behavioral effects on the energy needs for heating for the Austrian residential building sector.

4 Methodology of the developed Invert/EE-Lab Model

This chapter describes the key methodology of Invert/EE-Lab. It starts with an overview of the general structure and the calculation of energy demand. It subsequently presents the Weibull-based approach for modeling the service lifetime of buildings and building components, and the implemented decision-making processes using a nested logit model and various diffusion restrictions[39].

4.1 The bottom-up energy system model Invert/EE-Lab

Invert/EE-Lab is a dynamic engineering-based bottom-up model for simulating the energy demand for space heating and domestic hot water in buildings with the focus especially set on larger building stocks.

It also evaluates the effects of different promotion schemes and energy price settings on the energy carrier mix, CO_2 reduction and costs for RES-H support policies. Furthermore, it is designed to simulate different scenarios (price scenarios, insulation scenarios, different patterns of consumer behavior, etc.) and their respective impact on future trends of renewable as well as conventional energy sources on national and regional levels.

Three modules (see Figure 4.1) constitute the core of the model (kernel), one that calculates the energy needs and final energy demand for space heating and domestic hot water of buildings, a second module that calculates replacement and demolition rates and a third module that anticipates heating related investment decisions. These modules are connected to a database supplying information on relevant data, such as a detailed description of the building stock, heat supply technologies, energy prices, climate data, user-behavior, etc. The decision algorithm employs a myopical, utility-based logit approach, which optimizes

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[39] The research conducted for chapter 4 and 5 was partly financed by a research grand of the Austrian Marshall Plan Foundation. A draft version of these two chapters is published in Müller (2012).

objectives of agents under imperfect information conditions and thus represents the decision-making process concerning heating and domestic hot water preparation.

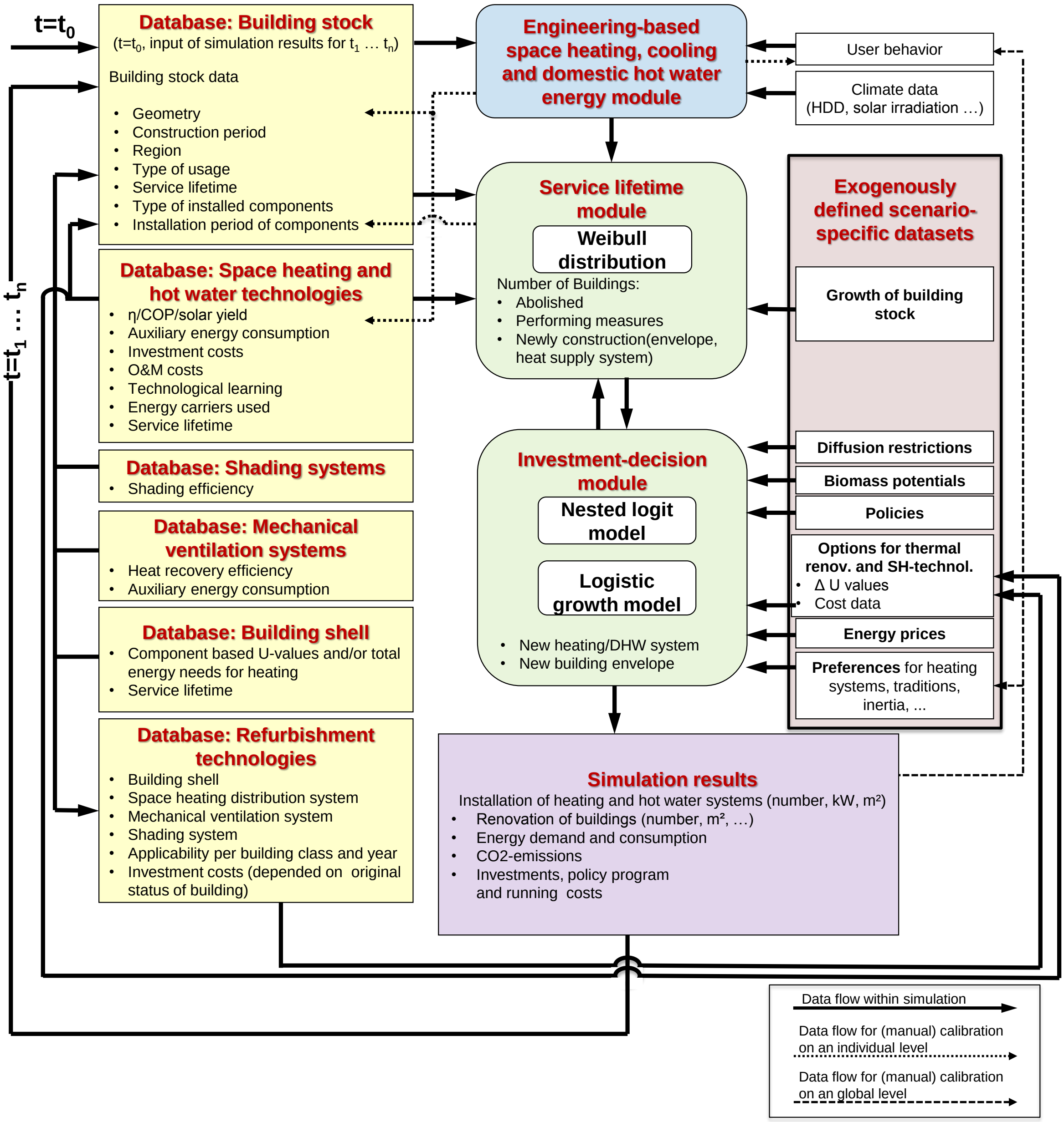

Figure 4.1 – Structure of the Invert/EE-Lab simulation model.

The building stock database used by the Invert/EE-Lab model groups the different buildings based on a set of properties. The top level, in this thesis called the “building category” level, divides buildings according to their fundamental building characteristic such as type of usage or size (in terms of dwellings of residential buildings). All policies implemented into the model can be defined for all building categories differently[40]. For the

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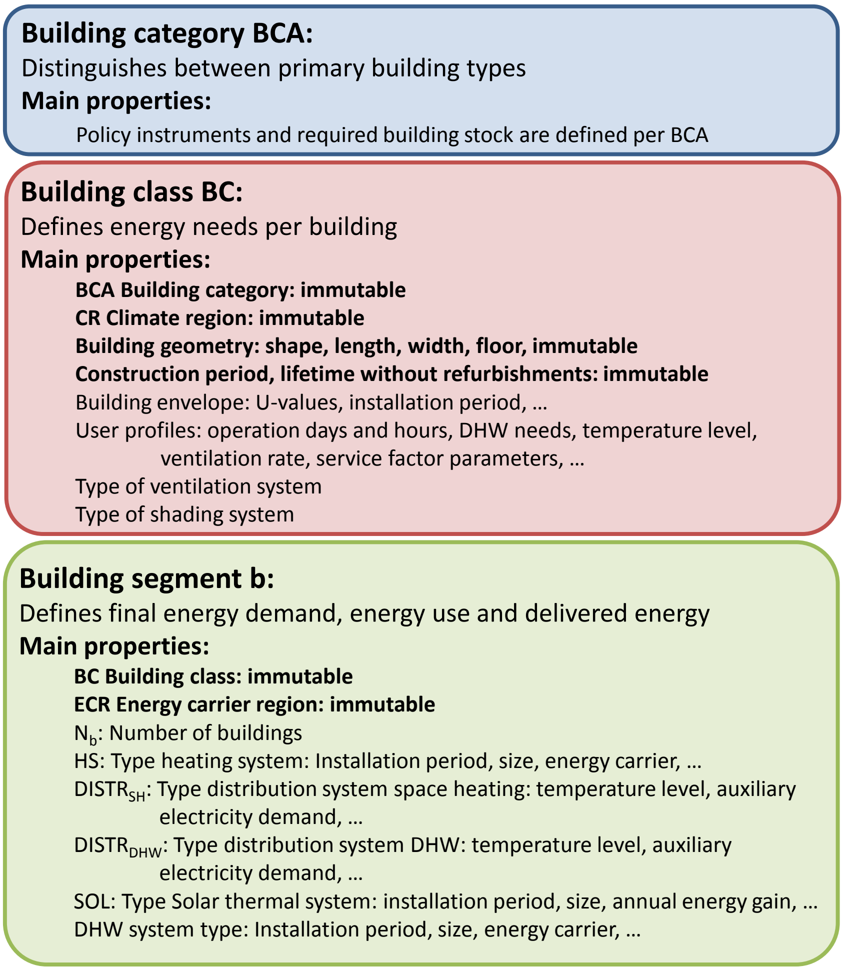
[40] And most policy settings can also be defined separately for new constructions, refurbished and unrefurbished buildings.

performed calculations the Austrian building stock is clustered into four residential building categories (single family homes (SFH), semi-detached houses, small multifamily houses and large apartment buildings) and into 12 clusters for non-residential buildings (see Table A.1).

The second building structure level, the "building classes" level, groups buildings that belong to the same top-level class and have the same energy needs, defined by the following criteria: geometry, types and properties of the building shell elements, shading- and mechanical ventilation system, climate region and user profiles. At the lowest level of the used hierarchical buildings structure, the "building segments" level, buildings that belong to the same building class type are groups according to their heat supply and distribution system and the region in terms of availability of energy carriers[41].



Building category BCA:
Distinguishes between primary building types
Main properties:
Policy instruments and required building stock are defined per BCA

Building class BC:
Defines energy needs per building
Main properties:
BCA Building category: immutable
CR Climate region: immutable
Building geometry: shape, length, width, floor, immutable
Construction period, lifetime without refurbishments: immutable
Building envelope: U-values, installation period, …
User profiles: operation days and hours, DHW needs, temperature level, ventilation rate, service factor parameters, …
Type of ventilation system
Type of shading system

Building segment b:
Defines final energy demand, energy use and delivered energy
Main properties:
BC Building class: immutable
ECR Energy carrier region: immutable
N_b: Number of buildings
HS: Type heating system: Installation period, size, energy carrier, …
$DISTR_{SH}$: Type distribution system space heating: temperature level, auxiliary electricity demand, …
$DISTR_{DHW}$: Type distribution system DHW: temperature level, auxiliary electricity demand, …
SOL: Type Solar thermal system: installation period, size, annual energy gain, …
DHW system type: Installation period, size, energy carrier, …

Figure 4.2 – Hierarchical structure for the definition of buildings and their main properties.

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[41] The expression "energy carrier region" is used in this thesis when referring to this region-specific property of buildings.

4.2 Software used for model implementation

The model is implemented using the programming language Python. Python is an object oriented, cross-platform, interpreting computer language widely used. The calculation data are implemented as numpy-object, using the numpy library (Oliphant, 2007), which is the standard python library for numerical floating-point calculations. The numpy library provides a convenient python interface, allowing a vectorized numerical operation with reasonable performance. The scipy library is applied for numerical functions, exceeding those implemented in the numpy library. For time critical operations, especially when the vectorization of operations fails, the cython library (Bradshaw et al.) is used. This library converts Python-like code into C-Code and compiles it before runtime, thus allowing operations to be done with a performance that is comparable to programs written in native FORTRAN or C. During runtime, variables are kept in the random access memory (RAM). However, the model allows all data generated in each simulation period to be stored on the hard disk (up to 100 GB per run) for post-simulation analyses that exceed the standard results produced by the model. The data are stored in HDF5 format or dumped as Python objects. The standard model input is provided by database-table-like csv-files, the input data are handled and stored in a sqlite3 database. The model supports storing the standard results as csv-files, sqlite3 or in a mysql database. Furthermore, it is capable to plot results automatically.

At the beginning of the model development, no parallel processing library that allows shared memory objects exists for numpy objects[42]. This limits the possible gains of parallelization of calculations processes, since it adds additional overhead for createing data in the random access memory. For the actual implementation, this overhead basically eliminates the gains of parallelization of individual computation intensive methods. Thus, instead of partial parallelization of individual simulation runs, the approach of allowing multiple simultaneous model runs was implemented. This, in fact, brings no advantage if only a single simulations run is demanded, but delivers almost overhead loss-free parallelization if multiple runs are performed. For the code parallelization the IPython library (Pérez and Granger, 2007) is used. An interface to the data-context object for external python (read and write), R, Matlab is provided, and called after each simulation step. Finally, to exchange data

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[42] The Global Array Object Toolkit v5.1 (released in February 2012) introduced an interface (GAINS) for numpy like objects and data processing.

exchange with other models during runtime, a web based SOAP (Simple Object Access protocol) Client was implemented using the Suds library.

The data and the calculation algorithm are strictly separated throughout the implementation. Therefore all technology-, climate-, user- and other scenario-specific data constitute input parameters which are part of the input dataset and not the model itself.

4.3 Regional scope of the model, applications and references

The development of the current Invert/EE-Lab tool was started in 2010 by the author of this thesis, based on the experience with predecessor models (partly co-developed by the author) existing within the working group.

Up to now the model Invert/EE-Lab has been applied for various countries, including AT, CZ, DE, DK, ES, FI, FR, GR, IT, LT, NL, PL, RO, UK in several projects. In the course of the project ENTRANZE and the currently ongoing project "Mapping H/C fuel deployment"[43] the building and technology database is going to be extended by calibrated input dataset for all countries of the EU-28, Serbia, Swiss, Norway and Iceland.

The following selected publications have applied the Invert/EE-Lab model for space heating-related analyses: Kranzl et al. (2010, 2011a, 2011b, 2011c, 2012, 2014a, 2014b), Kranzl and Müller (2010), Müller and Kranzl (2013a, 2013b), Müller et al. (2010, 2014b, 2014c), Müller and Biermayr (2011), Egger et al. (2011), Giakoumi et al. (2011), Gatautis et al. (2011), Jozwiak et al. (2011), Richardson et al. (2011), Beurskens et al. (2011), Bürger et al. (2011), Steinbach et al. (2011, 2015), Eichhammer et al. (2014), Henning et al. (2013).

4.4 The energy demand module

4.4.1 The calculation of energy needs

The energy needs for heating and cooling and the performance of the technical building system for heat supply and distribution are calculated using an engineering-based quasi-

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[43] "Mapping and analyses of the current and future (2020 - 2030) heating/cooling fuel deployment (fossil/renewables)", Service contract ENER/C2/2014-641.

steady-state monthly energy balance approach. Besides some simplifications, this method is in line with the Austrian implementation of EN ISO 13790:2008 (ÖNORM B 8110-5:2007; ÖNORM B 8110-6:2007) and (pr)EN 15603:2007 (ÖNORM H 5056:2007), which define the calculation procedures to derive the energy performance of (residential) buildings. A full description of the calculation algorithm is given by (Pech et al. 2007). Besides the restriction of using a single temperature zone model for conditioned zones other than attic and cellar and the limitation to sensible heat, the implemented model is fully capable of reproducing the more detailed approach of calculating the energy needs for space heating and cooling of commercial buildings as well. If the single zone assumption disregards the actual building usage and the calculation of the energy needs results in a substantial error, the building could be modeled based on several buildings adjacent to one another.

Using this method, transmission losses for the façade, windows, floors, cellar and upper ceiling or roof constructions, ventilation losses associated with different types of ventilation techniques (windows or different types of mechanical ventilation systems) and energy losses caused by thermal heat bridges are considered. On the other side of the energy balance, internal heat gains caused by electricity consuming appliances, lighting and occupants as well as heat losses of the domestic hot water supply system, and external gains based on solar radiation are included the in the calculation method.

4.4.2 Validation and verification of the energy needs calculation

In the following section, the results derived by the energy demand module of the Invert/EE-Lab model are compared to other implementations and approaches to calculate the energy needs of buildings.

First, the results are compared to reference calculations, provided by the implemented ÖNORM B 8110-6:2007. In these reference calculations, the buildings are described in detail, thus it can be ensured that the deviations between the results derived by the Invert/EE-Lab model are caused by implementation difference. The comparison of the energy need for heating, as can be seen in the following figure, reveals that the author’s implementation is able to reproduce the reference calculation data.

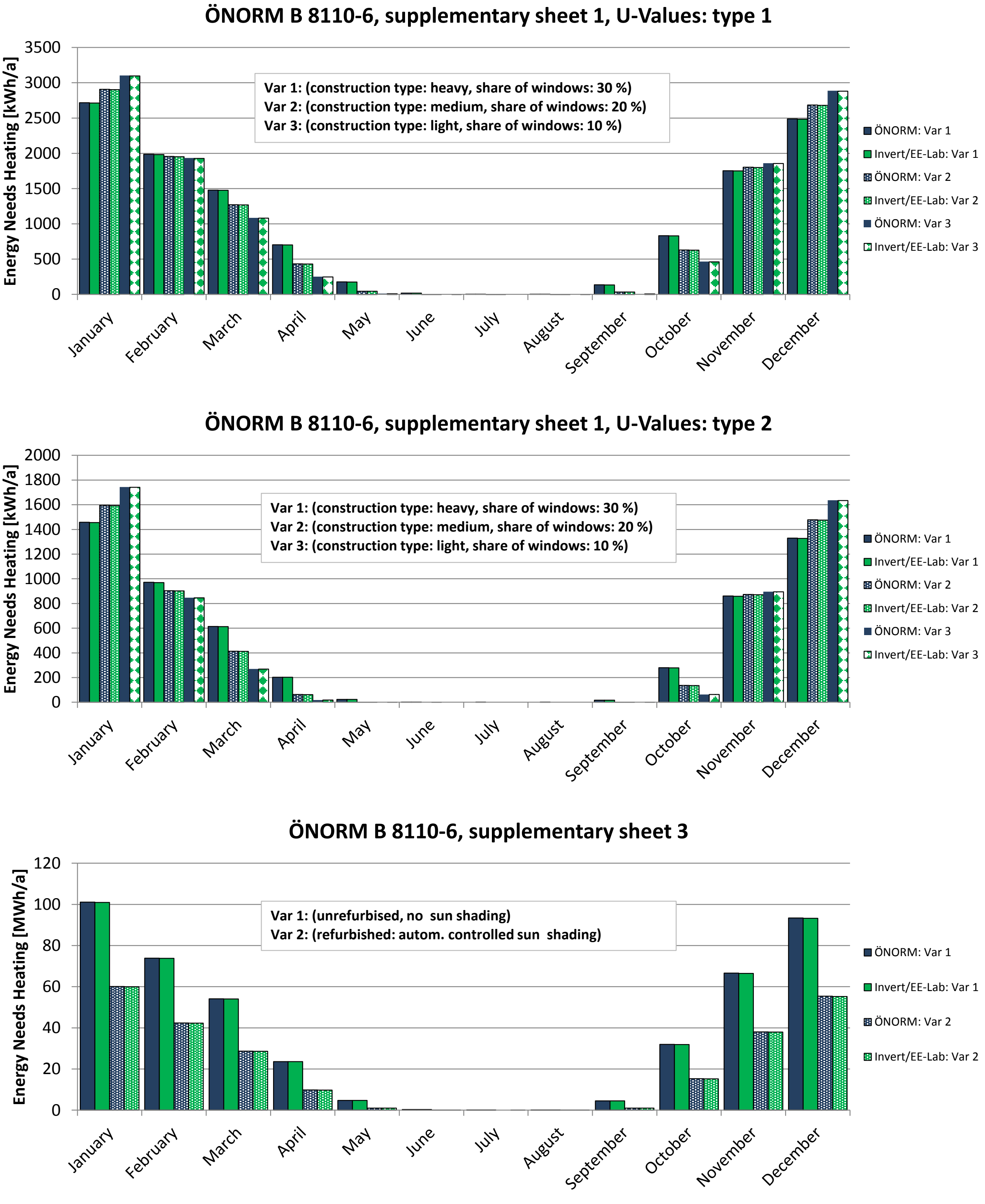

Figure 4.3 – Comparison of the energy needs results for heating derived by the energy demand module implemented in the Invert/EE-Lab model against reference calculation sheets provided by ÖNORM B 8110-6:2007, supplementary sheet 1-3.

The comparison of the energy needs for cooling reveals some deviations between the reference calculations and the Invert/EE-Lab model implementation. The analysis of possible differences in the implementations provides three reasons for the differences:

- In the Invert/EE-Lab model, a constant sun-shading-efficiency is implemented, which, in contrast to the calculation algorithms provided by ÖNORM B 8110-6:2007 does not change seasonally. Therefore, the energy need for cooling is lower in the Invert/EE-Lab model in April, May and October.
- In the reference calculations (supplementary sheets of ÖNORM B 8110-6:2007; OIB 2012b), the results for the energy needs for cooling indicate that the solar gains of opaque surfaces are not considered.
- In the reference calculations the specific internal gains for lighting might be applied to the heated gross and not the net (80% of gross) floor area, as described by ÖNORM B 8110-6:2007.

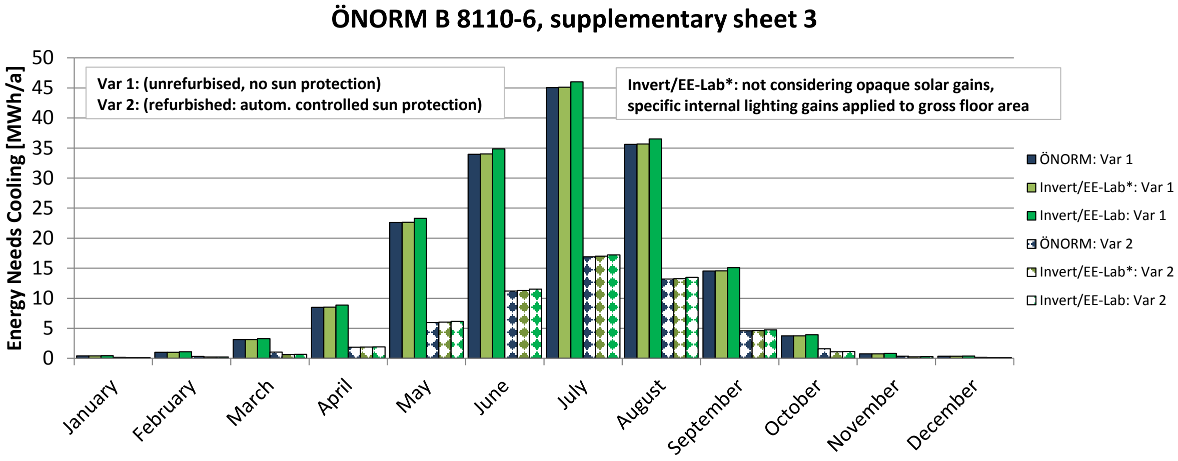

Figure 4.4 – Comparison of the energy needs results for cooling derived by the energy demand module implemented in the Invert/EE-Lab model against reference calculation sheets provided by ÖNORM B 8110-6:2007, supplementary sheet 3.

In the next step the specific energy losses of the implemented monthly quasi-steady-state method are compared to the simple hourly three-nodes dynamic model (5RC1 model as defined in the EN ISO 13790:2008) and the detailed dynamic method. The R-C three nodes[44] (resistive capacitive equivalent method – hourly at three nodes) model, defines a distinction between indoor air temperature and mean radiant surface temperatures (for internal surfaces facing the evaluated zone). This improves the accuracy since it allows to take into account the radiant and convective components of thermal, solar and internal gains.

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[44] Resistive-Capacitive equivalent method – hourly at three nodes.

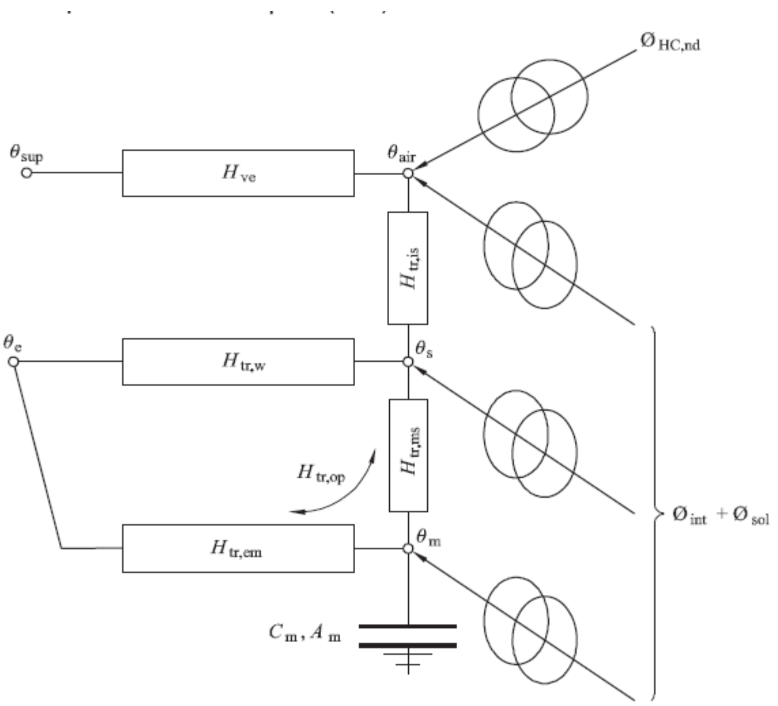

Figure 4.5 – Scheme of the R-C (5RC1) model with three nodes. Source: EN ISO 13790:2008

One main difference between the quasi-steady-state and the R-C model in the heating case is that, due to the limited heat transmission between the wall surface node and the air node, the indoor surface temperature of the surfaces is lower than the air temperature. This has the effect that, when considering the same indoor air temperature, the transmission heat losses are lower in the R-C model.

The dynamic R-C model distinguishes between the air temperature θ_{air} and the operative temperature θ_{op}, which incorporates the temperature difference between the air and radiant temperatures (e.g. walls, ceilings). The simple hourly dynamic energy needs calculation method as described by the EN ISO 13790:2008 uses an approximation to derive the operative temperature $\theta_{op,}$ where the internal surface convective components are weighted by 3/8 and the radiative components are weighted by 5/8. The operative temperature is then expressed by

$$\theta_{op} = 0.3 \cdot \theta_{air} + 0.7 \cdot \theta_s \tag{4.1}$$

where

θ_{op} ... Operative temperature

θ_{air} ... Air temperature

θ_s ... Temperature of the central node (also used: θ_{set})

The full set of equations for the simple hourly dynamic approach is given in the Annex C of EN ISO 13790:2008. Pernigotto and Gasparella (2013a, 2013b) compared the results of the quasi-steady state monthly energy balance approach (EN ISO 13790:2008) with the detailed dynamic simulation approach using the TRNSYS simulation environment (TRNSYS, 2013). Their results indicate that the thermal losses calculated with the quasi-steady state approach deviates from the results derived dynamic approach by 5% or less, if the operative temperature is used (Pernigotto and Gasparella, 2013a). When it comes to thermal gains, the differences are larger. In their second paper, the analysis is done by considering the four main heat gains separately: (1) solar gains entering through glazings, (2) solar gains transmitted through the opaque elements, (3) internal gains and (4) infrared extra flow towards the sky vault (Pernigotto and Gasparella, 2013b). Their finds are that for the solar gains through glazings the monthly approach overestimates the gains in a range between up to ~ 30% (insulated buildings[45]) and ~50% (uninsulated buildings). For the solar gains through the opaque surface areas, the quasi-steady state approach underestimates the gains by about 25%. Internal gains are overestimated by the EN ISO 13790:2008 quasi-steady state approach by 10-20% for uninsulated and 5-10% for insulated buildings. Finally, for the infrared energy flows towards the sky vault, they conclude that in the case of insulated buildings the EN ISO 13790:2008 standard fits quite well, while for uninsulated cases the quasi-steady state approach overestimates the energy flux by about 18%.

Add this point, the question arises what these differences mean for the overall energy needs of buildings. Van der Veken et al. (2004) compares a (quasi-)steady state monthly approach[46] with two dynamic methods using TRNSYS and ESP-r ("Environmental System Performance research", Citherlet, 2001; ESRU, 2002). Their finds are that the quasi-steady state model overestimates the net energy demand by about 4%, and that the net cooling demand is *"also comparable to the outcomes of ESP-r and TRNSYS*" and "*remarkably precise*". Yet they also state that this holds true only if the correct average indoor temperature is used. De Lieto Vollaro et al. (2015) perform a similar comparison. The quasi-steady state approach is analyzed via the application of the AERMEC MC 11300, an energy calculation software tool based on the Italian version of the EN ISO 13790 Standard. TRNSYS is used

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[45] The descriptions of the analyzed reference building settings and alternative configurations are given in their paper.

[46] The EPW model is used, which "*is a Visual Basic implementation of the Flemish Energy Performance Regulation (EPR) of Directive 2002/91/EC*".

for deriving the results based on the detailed dynamic simulation approach. The models are then applied to a historical building in the Italian city of Orte, about 70 km north of Rome. Applied to the their settings, the quasi-steady state monthly approach underestimates the energy demand for heating by 12-14%, while the energy demand cooling is overestimated by 12-14%.

Another comparison of static and dynamic methods is conducted by Ahdikari et al. (2013). In their paper the authors evaluate the energy consumption of two historical buildings (the Church of the Purification of Santa Maria in Caronno Pertusella and the church Santo Stefano Oratory in Lentate sul Seveso) in Italy. For their comparative analysis, they use three different energy calculation models: DOCETpro 2010 (static software), Casanova (sketch design) and BEST Openstudio (dynamic software that works with the EnergyPlus engine). Furthermore, they perform the simulation with the static software on three datasets based on synthetic method—using respectively standard and measured U-value—and analytic method), and the dynamic software on two datasets (using standard assumptions and the observed management of the building). They conclude that the static simulation method based on the synthetic methods, standard U-values and standard building management highly overestimate the energy consumption (52%-63%). Their results indicate that the results of the energy consumption calculation rather depend on the uncertainty of the input data (measured versus standard U-values, standard versus real utilization and management of the buildings and ability of the model to process non-standard geometry components). While on a sub-annual/sub-monthly level the dynamic approach needs to be applied to gather close-to-real consumption data, on an annual level the analytic static approach with measured U-values does not perform significantly worse than the dynamic approach using real management datasets of the analyzed buildings.

In the following, similar comparison, based on the quasi-steady state approach implemented in the Invert/EE-Lab model, is shown. Here the energy needs results based on the Invert/EE-Lab model are compared with the results derived using the EnergyPlus model (Crawley, 2001) as well as a spreadsheet implementation of the simple hourly dynamic three-nodes R-C model. The EnergyPlus and the spreadsheet R-C model calculations are done by the Politecnico di Milano and National Renewable Energy Centre. The Invert/EE-Lab calculations are performed by the author of this thesis. The comparison was done in the ENTRANZE project (Zangheri et al., 2014); the associated report can be downloaded from http://www.entranze.eu. The aim of this comparison is to analyze whether or not the quasi-steady state monthly approach derives some systematic deviations compared to a detailed dynamic simulation approach, such as implemented in the EnergyPlus model. For this comparison, four building geometry- and occupation-types are defined. The energy needs are then calculated for 10 different locations in Europe, considering U-values which are typically found in unrefurbished buildings in those regions. The considered locations include cold regions such as Helsinki, moderate climate conditions such as can be found in Vienna, Berlin, Prague and Paris, as well as cities with warm climate conditions such as Rome, Madrid and Seville. A comparison of the Summer Severity Index, an indicator for the cooling needs with the Winter Severity Index, indicating the energy needs for the heating of 25 European cities is shown in Figure 4.6.

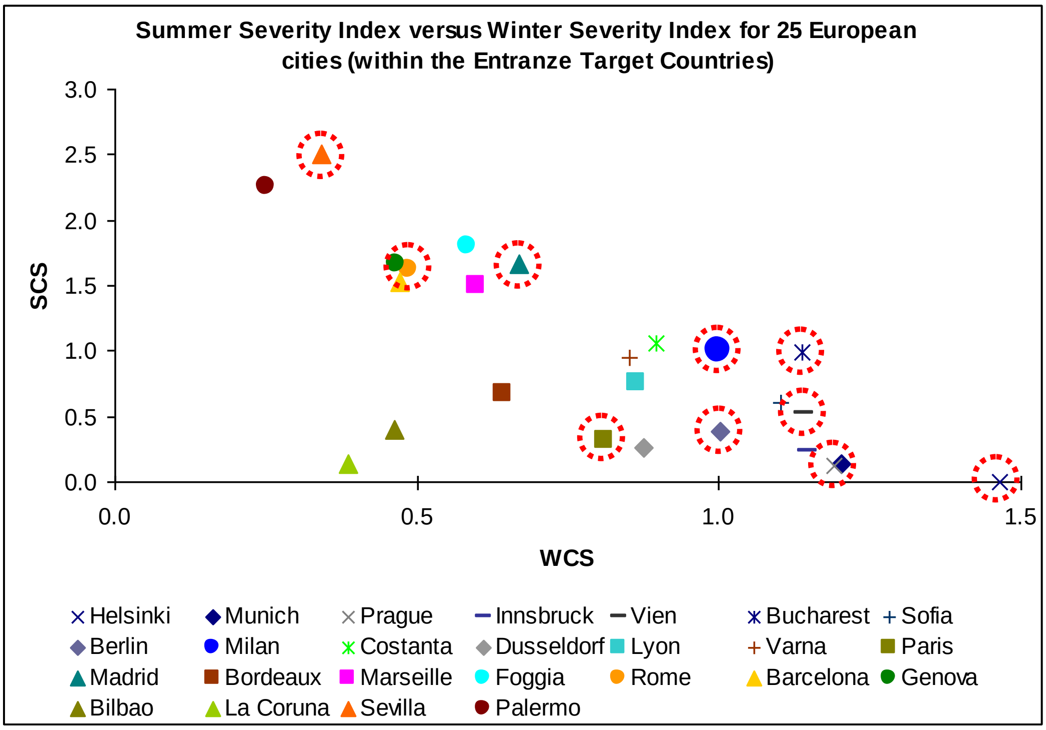

Figure 4.6 – Summer Severity Index (CS) versus Winter Severity Index (WS) for 25 European cities. Source: Zangheri et al., 2014

A sub-selection of the performed comparison are shown below, namely the results for single family houses (SFH) and schools in the two hottest regions (Madrid and Seville), under moderate climate conditions (Berlin) and in the coldest analyzed climate (Helsinki). The full set of analyzed and compared building settings can be found in Zangheri et al. (2014).

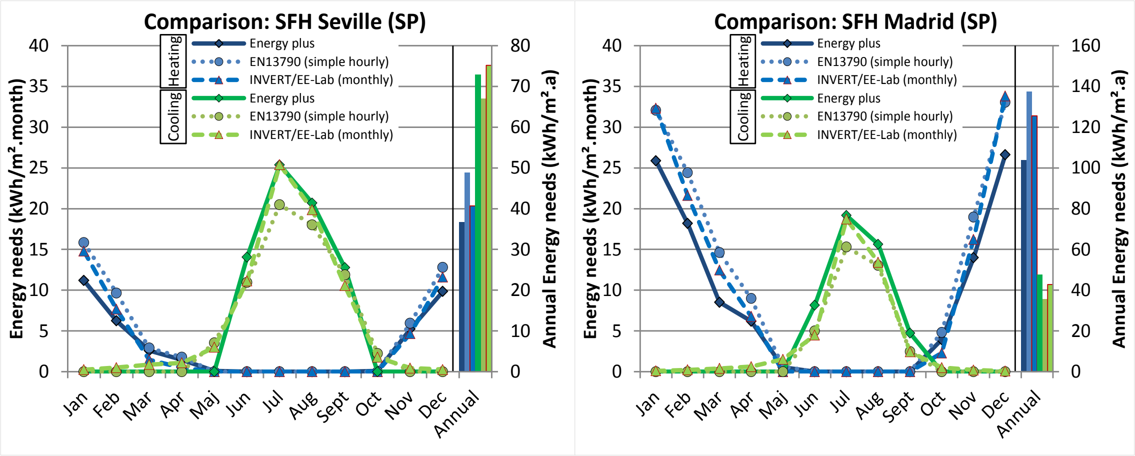

Figure 4.7 – Comparison of monthly energy needs for heating and cooling (only sensible component) between Energy Plus, EN13790 and Invert/EE-Lab calculations for single house, Seville and Madrid. Source: Zangheri et al., 2014

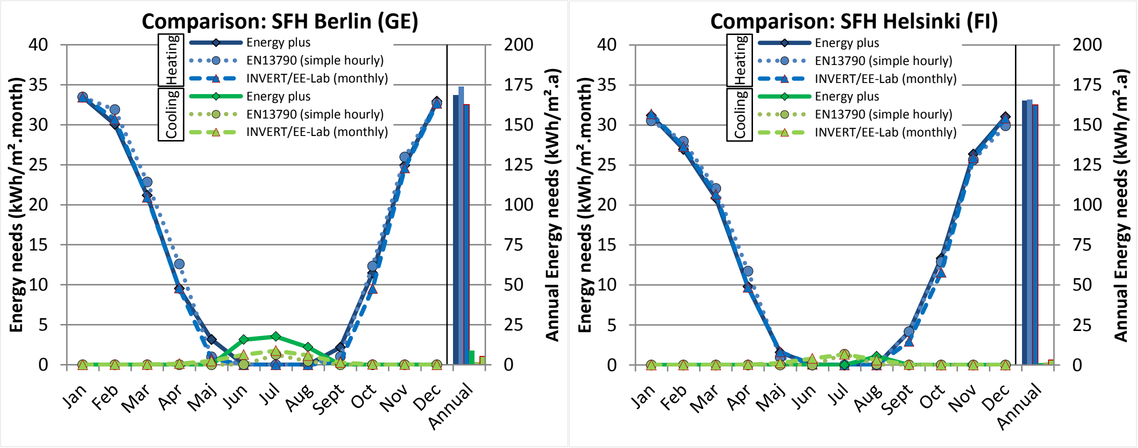

Figure 4.8 – Comparison of monthly energy needs for heating and cooling (only sensible component) between Energy Plus, EN13790 and Invert/EE-Lab calculations for single house, Berlin and Helsinki. Source: Zangheri et al., 2014

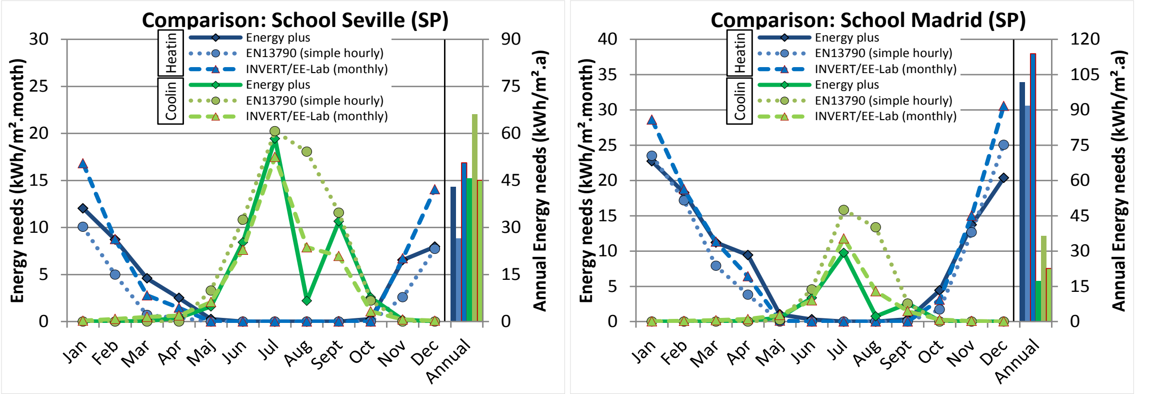

Figure 4.9 – Comparison of monthly energy needs for heating and cooling (only sensible component) between Energy Plus, EN13790 simple-hourly spreadsheet implementation and Invert/EE-Lab calculations for school, Seville and Madrid. Source: Zangheri et al., 2014

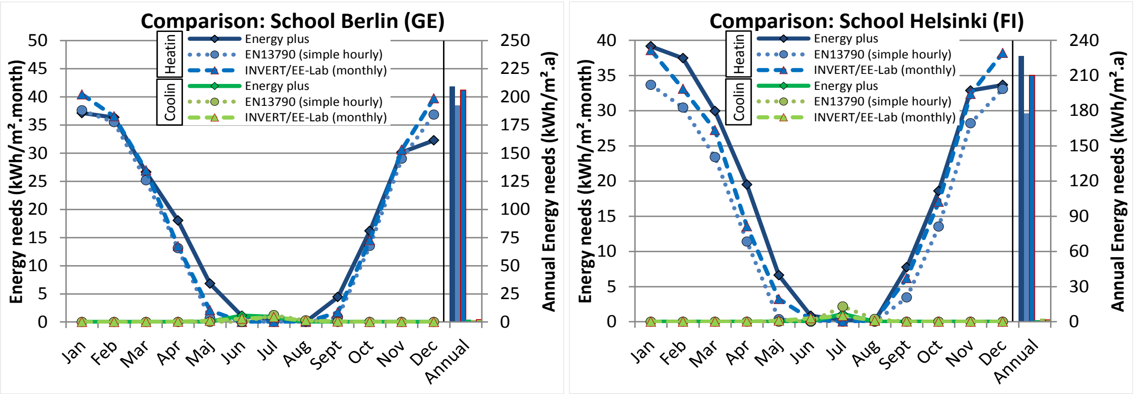

Figure 4.10 – Comparison of monthly energy needs for heating and cooling (only sensible component) between Energy Plus, EN13790 simple-hourly spreadsheet implementation and Invert/EE-Lab calculations for school, Berlin and Helsinki. Source: Zangheri et al., 2014

In general, it can be observed that the simple hourly dynamic model based on EN ISO 13790:2008 as well as the quasi-steady-state method deliver energy needs for heating and cooling comparable to the detailed dynamical approach applied by the EnergyPlus model. While deviations between the model results occur, systematic errors are not observed between the EnergyPlus and the Invert/EE-Lab model. The differences are mainly caused by differing building and building-usage formulations[47], rather than by the calculation approaches and they (Zangheri et al.) conclude that the discrepancies may be attributed to:

- Some differences in the description of the buildings due to the descriptive limitations of the Invert/EE-Lab and the EN13790 simple-hourly spreadsheet implementation method, as compared to Energy Plus software;
- The simplified calculation of solar gains and the capacitive behavior of building elements done by the quasi-stationary method, more relevant in warmer climatic regions.

Furthermore, they conclude that for transition periods where a building eventually has an energy need for cooling and an energy need for heating in the same month, the monthly approach, building on utilization factors for gains (cooling) or losses (heating), derives better results than the simple hourly approach using climate data for a typical day per month.

Tools like EnergyPlus require a huge demand of input data, which are not available for larger building stocks. They also come to the conclusion that for the analysis of trajectories of the future energy needs and consumption for heating and cooling in different

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[47] Neither the Invert/EE-Lab model nor the EN13790 simple-hourly spreadsheet implementation is able to describe buildings to same degree of detail as it is done in this analysis using the EnergyPlus model.

countries, the quasi-steady state monthly energy balance approach is sufficient (Zangheri et al., 2014).

4.4.3 The calculation of delivered energy and the final energy demand

Compared to the calculation according to the ÖNORM H 5056:2007, the following (major) simplifications has been done:

- Annual boiler and heat pump efficiency

  The annual, exogenously defined, efficiencies for boilers are based on the average annual efficiencies found in literature (Loga et al., 2001) or calculated using external tools (most important: OIB, 2012b). The model algorithm does not correct the efficiency for part load operation, start and stop cycles and the modulation capabilities of the boiler.

- Efficiency of the solar thermal system

  The solar thermal system is calculated according ÖNORM H 5056, however similar to the annual boiler efficiencies, the total annual solar thermal heat contributing to space heating and DHW is exogenously defined for:

  - Reference climate conditions (represented by the climate zone with the lowest index (climate zone 1));
  - Collectors oriented southwards;
  - And the monthly energy demanded from the heat storage (energy needs including the losses of the distribution system) exceeds the monthly solar contribution.

  Based on these definition, the real solar collector contribution is calculated for different conditions (different climate zones, orientation, collector size) endogenously by the model.

- Heat distribution system and its supply line temperature

  Even though the efficiency of the boiler does not endogenously adapt for the factor listed above, it is important to consider the effects of the supply line temperature on the efficiency of the heating system. To do so, equation (4.2) is used as an approximation.

$$\eta_{H,sys,\mathrm{i},simplified} = f_{\theta_{SL},i} \cdot \eta_{H,sys,\mathrm{i},35}\ [-] \tag{4.2}$$

where

$f_{\theta_{SL},i}$ ... Correction factor for the annual boiler efficiency of technology *i* at a supply line temperatur of θ_{SL}
κ_i ... Temperatur coefficient factor of technology *i*
θ_{SL} ... Supply line temperatur of heat distribution system
$\eta_{H,sys,\mathrm{i},35}$ ... Average annual system efficiency of heat supply system technology *i* at $\theta_{SL} = 35°C$
$\eta_{H,sys,\mathrm{i},simplified}$ ... Average annual system efficiency of heat supply system technology *i* at θ_{SL}

In case of heat pumps, the following additional condition applies:

$\eta_{H,sys,\mathrm{HP},simplified} \geq 0.96$

In case a building undergoes a thermal renovation, the heat demand of the building is reduced. As a result, even if the heat distribution system and heat emitting surfaces are not changed during the renovation, the supply line temperature can be lowered, compared to the status before the renovation, since the ratio between heat demand and heat emitting surface is reduced. This relation is approximated by the following equation.

$$\theta_{SL,ren} = \left(\theta_{SL,orig} - 35\right) \cdot \frac{Q_{H,nd,ren}}{Q_{H,nd,orig}} + 35 \left[°C\right] \tag{4.3}$$

where

$\theta_{SL,ren}$ ... Supply line temperatur of heat distribution system after a renovation
$\theta_{SL,orig}$ ... Supply line temperatur of heat distribution system before a renovation
$Q_{H,nd,ren}$ ... Energy need for space heating after a renovation
$Q_{H,nd,orig}$ ... Energy need for space heating before a renovation

Losses stemming from the space heating distribution system are considered to occur within the thermal building shell and to be fully recoverable.

- DHW distribution system

  The boiler efficiency $\eta_{DHW,boiler,i}$ of the DHW system is considered to be independent from the supply line temperature. The total DHW efficiency is defined by the boiler efficiency and the efficiency of the DHW distribution system *j*, expressed in (4.4).

$$\eta_{DHW,sys,\mathrm{i},\mathrm{j},simplified} = \eta_{DHW,\mathrm{distr},\mathrm{j}} \cdot \eta_{DHW,boiler,\mathrm{i}} \left[-\right] \tag{4.4}$$

where

$\eta_{DHW,sys,i,j,simplified}$ ... Total efficiency of the DHW supply system
$\eta_{DHW,distr,j}$ ... Efficiency of the DHW distribution system *j*
$\eta_{DHW,boiler,i}$ ... Efficiency of the DHW heat production system *i* (including heat storage)

A certain share of the DHW system losses is considered to contribute to the space heating supply (recoverable losses). The energy that contributes to space heating is defined in equation (4.5).

$$\begin{aligned} &Q_{H,gain,DHWloss,recover,j,\mathrm{b},m} = Q_{DHW,nd,b,m} \cdot f_{DHW,revocer\_H,j} \cdot \left(\eta_{DHW,\mathrm{distr,j}} - 1\right) / \eta_{DHW,\mathrm{distr,j}} \text{ [kWh/ yr]} \\ &Q_{H,gain,DHWloss,recover,j,\mathrm{b},m} \le Q_{H,nd,b,m} \text{ [kWh/ yr]} \end{aligned} \tag{4.5}$$

where

$Q_{H,gain,DHWloss,recover,j,\mathrm{b},m}$ ... Recoverable heat losses from DHW supply contributing to space heating in building *b*, using heat distribution system *j* and month *m*

$Q_{DHW,nd,b,m}$ ... Energy needs for DHW in month *m*

$Q_{H,nd,b,m}$ ... Energy needs for space heating in month *m*

$f_{DHW,revocer\_H,j}$ ... Technology factor defining the share of recoverable DHW distribution losses

- Auxiliary electricity demand for boilers and heat storage

The auxiliary energy demand for system controlling and regulation as well as pumps are approximated by the following equations:

$$P_{aux,hs} = P_{aux,0} + \kappa_{aux,hs} P_{hs,N} \left[W\right] \tag{4.6}$$

$$E_{aux,hs} = P_{aux,hs} \cdot h_{opt} \left[Wh/yr\right] \tag{4.7}$$

where

$P_{hs,N}$ ... Nominal power of boiler [W]

$P_{aux,0}$, $\kappa_{aux,hs}$ ... Coefficient of the modelled auxilliary power demand [W], [-]

$P_{aux,hs}$ ... Auxilliary power of demand of the heating supply system (boiler) [W]

$\mathrm{h}_{\mathrm{opt}}$ ... Annual operation hours [h/yr]

$E_{aux,hs}$ ... Annual auxilliary electricity demand of the heating supply system [Wh/yr]

The data currently used in the model runs (Table 4.1) are based on measurements performed by BLT Wieselburg, FBV (2004), data provided by Pech et al. (2007), as well as manufacturer's information of various oil and gas boiler.

Table 4.1 – Average specific auxiliary power demand of boilers.

Heating system type	Power demand factor	
	$P_{aux,0}$ [W/(kW$_N$ yr)]	$\kappa_{aux,hs}$ [W/(kW$_{hs,N}$ yr)]
Gas boiler, heat pumps, manually operated boilers for solid energy carriers	0	5
District heating		10
Oil boilers		15
Automatically operated boilers for solid energy carriers		30

- Auxiliary electricity demand for heat distribution pumps

  In order to estimate the energy demand of pumps the following cycles are distinguished:

  - Space heating distribution
  - Domestic hot water distribution
  - Solar collector cycle

  The annual electricity demands of pumps are estimated based on the following equations (4.8) and (4.9). For the solar collector cycle the same methodology is applied, yet the installed solar collector area instead of the building heat load is used as reference variable.

$$P_{aux,dist,hs/dhw} = P_{aux,distr,hs/dhw,0} \cdot \left(1 + n_{p,dw} \cdot (n_{dw} - 1)\right) + \kappa_{aux,distr,hs/dwh} \cdot P_{hs/dhw,HL} \quad [W] \tag{4.8}$$

$$E_{aux,dist,hs/dhw} = P_{aux,dist,hs/dhw} \cdot h_{fl,a} \ \left[Wh/yr\right] \tag{4.9}$$

where

$E_{aux,dist,hs/dhw}$ ... Annual electricty demand for space heating and DHW distribution pumps
$h_{fl,a}$ ... Annual full load operation hours [h]
$P_{aux,dist,hs/dhw}$ ... Auxiliary power demand of space heating or dhw distribution pumps
$P_{hs/dhw,N}$ ... Heat loat of building, calculated nominal power for dhw supply [W]
n_{dw} ... Number of dwellings per building [-]
$n_{p,dw}$ ... Number of heat distribution pumps installed per dwelling [-]

The data currently used are calculated based on Pech et al. (2007) and FBV (2004).

Definition of final energy demand and energy use in the model

The energy use $Q_{sys,Norm}$ based on the calculation norm EN 15603 is calculated according to equation (4.10) and considers space heating, air conditioning and domestic hot water production.

$$
\begin{aligned}
Q_{sys} = {} & \frac{Q_{\mathrm{H,sen},nd} + Q_{\mathrm{H,lat},nd}}{\eta_{H,sys}} + \frac{Q_{C,sen,nd} + Q_{C,lat,nd}}{\eta_{C,sys}} + \frac{Q_{DHW,nd}}{\eta_{DHW,sys}} + \qquad \left[kWh/yr\right] \\
& - Q_{sol} - Q_{ambient,HP} - Q_{H,loss,recover} - Q_{DHW,loss,recover} + \\
& + Q_{aux} + Q_{ele,appliances+lighting}
\end{aligned}
\tag{4.10}
$$

where

Q_{sys}	... Energy use based on ÖNORM H 5056
$Q_{H/C,sen,nd}$	... Sensible energy needs for heating / cooling based on ÖNORM B 8110
$Q_{H/C.lat,nd}$	... Latent energy needs for heating / cooling based on ÖNORM B 8110
$Q_{DHW,nd}$	... Energy needs for domestic hot water production
Q_{sol}	... Energy contribution from active solar thermal technologies
$Q_{ambient,HP}$	... Ambient energy contribution utilized by heat pumps
Q_{aux}	... Auxilliary (electric) energy demand
$Q_{ele,appliances+lighting}$	... (Electric) energy demand by appliances and lighting
$Q_{H/DHW,loss,recover}$	... Recoverable energy losses of the heating and DHW system
$\eta_{H,sys}, \eta_{C,sys}, \eta_{DHW,sys}$	... Overall system efficiency for the heating / cooling / DHW system

In the developed Invert/EE-lab model, the air conditioning system is not within the scope of the model, even though the energy needs for cooling are calculated. Therefore, the energy use $Q_{sys,Invert/EE\text{-}Lab}$ as derived by the Invert/EE-Lab model does not contain the energy demand for cooling (see equations (4.11)).

$$
\begin{aligned}
Q_{sys,Invert/EE-Lab} &= Q_{H,sys} + Q_{DHW,sys} \; (+Q_{aux} + Q_{ele,appliances+lighting}) \quad \left[kWh/yr\right] \\
Q_{H,sys} &= \frac{Q_{H,sens,nd} - Q_{H,sol} - Q_{H,\mathrm{ambient.HP}} - Q_{H,gain,DHWloss,recover}}{\eta_{H,sys,simplified}} \left[kWh/yr\right] \\
Q_{DHW,sys} &= \frac{Q_{DHW,nd} - Q_{DHW,sol} - Q_{DHW,\mathrm{ambient.HP}}}{\eta_{DHW,sys}} \left[kWh/yr\right]
\end{aligned}
\tag{4.11}
$$

where

$Q_{sys,Invert/EE-Lab}$ ... Energy use derived by the Invert/EE-Lab model

$Q_{H,sys}$ ... Energy use for heating

$Q_{DHW,sys}$ ... Energy use domestic hot water production

$Q_{H,sol}, Q_{\text{DHW,sol}}$ ... Energy from Solar thermal collectors contributing to space heating / domestic hot water preparation

$Q_{H,\text{ambient}}, Q_{DHW,\text{ambient}}$ ... Ambient energy utilized by heat pumps contributing to space heating / domestic hot water preparation

$(Q_{aux} + Q_{ele,appliances+lighting})$ ... Auxilliary energy demand and electricity demand for appliances and lighting are considered but not shown in in the scenarios in Chapter 7.

$Q_{H,loss,recover}$ ... Considered to be Zero

$\eta_{H,sys}, \eta_{DHW,sys}$ ... System efficiency for the heating / DHW system

In contrast to the terms “energy use” and “delivered energy” defined according to EN15603, the “final energy demand” includes also energy from on-site renewable energy carriers gathered by active technologies such as solar thermal collectors, heat pumps, or on-site PV systems[48] (see Figure 1.1).

$$Q_{FED,Invert/EE-Lab} = Q_{H,sys} + Q_{DHW,sys} + Q_{sol} + Q_{\text{ambient.HP}} (+Q_{aux} + Q_{ele,appliances+lighting}) \quad [kWh/yr] \tag{4.12}$$

where

$Q_{FED,Invert/EE-Lab}$ ... Annual final energy demand as calculated by the Invert/EE-Lab model

Q_{sol} ... Annual solar energy contribution (active systems) [kWh/yr]

$Q_{ambient,HP}$ ... Annual ambient energy contribution (heat pumps) [kWh/yr]

4.4.4 Introducing behavioral aspects in the energy demand calculation

When applying standard calculation methods, the calculated energy consumption does not exactly match the real energy consumption. This is to some degree intentionally, since the energy performance indicator aims to assess the building and not their users. Therefore, the calculation procedures explicitly calculate the energy demand of buildings based on predefined norm-indoor set temperatures (e.g. 20 °C for residential buildings).

Existing research has shown that the so called user-behavior is considered to have a large impact on the actual energy use. On an aggregated level, Holzmann et al. (2013) present an 8-factor decomposition of the final energy use in the Austrian residential sector. The analyzed dataset covers the time period of 1993 to 2009. Two of their main findings are that

---

[48] The *“energy use”* takes on-site electricity generation (e.g. PV) into account.

(1) the rising comfort needs outweigh the significantly technical energy efficiency improvements observed for the period. And (2) that consumer behavior reduced the final energy use by 49% in 1993 and 40% in 2009. They further conclude that omitting the consumer behavior effect can substantially bias the outcomes of estimating the effects of energy efficiency measures.

Systematic research on this issue has been done by Haas et al. (1998). Based on the comparison of the calculated and the observed energy demand of approximately 400 households, they estimate an econometric model, covering systematic deviations between the calculated energy demand considering an average indoor temperature of 20 °C and the observed energy consumption. One of their important finding is that the deviation between measured and calculated energy demand, expressed in a so called service factor, depends on the specific energy demand of the building, the heated area per dwelling, whether or not a centralized heating system is used, and in case a centralized heating system is installed on the heating degree days (HDD). Another finding is that even though the heating costs have significant impact on the service factor, this variable does not show linear behavior, but apparently needs to exceed some threshold to reveal the influence.

Similar analyses are conducted by Loga et al. (2003) and Born et al. (2003). Based on an annual energy demand calculation using heating degrees with variable heating limit temperature, they also analyze the differences between the calculated and the measured energy demand. Loga (2004) concludes that the heating degree days approach, using a variable heating limit temperature, reproduces the energy demand according to the monthly energy balance approach, as applied in the Invert/EE-Lab model, with sufficient precision. This leads to the conclusion that the deviation of the calculated energy demand and the measured energy is not influenced by the different calculation methods. Therefore their quantified results on the extent of the user behavior can be integrated in the Invert/EE-Lab model. A comparison of the results of Haas et al. (1998) with those of Loga et al. (2003) reveals that the drivers and results are very similar. In the latter, also the specific heat demand of the building and the size of the dwelling are the main drivers. In the user model according to Loga et al. (2003), the realized average indoor temperature differs from the reference value of 21 °C, which marks the center of the human comfort zone chart, due to three factors:

- Lower indoor set temperature during night time (night-setback);
- Partially-heated areas (non-directly and sub-set-point-temperature heated areas);

- And user behavior, which is driven by heating costs aspects.

Majcen et al. (2013) present a comparison of actual and theoretical gas consumption per dwelling for the Dutch building stock. Their findings, clustered by energy labels, show the significant correlation between the thermal quality of the building and the deviation of actual and theoretical energy (gas) consumption (Figure 4.11). For dwellings of the energy label C the actual gas consumption, in average, meets the theoretical calculation. In dwellings with a better energy label, the actual average gas consumption exceeds the theoretical demand, while the opposite is true for buildings with a label of D or worse.

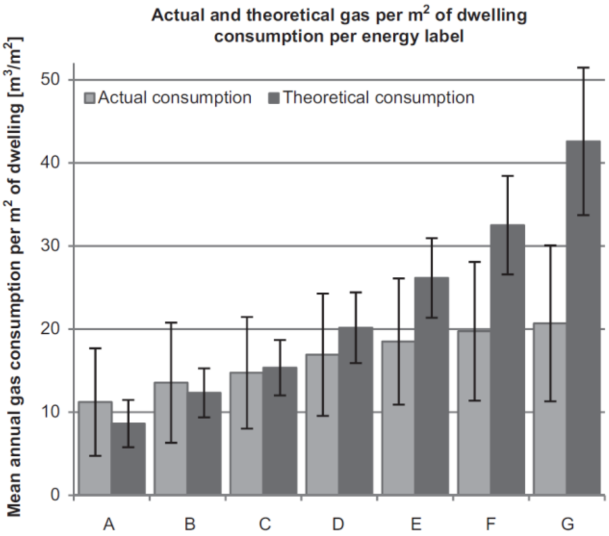

Figure 4.11 – Actual and theoretical gas consumption per m^2 of dwelling area per energy label. Source: Majcen et al., 2013

Further examples are given by Branco et al. (2004), who observe an average indoor temperature of 22.5 °C for a building with an estimated HWB of 40-43 kWh/m², similar results are reported by Mahlknecht et al. (2011) or Cali (2011).

To account for such findings, the energy calculation procedure of the Invert/EE-Lab model is augmented by various behavioral aspects observed for space heating. Therefore, the resulting final energy demand is closer to the energy consumption of buildings under real conditions. In addition to the influence factors as defined by Loga et al., a correction factor f_{hs} for the heating system type based on (Biermayr 1999) is introduced. Considering the user behavior, the average indoor set temperature for heating is defined by the equation (4.13).

$$\theta_{i,h} = \theta_e + f_t\, f_a\, f_{use}\, f_{hs} \left(\theta_{i,h,\mathrm{set}} - \theta_e\right) \quad [°C] \tag{4.13}$$

where

$\theta_{i,h}$ ... Average indoor temperature, heating (°C)
θ_e ... Average outdoor temperature (°C)
$\theta_{\mathrm{i,h,set}}$ ... Desired nominal indoor set temperature, heating (°C)
f_t ... Correction factor for temporal temperature reductions (night mode)
f_a ... Correction factor for non-directly heated areas
f_{use} ... Correction factor for user behavior
f_{hs} ... Correction factor heatingsystem
$\theta_{\mathrm{i,h,min}}$ ... Lower boundary for the indoor temperature, heating (°C)
$\theta_{\mathrm{i,h,max}}$ ... Upper boundary for the indoor temperature, heating (°C)

$\theta_{i,h} \in \left\{\theta_{i,h,\min}, \theta_{i,h,\max}\right\}$

In the field of modeling the demand for a certain good using prescriptive statistical methods, the price α_{price} and the income α_{income} elasticities are among the most commonly used variables.

An analysis on the price elasticity is done by Alberini et al. (2011). In their paper, they present the estimated price elasticity of the residential gas and electricity of another 17 studies (including their own). The (long-term) price elasticities found in these studies for the residential energy consumption, of energy carriers mainly used for space heating and DHW production, are in the range of about -0.1 to -0.8[49]. Their own (long-term) price elasticity of electricity is found to be slightly higher, ranging between about -0.3 to -1.3.

Nesbakken (1999) conducted another study on income and price elasticity; results for the estimated price and income elasticity for 11 studies (including his own work) are depicted in his paper. The (long-term) price elasticities shown in this publication range from -0.2 to -0.8[50]. The estimated income elasticities are in general, yet not necessarily on an individual study-based level, lower than the electricity price elasticity. The (long-term) income elasticities for electricity shown in the paper range from 0.02 to about 0.4.

Biermayr (1999) performs such an analysis for the Austrian heating sector (see also Haas et al., 1998). He concludes that, based on his dataset, the hypothesis that energy prices do not have a (linear) influence on the annual energy consumption cannot be withdraw.

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[49] One study estimated the own price elasticity for heating oil in Germany based on data for the period of 1998 – 2003 of -1.68 to -2.03. Another study estimated an own price elasticity of district heating in Denmark of 0.02 for the period of 1984 to 1995.

[50] Again one publication (published in 1983) estimated the total elasticity of electricity for the US of -1.4.

However, he suggests that the influence of energy prices and thus the running energy costs might show a non-linear threshold behavior. An estimated binary price elasticity of about -0.25 is received by introducing a binary threshold variable for the energy price. Furthermore, he assessed the effect of the income on the Austrian residential space heating energy consumption. For the long-term income elasticity a range of 0.12 to 0.79 was derived. Higher income tends to correlate with larger living areas. Therefore, the estimated income elasticity of the area-specific energy consumption is expected to be much lower than the one referring to the total energy consumption. This is reflected in the different multi-factor regression models defined in his work. The models which do not incorporate the living space, neither directly nor indirectly via the binary variable: single family house or not, result in an income elasticity of about 0.8. The structural discontinuous regression model, which also includes a dummy variable for the building type (single family house or not) results in an income elasticity of about 0.45. If the living area is included directly, the estimated income elasticity drops to 0.2.

The estimated income elasticities need a critical review, since multicollinearity occurs for most models in some form. Nonetheless, based on the results of studies discussed above, the author of this thesis concludes that it is not unreasonable to consider that the short-term income elasticity is in the same magnitude than the price elasticity: $-\alpha_{income} \sim \alpha_{price}$.

The user behavior effect, as implemented in the developed model, extents the concept depicted in equation (4.13), which is mainly based on Loga et al., by adding a directly economically driven behavioral effect. The "*energy-consumption-dependent running costs against the household income"* is chosen as reference variable. Furthermore, it is argued that the user effect derived by Loga et al. (2003) is mainly caused by economic and to a minor degree by technical aspects. Under this assumption, the effect of the economic variable: "*energy-consumption-dependent running costs against the household income*" has a comparable effect as thermal quality of the building shell and can be implemented in the user behavior model shown in (4.14).

In the user behavior model defined by Loga, two parameters have an effect on the scale of the user behavior: the surface coefficient of heat transfer h, and the heated gross floor area per apartment $A_{gfa,dw}$.

$$h = \frac{H}{A_{nfa,build}} = \frac{H_{tr} + H_{ve}}{A_{nfa,build}} \left[\frac{W}{m^2 K} \right] \tag{4.14}$$

where

$H_{tr} + H_{ve}$ ... Heat transfer coefficient by transmission and ventilation contuctivity [W/K]

$A_{nfa,build}$ ... Heated net floor area (0.7-0.8 $A_{gfa,build}$) [m²]

$A_{gfa,build}$ ... Heated gross floor area [m²]

h ... Surface coefficient of heat transfer [W/(m²K)]

The developed model of the effects of the user behavior used in this thesis calculates a surface coefficient of heat transfer h_{corr}, corrected by effects which have an impact on the economic variable: “*energy-consumption-dependent running costs against the household income*”: the energy consumption-dependent (=marginal) heating costs $c_{run,hs}$ considering efficiency of the heating system and the energy carrier price, the income of the household $Y_{household}$ and the site-specific heating degree days.

$$h_{corr} = \left(\frac{c_{run,hs}}{c_{run,ref}} \right)^{\alpha_{c,run}} \left(\frac{Y_{household}}{Y_{household,ref}} \right)^{\alpha_{Income}} \left(\frac{HDD_{\text{building side}}}{3240} \right)^{\alpha_{hdd}} h \left[\frac{W}{m^2 K} \right] \tag{4.15}$$

where

h_{corr} ... Surface coefficient of heat transfer used in the user model, corrected by running energy costs, household income and heating degree days $\left[\text{W/(m²K)}\right]$

$HDD_{building\ side}$ ... Heating degree days at the specific building site conditions [Kd]

3240 ... Average long term heating degree days in Germany1980-2004 (estimated HDD Loga used to calibrated his model)

$c_{run,ref}$ ... Reference running energy costs (estimated reference marginal heating costs on which Loga et al. calibrated there model; standard natural gas boiler, energy prices of 2000: $c_{run,ref}$ =60 €/MWh)

$c_{run,hs}$ ... Marginal (running) heating costs based on the actual efficiency of the heating system and the price of the energy carrier

$Y_{household,(ref)}$ ... (Reference-)Household income

$\alpha_{c,run}, \alpha_{hdd}, \alpha_{Income} = 1$ for Households

Loga et al. (1999) derived the correction factor for the temporal heat reduction f_t, (nightly temperature setback), which depends on the thermal transfer coefficient by transmission and ventilation $H = H_{tr} + H_{ve}$ and the heated dwelling area, using dynamic building simulation tools, see (4.16) . Since I contend that the nightly setback of the temperature rather results from comfort reasons, as the quality of sleep in general tends to increase if the temperature is in the range of 18 °C instead of 21 °C, than from economic reasons, the corrected surface coefficient of heat transfer h_{corr} is not applied.

$$f_t = 0.9 + \frac{0.1}{1+h} [-] \tag{4.16}$$

where

h ... Surface coefficient of heat transfer $[W/(m^2K)]$

The correction factor that describes user behavior is implemented according to (Loga et al. 2003), but is augmented by the HDD, energy price and income adjusted heat transfer coefficient h_{corr}.

$$f_{use} = 0.5 + \frac{2}{3 + 0.6 \cdot h_{corr}} \tag{4.17}$$

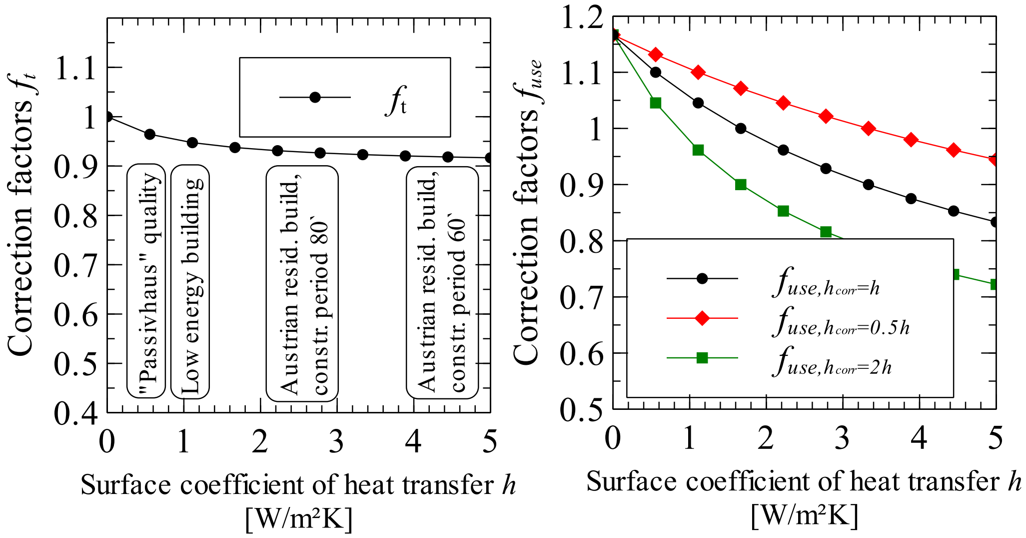

Figure 4.12 – Correction factors for night-setback and user behavior as implemented in the Invert/EE-Lab Model, based on the concept described in Loga et al. (2003).

This user model according to Loga et al. (1999) and Loga et al. (2001) define the partially-heated areas in dependents of the heated gross floor area per dwelling and the heat conductivity of the building envelope. Since it is reasonable to assume that this share will increase with increasing costs for heating, again the adjusted heat transfer coefficient h_{corr} is used.

$$f_a = \frac{1}{0.5\sqrt{h_{corr}} \cdot s_{nfa}^2 + 1} [-] \tag{4.18}$$

$$s_{nfa} = 0.25 + 0.2 \arctan \frac{A_{nfa,dw} - 100}{50} \tag{4.19}$$

where

s_{nfa} ... Share of heated gross floor area not directly heated [-]

$A_{nfa,dw}$ ... Heated net floor area per dwelling [m²]

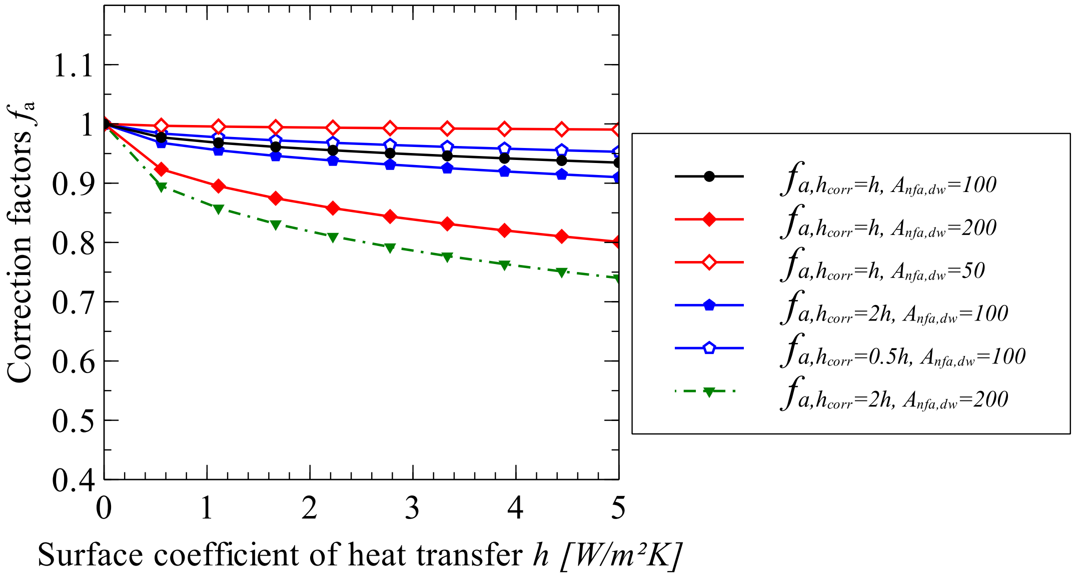

Figure 4.13 – Correction factors for partially-heated areas as implemented in the Invert/EE-Lab Model, based on the concept described in Loga et al. (2001).

The binary correction factor f_{hs} refers to the type heating system. It accounts for the observed reduction in energy consumption, if a single stove heating system is used. Based on the finding of Biermayr (1999) that the service factor of buildings with a non-central heating system is 19% (single family homes) and 8% (apartment buildings) lower than that of buildings with an apartment or building central heating system, the value f_{hs} is set to 0.85.

$$f_{hs} = \left\{ \begin{array}{c} 0.85 \text{ (existing heating system: single stove} \\ 1 \text{ (building or apartment central heating system)} \end{array} \right\} \qquad (4.20)$$

4.5 Determining building renovation, construction and demolition activities

Literature provides two basic approaches to calculate the service lifetime or the remaining service lifetime of building components, buildings or devices: the first approach is based on economic considerations, and the second on a technical property: the reliability that a component will provide its function with a certain probability. Examples for economic approaches can be found in Köhne (2007) and Krug (1985). Bahr (2008) gives furthermore a comprehensive overview of maintenance costs and calculation procedures for estimating them. According to the economic approach, the lifetime of a building ends when maintenance costs exceed its value, measured as the possible revenues gained by renting or selling the building. It is obvious that the lifetime based on this economic approach cannot exceed its technical lifetime. Methods to describe the remaining technical lifetime can be found in Menkhoff (1995), Pfeifer and Arlt (2005) or Meyer et al. (1995). All these approaches aim to define the remaining service lifetime of an individual building element, considering its past. This, however, requires to inspect and subsequently evaluate an actual building and its elements. Such an approach cannot be applied to a larger stock of buildings. Thus, this work has to rely on a simpler, indicator based methodology. Data for the average lifetime of building related building elements can be found in e.g. Bahr and Lennerts (2010), Bauer (2013), Hansen (2009), IEMB (2004), BBR (2001), Meyer et al. (1995) or Ritter (2001). Most of these sources provide minimum (or 5% quantiles), maximum (or 95% quantiles) and average service lifetime values for different components. An exception to that are Meyer et al. who evaluate the share of building components still in operation for different components and installations periods over the lifetime and Bauer who assesses for the Austrian social housing building stock the age of buildings where the first renovations was performed.

4.5.1 The service lifetime of heating systems, building envelope components and buildings

In this work the probability (expressed as share) that buildings are demolished, refurbished or that their heating or DHW systems are replaced is calculated based on the cumulated failure rate of building components considering Weibull distributions. By applying this concept, the failure rate of components is defined by two parameters: the characteristic service lifetime λ and a shape parameter k. The cumulated failure rate of the considered component with a certain age a_t is then defined by equation (4.21).

$$\Phi_{cum.replaced,t} = 1 - e^{-\left(\frac{a_t}{\lambda}\right)^k} \tag{4.21}$$

where

$\Phi_{cum,replaced,t}$ ... Cumulated replacement rate (or failure rate) in t based on Weibull distribution

k ... Shape parameter of Weibull distribution

λ ... Characteristic lifetime of building element [yr]
(lifetime at which a cumulative failure rate of 63.2% occurs)

a_t ... Age of building element in t [yr]

In the implementation of this process, the basic concept shown in (4.21) is extended by introducing a failure-free lifetime and an upper lifetime, see equation (4.22).

$$\Phi_{cum.replaced,t} = \left\{ \begin{array}{ll} a_t \geq a_{\max} & : 1 \\ a_0 < a_t < a_{\max} & : 1 - e^{-\left(\frac{t-a_0}{\lambda - a_0}\right)^{k \cdot \frac{a_0}{\lambda - a_0}}} \\ a_t < a_0 & : 0 \end{array} \right\} \tag{4.22}$$

where

a_0 ... Failure-free lifetime of considered component [yr]
used: $T_{\min} = \lambda / 3$

$a_{\max}$ ... Maximum lifetime of considered component [yr]
used: $T_{\max} = 3\lambda$

Under this presumption, the share of buildings which apply certain measures ($s_{measure}$) within a given period of time: $t\text{-}n_{sim.step.with}$ to t can be derived by equation (4.23).

$$s_{measure,t} = \frac{\Phi_{cum.replaced,t}}{\Phi_{cum.replaced,t-n_{sim.step\_width}}} \tag{4.23}$$

where

$s_{measure,t}$ ... Share of buildings applying a specific measure in t

$\Phi_{cum,replaced,t}$ ... Cumulated replacement rate in t based on Weibull distribution

$\Phi_{cum,replaced,t-n_{sim\_step\_width}}$ ... Cumulated replacement rate in previous simulation period

$n_{sim\_step\_width}$ ... Simulation step width [yr]

This approach statically defines the end of the lifetime of building components, since the input data used to calculate the failure rate of components in a given period of time, were derived from historical data only and the specific situation in the considered period is not taken into account. In reality however, it can be expected that the average costs of a specific measure (e.g. changing windows) has an influences on the decision of investors who decide whether or not to apply this measure[51]. If for a specific measure the energy costs savings by far exceed the levelized investment costs, it is reasonable to assume that a larger share is going to perform the measure. In contrast, if decision-makers can choose from very expensive measures only, a drop in the rate of measures is expected to be observed.

Describing (in a mathematical sense) and calibrating this process based on historical data is difficult, since directly comparable data, to the author's knowledge, are not available

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[51] This consideration actually constitutes the basis for the economic approach.

in literature. In fact, historical data derived by Meyer et al. (1995) and others already include this process to some extent. Even if data for the calibration are rare, one needs to be aware that if a static approach is implemented only, the validity of the model is limited in a specific way that might have an important effect on the results. To overcome this limitation, a dynamic adaptation of the measure rate $s_{measure}$ is considered in the developed model. The average total levelized costs of a specific measure (annuity of investment costs plus current running costs minus energy costs savings) compared to the current costs $r_{cost,measure}$ defined by equation (4.25) are used to scale the measure rate up or down.

$$\begin{aligned} c_{measure,i} &= c_{run,hs,i} + \alpha \cdot I_{measure,i} - \Delta c_{energy,i} \quad [€/yr] \\ c_{measure,mean} &= \sum_{i}^{I} s_i c_{measure,i} \end{aligned} \tag{4.24}$$

$$r_{cost,measure} = \frac{c_{measure,mean}}{c_{no\_measure}} \tag{4.25}$$

where

$c_{run,hs}$ ... Annual running energy costs and O&M costs, $c_{no\_measure} = c_{run,hs}$
$\alpha \cdot \mathrm{I}_{measure,i}$ ... Levelized investment costs of renovation measure *i*
$\Delta c_{energy,i}$ ... Avoided annual energy costs by a specific measure
$c_{measure,i}$ ... Net costs of measure *i*
$c_{measure,mean}$ ... Average net costs of all measures
s_i ... Share of measure *i*
$r_{cost,measure}$ ... Weighted average cost ratio of available measures compared to status quo

The assumed mathematical relationship of the adaptation process is described by equation (4.26) and depicted in Figure 4.14.

$$f_{measure,adaptation,t} = \left\{ \begin{array}{cc} r_{cost,measure,t} < 1 - r_{threshold} & \min\left(f_{scale,\max},\ f_{scale,Base}^{\left(r_{cost,measure,t} - 1 + r_{threshold}\right)} \right) \\ 1 - r_{threshold} < r_{cost,measure} < 1 + r_{threshold} & 1 \\ r_{cost,measure,t} > 1 + r_{threshold} & \max\left(f_{scale,\min},\ f_{scale,Base}^{\left(r_{cost,measure,t} - 1 - r_{threshold}\right)} \right) \end{array} \right\} \quad [-] \tag{4.26}$$

where

$f_{measure,adaptation,t}$ ... Cost-based scaling factor used to adapt
the measurement rate according to the Weibul approach
$f_{scaleBase}$ ... Base for calcation of the adaptation factor, $f_{scaleBase} > 0$
$f_{scale\max}$ ... Upper adaption boundary, $f_{scale\max} \geq 1$
$f_{scale\min}$ ... Lower adaption boundary, $0 < f_{scale\max} \leq 1$

For the subsequent scenario analysis, the following parameters are used (Figure 4.14): $f_{scale,base}$=0.5, $r_{treshold}$=0.2, $f_{scale,max}$=1.5 and $f_{scale,min}$=0.5. This calibration corresponds to an elasticity of about 0.5 for an $r_{cost,measure}$ between 0.4 and 0.8 (=applying a measure is cost effective). For an $r_{measure}$ between 1.2 and 2.4 the elasticity is close to 1. This means that the investor's responses to cost increases due to renovation activities is higher (postponing measures[52]) than the response to cost savings (accelerated renovation cycles).

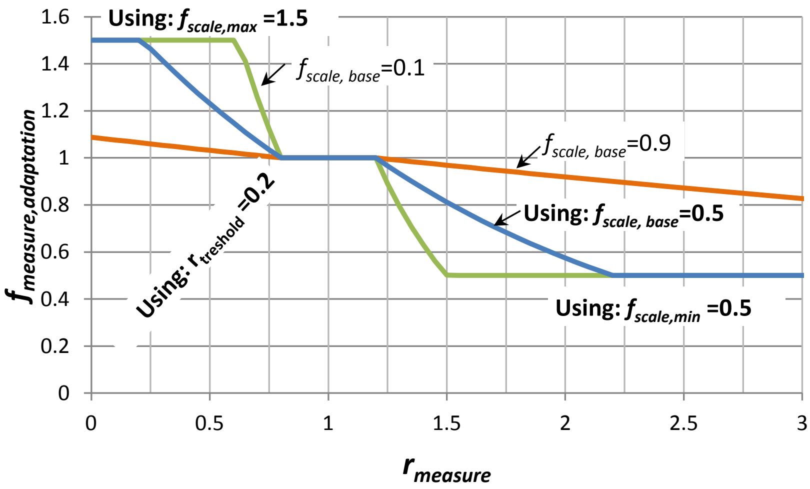

Figure 4.14 – Parameters for the share of buildings applying measures according to cost-based adaptation approach in relation to the average cost ratio between costs of measures versus status quo.

Considering the cost-efficiencies of available measures, the share of buildings $s_{measure,dyn,t}$ which apply some measures in t (4.27) is then calculated by scaling the replacement rate derived by the Weibull process $s_{measure,t}$ (4.23) using (4.26).

$$s_{measure,dyn,t} = s_{measure,t} \cdot f_{measure,adaptation,t} \tag{4.27}$$

where

$s_{measure,t}$ ... Share applying some measure according to the Weibul approach
$s_{measure,dyn,t}$ ... Adapted share considering the average costs efficiency of available measures

4.5.2 The lifetime of buildings

The demolition rate of buildings does not only depend on the construction period and thus the age of the building in a specific year, but also on prior refurbishments. Such refurbishments have a significant influence on the building's value, which is one of the key parameters that defines whether or not a building should be pulled down and replaced by a new one, or whether refurbishment/renovation is the more economical way to go. Wüesth et al. (1994) describe four property management strategies and introduce a model to calculate building demolition for the time period of 1990-2030 for the Swiss building stock. The

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[52] The defined process alters the effective characteristic lifetime of building components.

service lifetime of buildings in this model is not an exogenously defined fixed parameter, but depends on measures taken in previous renovation cycles. For the demolition of buildings a similar approach was considered.

In the developed Invert/EE-Lab model, the Weibull distribution is used to describe the service lifetime of buildings if no measures were taken. To account for maintenance and renovation cycles, refurbishments taken in previous periods increase the characteristic lifetime of buildings and thus decrease the relative age of buildings. The cumulated demolition rate of buildings in period t considering previous investments is defined by equation (4.28).

$$\Phi_{cum.demolition,\, build.,t} = 1 - e^{-\left(\frac{a_{build.,t}}{\lambda_{build.} + f_{addLT} \sum \lambda_{renovation}}\right)^{k}} \qquad (4.28)$$

where

$\Phi_{cum,\mathrm{demolition,build},t}$ ... Cumulated demolition rate in t

k ... Shape parameter of Weibull distribution

$\lambda_{build.}$ ... Characteristic lifetime of buildings

$a_{build.t}$ ... Age of building in t

$\sum \lambda_{\mathrm{Renovation}}$ ... Average characteristic lifetime of building renovation measures (sum over renovation cyles)

f_{addLT} ... Calibration factor, used: $f_{addLT,thermal\_renovation} = 0.5$

$f_{addLT,\mathrm{maintenance}} = 0.25$

The share of buildings which is demolished within a given period of time: $t\text{-}n_{sim.step.with}$ - t is defined by (4.29).

$$s_{demolition,build.,t} = \frac{\Phi_{cum.\mathrm{demolition,build.},t}}{\Phi_{cum.\mathrm{demolition,build.},t-n_{sim\_step\_width}}} \qquad (4.29)$$

where

$s_{demolition,build.,t}$ ... Share of buildings beeing demolished in t

$\Phi_{cum,demolition,t}$ ... Cumulated demolition rate in t

$\Phi_{cum,demolition,t-n_{step\_width}}$ ... Cumulated demolition rate in previous simulation period

4.5.3 Age distribution within a construction or installation period

It is considered that buildings within a building class were constructed or renovated within a given period of time (e.g. construction period). This means that the age of buildings and components within a class is also distributed. To account for the actual age distribution in *t*, the cumulated replacement rate is derived from the averaging replacement rate (4.30).

$$\Phi_{cum.replace,t} = \left(a_{\max,t} - a_{\min,t} + 1\right)^{-1} \cdot \sum_{a=a_{\min,t}}^{a_{\max,t}} 1 - e^{-\left(\frac{a_t}{\lambda}\right)^k} \tag{4.30}$$

where

$a_{\max,t}$ ... Age of oldest component or building within a construction/installation period [yr]

$a_{\min,t}$ ... Age of youngest component or building within a construction/installation period[yr]

The equation above holds only, if construction, renovation or installation activities where initially equally distributed within the considered period. This can be reasonably assumed for construction activities. For renovation activities or the installation of heating systems, such an assumption fails if the buildings went through a replacement or refurbishment cycle already (see Figure 6.5 and Figure 6.6). Therefore, the implemented replacement-cycle approach, if applied to estimate historical activities (see section 6.1.2), also estimates the best-fitting third-order polynomial function to represent the initial distribution $s_{\text{initial},a}$ of installations (see equation (4.31)) and divides segments if the distribution cannot be adequately described by this kind of function.

$$\begin{gathered} \Phi_{cum.replace,t} = 1 - \sum_{a=a_{\min,t}}^{a_{\max,t}} s_{\text{initial},a}\, e^{-\left(\frac{a}{\lambda}\right)^k} \\ \sum_{a=a_{\min,t}}^{a_{\max,t}} s_{\text{initial},a} = 1 \end{gathered} \tag{4.31}$$

where

$\phi_{cum,\text{replaced},t}$ ... Cumulated demolition rate in t (not considering failure free lifetime)

$s_{initial,a}$ ... Initial share of element installed in $t - a$ within the installation period $t - a_{\max}$ until $t - a_{\min}$

$s_{initial,a} = x_0 + x_1 \cdot (a - a_{\min}) + x_2 \cdot (a - a_{\min})^2 + x_3 \cdot (a - a_{\min})^3$

4.5.4 New buildings

The discrepancy between demanded number of buildings, which are defined exogenously per building category, and existing buildings determines the number of new buildings. If the existing building stock exceeds the demanded number[53], buildings become unoccupied. Unoccupied buildings are assumed to be non-heated and do not attract any investments.

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[53] E.g. in regions with a decreasing population.

4.6 The decision process: decision criteria and empirical evidence of individual decision aspects

In this chapter, the decision criteria of investors, when investing in components related to space heating and its energy demand, as well as the empirical evidence of individual decision calculus are investigated. To do so, the author gives a brief summary of existing literature on this research area and assesses the data of a survey conducted within the Lifestyle 2030 project (Bogner et al., 2012).

4.6.1 Criteria affecting the decision into which heating systems and building refurbishments to invest

The decision-process and relevant decision criteria of decision-makers investing in components affecting the space heating-related energy use of buildings and underlying investment criteria are assessed in many existing publications.

On an aggregated level, Müller et al. (2011) compare the market penetration of heating systems in Austria, Finland, Sweden and the Netherlands. One of their conclusions is that heating systems commonly installed in these countries have similar total heating costs (compared within a country). Furthermore the widely applied heating systems are those, which have low total annual costs. Thus, the authors conclude that the total heating costs have a significant influence on the decision, yet costs might not be the sole decision criterion.

A more detailed analysis is presented by Braun (2010). Based on data from a conducted survey, she analyzes the decision criteria for newly installed heat supply systems in the German residential building sector using a multinomial logit model. The explanatory variables are income, the number of household members, the average education level of the representative household members, the construction year and type of the building and the location of the building. On a broader level the information on the building's location used is whether or not the building is located in the former German Democratic Republic; on a regional level whether or not the building is located in rural or urban areas. Heating costs are not used as an explanatory variable. Conclusions from her analysis are that neither income, the number of household members nor the average education level have a major impact on the decision. A significant influence on the decision is the location of the building - which can be seen as an estimator of the availability of heating systems - and the construction period of the building. The Pseudo R² of her model on the full sample (7171 observations) is 0.151[54]. The very low explanatory value of the model reveals that the model misses some important explanatory variables. Braun concludes, based on other work done in this field of research, that the costs of heating systems have a major role.

A similar analysis was done by Henkel (2012). In an online-survey, he asked investors who have recently installed a new heating system in their homes about the main reasons for their decision for a specific heating system. In the case of newly installed conventional heating systems (oil and gas fueled boilers) about 50% stated that the main reason was that this particular energy carrier had been used already before in the building. Other important criteria are economic reasons, and in the case of oil, the unavailability of natural gas. In the case of alternative heating systems (wood pellets and heat pump with solar thermal systems) 1/3 mentioned the high natural gas and heating oil prices as main reason for their decision. In the case of pellet heating systems another 25% based their decision on economic reasons (incl. low operational costs). For the combination of heat pumps and solar thermal systems, economic reasons are decisive for about 45%. 15% to 20% mentioned environmental friendliness as their most important criterion.

Michelsen and Madlener (2013) analyze the homeowners' motivation of investing in renewable heating systems (RHS), based on a survey conducted among German homeowners who have recently installed renewable heating systems. One of their findings is that the decision process is heterogeneous and complex, as multiple criteria are taken into account (see also Michelsen and Madlener, 2012). Based on their results, they cluster RHS adopters into three groups: (1) the convenience-oriented adopters (54.4%) who decide based "*on fitting into the daily routine*" and "*attention-less system*". (2) The second largest group (32.2%), the consequences-aware adopter, decides based on short-term (cost-based) and long-term (rising energy prices, security of supply and environmental concerns) consequences. (3) The smallest group, the multilaterally-motivated adopters (13.4%), compares competing alternatives intensively and decide in particular based on cost aspects (including subsidies) and comfort aspects.

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[54] The model for the sample subgroup of house owners only (3928 observations) results in a Pseudo R² of 0.065 only.

Achtnicht and Madlener (2014) present the results of a survey of about 400 German owner occupied households, situated in detached, semi-detached or row houses. In the survey, home-owners were asked (directly) for reasons why they did or did not retrofit their building. In a second stage, they were confronted with a choice experiment with different retrofitting options. Being asked about general reasons for retrofitting a building, the top answer was "high energy costs" (65%), followed by "Renovation is due in any case" (46%). Increasing comfort (37%) and environmental concern (29%) came in third and fourth place (out of 14). On the other hand, asked for barriers, the two top answers given were: "a renovation of heating (66%)/building envelope (61%) is not necessary". On third and fourth position (out of 18) came: "lacking financial resources" (59%) and "not sure whether such measures will pay off". Confronted with a hypothetical retrofitting option that reduces the running energy cost and CO_2-Emissions by 50% and a pay-back period of 15 years[55], nearly 60% would keep the status quo. Achtnicht and Madlener conclude that their results suggest that most home owner consider renovation or replacement only in case the building component approaches the end of its lifetime. And further, if an investment opportunity occurs, home owners assess, whether or not efficiency improvements are affordable and profitable.

Schulz (2011) analyzes, based on expert judgments, the importance of different decision criteria for various decision agents in the building sector. For the residential building sector he defines four categories of investors, with respect to the owner-user-relationship (and the subsequently arising user-investor dilemma):

- Owners of small residential buildings using the building on their own;
- Owners of residential buildings renting out their building(s);
- Community associations of apartment buildings;
- Public housing associations.

He concludes that the first three agents, even though there are some differences, weight their investment decision criteria in a similar way: Most important are the *capital needs*, furthermore rather stable *energy prices* and low *annual energy costs* are preferred. *Pay-back-time* and the *total annual costs* including the annuity of investment costs play a minor role in the decision process; however they are already covered in the criteria *capital needs* and *low energy costs* which can be transformed into the latter ones. Public housing

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[55] Considering a depreciation time of 20 years, this investment opportunity has internal rate of return of about 3%.

associations apply a different decision calculus, allocating the value of buildings. For them, the possibilities of getting higher rents have a higher importance than the annual energy costs. In a follow-up analysis, Steinbach (2015) further disaggregates the first investor type (owners of small residential buildings using the building on their own) into five investment agents, considering their individual motivations for settings actions, social values (e.g. sustainability) and barriers. Again economic criteria such as investment needs (2 groups) and pay-back period (2 groups) and energy cost savings (1 group) are the most important criteria.

4.6.2 The influence of the affinity to the Sinus-Milieus cluster on the decision process for building renovation and heating system

In the course of the *project Outlook "Life Style 2030"*, a survey was conducted in which the energy consumption and appliances in households, and information on the buildings were asked. In addition, the decision-makers' affiliation to certain lifestyle groups, using the Sinus-Milieus® cluster (Figure 4.15), are queried (Bogner et al., 2012). The questionnaire was compiled by the project team groups: the Austrian Energy Agency and the Energy Economic Group[56] on the Vienna University of Technology. The survey was done online and face-to-face (140 interviews in order to reach the 60-85 year old target group) and was conducted by the market research institute Karmasin. The sample size is ~1000 household representatives within the age of 18 - 85 years.

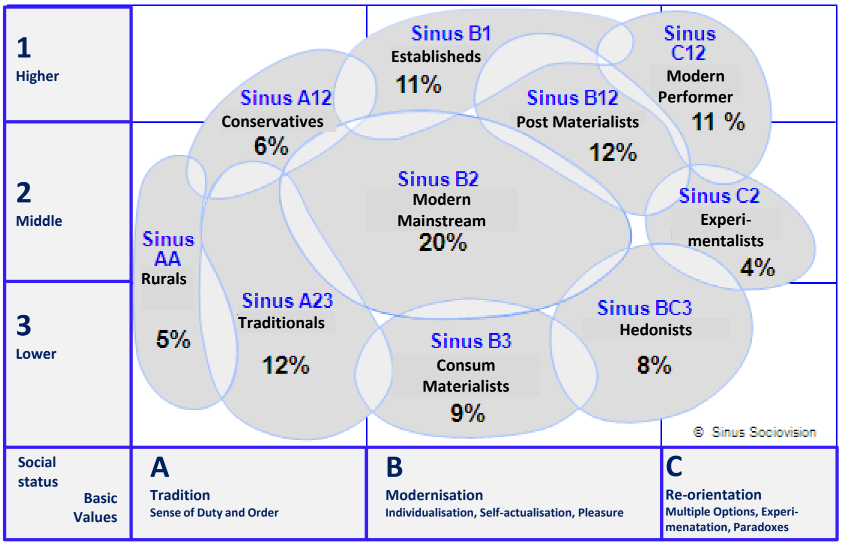

Figure 4.15 – Sinus-Milieus® of the Austrian TV-Population in 2009. Source: mediaresearch.orf.at/index2.htm?fernsehen/fernsehen_sinus.htm, 5.10.2009, my translation

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[56] The author of this thesis constituted the project team of the EEG.

Based on the original Sinus-Milieus clusters shown above, the clusters included in this survey are:

- Incurious group (with respect to energy consumption and environmental conservation) (LSG 1), situated in the area of groups Sinus B2-B3;
- Environmental conservationists (LSG 2), situated in the area of groups Sinus BC3-B12-(C12);
- Discerning group (LSG 3), situated in the area of groups Sinus B12-C12-(B1);
- Traditionalist (LSG 4), situated in the area of groups Sinus A23-B2-(A12);
- Established group (LSG 5), situated in the area of group Sinus B1-(A12);
- Alternative lifestyle group (LSG 6), situated in the area of groups Sinus BC3-(C2);
- Pensioners and sedate lifestyle group (LSG 7), situated in the area of groups Sinus A23-AA-(A12).

To assess the decision-making process with respect to investments in (thermal) building renovation and heat supply systems, the author focuses on the systems currently installed and uses this indicator as an approximation for future decisions.

Out of the sample of 1053, only a sample of 94 answers provide a valid indication to the age of the building in which they are living, a set of 66 answers includes the degree of renovation status of the building. The building age revealed that the groups can be divided into two clusters. The milieu clusters LSG 2, 3, 4, and 5 are living in buildings with an average age of 25-35 years, whereas the average building age of the remaining three milieu clusters are in the range of 50 to 55 years and thus almost twice as old. About 80% (66) of the sample gave a valid answer about the renovation status of the building: unrefurbished, partly or comprehensively refurbished. The only milieu group that inhabits older buildings with a lower share on comprehensive or partial renovated buildings is the Alternative lifestyle group (LSG 6). However, since the response rate for this particular question is very low (5%-7%, except for LSG 6: 11%), the results are not very solid.

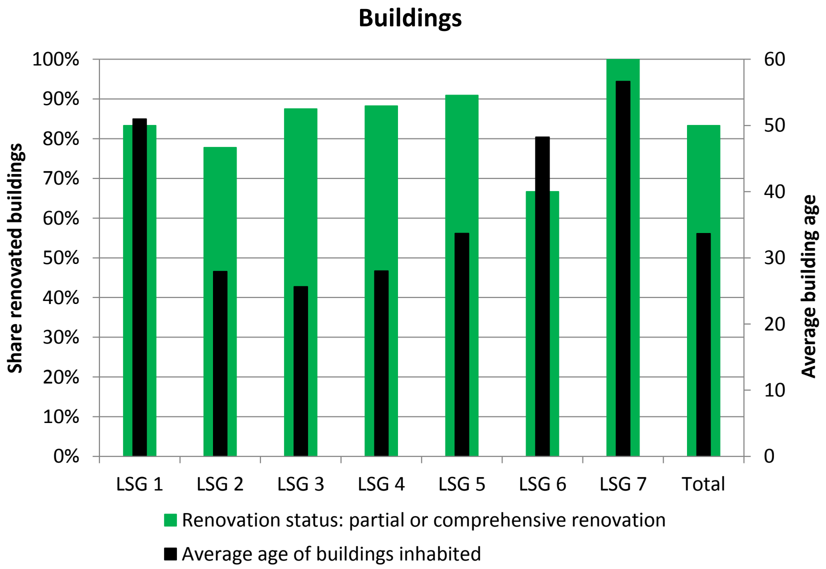

Figure 4.16 – Renovation status (black bars) and average age of the inhabited building (green bars).

Given the small data sample and the, broadly speaking, diminishing deviations in the renovation status of the buildings, a hypothesis postulating that *no differences in the building renovation status can be found*, cannot be dismissed.

For the assessment of heat supply systems, a sample of 960 (out of 1053) valid and useful (energy carrier is known and provided) answers is available. Therefore, results stand on a solid ground for this analysis. The research hypothesis H0 runs as follows: currently installed heat supply systems do not indicate that the different lifestyle groups, using the Sinus-Milieu Cluster concept, have individual preferences for heating systems utilizing renewable energy carriers (RES-H). The counter hypothesis H1 states that such individual preferences can be found in the data sample.

In general, the use of district heating depends on the availability at the specific site and only to a minor degree on the individual preference of the decision-maker. Thus, the variance of district heating between different lifestyle groups is used as a reference and is compared to the variance of RES-H systems. If RES-H systems have a significantly higher variance than district heating systems, it can be concluded that the data reveal some individual preferences for RES-H systems and hypothesis H0 has to be rejected.

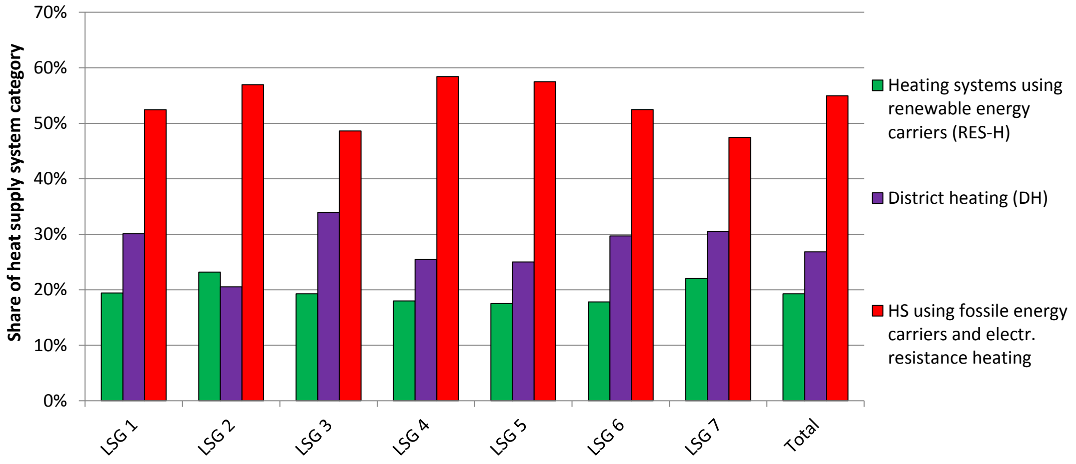

Figure 4.17 – Share of heat supply system categories per lifestyle group. (The total share exceeds 100% because solar thermal collectors were nominated as secondary heating system.)

The market share for district heating systems is based on the total number of observations (4.32), whereas the share of RES-H systems is based on the share of all heating systems except for district heating, for which the utilization is mainly defined by its availability (4.33).

$$\sigma^2_{district\ heating} = \left(n_{SM}-1\right)^{-1}\sum_{i=1}^{n_{SM}}\left(\frac{s_{district\ heating,i}}{s_{district\ heating,mean}}-1\right)^2 \qquad (4.32)$$

$$\sigma^2_{RES-H} = \left(n_{SM}-1\right)^{-1}\sum_{i=1}^{n_{SM}}\left(\frac{s_{RES-H,\mathrm{j}}}{\left(1-s_{district\ heating,j}\right)s_{RES-H,mean}}-1\right)^2 \qquad (4.33)$$

where

σ^2_j ... Variance of heating system categories j between Sinus-Milieu Clusters either district heating (DH) or RES-H
n_{SM} ... Number of Sinus-Milieu Clusters ($n_{SM}=7$)
$s_{j,i}$ ... Share of heating system category j in Milieu Cluster i
s_j ... Share of heating system category j on the full sample

The results of this analysis, shown in Table 4.2, do not indicate a strong evidence that the shares of RES-H systems vary to a larger degree than those of district heating systems. If all clusters are considered, the variance of district heating is larger than that of heating systems utilizing renewable energy carriers. If the environmentally friendly lifestyle group (LSG 2), which shows an extra low share of district heating compared to other groups, is not accounted for when calculating the variance of DH, district heating still does not have a lower variance. A further correction in which the share of district heating is corrected by the share of dwellings in apartment buildings, which tend to have a higher access to district heating, compared to single and double family houses, gives a variance for district heating which is slightly lower than that of RES-H.

Table 4.2 – Variance of share of heating system categories between Sinus-Milieu clusters.

	Sinus-Milieu Cluster		
	All clusters	**$\sigma^2_{district\ heating}$: all clusters except LSG2**	**$\sigma^2_{district\ heating}$: exclude LSG 2, adjust for availability of DH**
$\sigma^2_{RES\text{-}H}$	11.6^2 % (11.4^2 % if calculated based on (4.32))		
$\sigma^2_{district\ heating}$	16.7^2 %	11.6^2 %	10.7^2 %

LSG2 … Environmental conservationists
DH … District heating
Availability of district heating adjusted by considering the building type: apartment versus single/double-family house
The variance of σ^2 for fossil energy carriers: natural gas and heating oil products (which held an average share of 45%) amounts to 12^2 %, that of apartment or building central heating systems (share of 33%) to 20^2 %

For comparison the variance of RES-H is calculated, assuming a higher share (expressed as a factor of the average share) of those systems in the environmental conservationist lifestyle group (LSG 2).

Table 4.3 – Reference variance of RES-H systems within different lifestyle clusters assuming a higher share of these systems in LSG 2.

	Share of RES-H systems in LSG 2 as factor of average share				
	110%	**120%**	**130%**	**140%**	**150%**
$\sigma^2_{RES\text{-}H}$	12.6^2%	14.0^2%	16.1^2%	15.8^2%	21.2^2%

Based on the results outlined above, the author concludes that the data sample does not reveal a difference of the individual preference exceeding +10% compared to the average preference for RES-H systems. Therefore, hypothesis H0 – currently installed heat supply systems do not indicate that the different lifestyle groups, using the Sinus-Milieu Cluster concept, have individual preferences for heating systems utilizing renewable energy carriers (RES-H) – cannot be rejected.

4.7 The decision algorithm for heating and DHW systems

4.7.1 The multinomial logit model

A logit model, a well-established approach within the discrete choice theory, constitutes the basic methodology of the decision algorithm. This approach has already been applied for modeling the heating sectors by other working groups (e.g. Giraudet et al. 2011;

Henkel, 2012; Marnay and Stadler, 2008; Braun, 2010; Bauerman, 2011); their results indicate that this approach is also pertinent for the specific research questions of this work. In a very simple form, and if the independence from irrelevant alternatives (IIA) (Marschak, 1960) is not violated, the share $s_{MNLM,i}$ of an alternative i within a building segment b in period t is derived by a multinomial logit model (MNLM) as defined in equation (4.34).

$$s_{MNLM,b,t,i} = \frac{e^{-\beta_{b,i} r_{b,t,i}}}{\sum_{i=1}^{I} e^{-\beta_{b,i} r_{b,t,i}}} \tag{4.34}$$

where

$s_{MNLM,b,t,i}$ ... Market share of alternative i in building b at the time period t derived by the mulinomial logit model

$\beta_{b,i}$ ... Scaled variance of the decision parameter (assuming that the unobserved parameters are Type-I extrem value distributed)

$r_{b,t,i}$ ... Relative penalty: penalty ("costs") of alternative i against weighted average penalty of all alternatives in the building b at the time period t

For each building (segment) b, the relative penalty $r_{b,t,i}$ (defined in (4.35)) of a technology option i at a given time t is derived based on the average penalty (equation (4.36)) of all technology options, weighed by their market shares in building b in t[57].

$$r_{b,t,i} = \frac{\mu_{b,t,i}}{\mu_{b,t,mean}} \quad \forall b,t,i \tag{4.35}$$

$$\mu_{b,t,mean} = \sum_{i=1}^{I} s_{b,t,i} \cdot \mu_{b,t,i} \quad \forall b,t \tag{4.36}$$

where

$\mu_{b,t,i}$ ... Penalty of alternative i at time period t in building b

$\mu_{b,t,mean}$ ... Average penalty of all alternatives, weighted by market share at period t on installation in building b

$s_{b,t,i}$ ... Market share of alternative i in building b at time period t (derived by (4.58))

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[57] If the average penalty is not calculated based on the actual market share of technologies, irrelevant alternatives (such as technologies with very high costs (and thus very low markets shares) or technologies with very low costs but also a very restricted potential) would have an influence on the decision (since the logit model is not isoelastic).

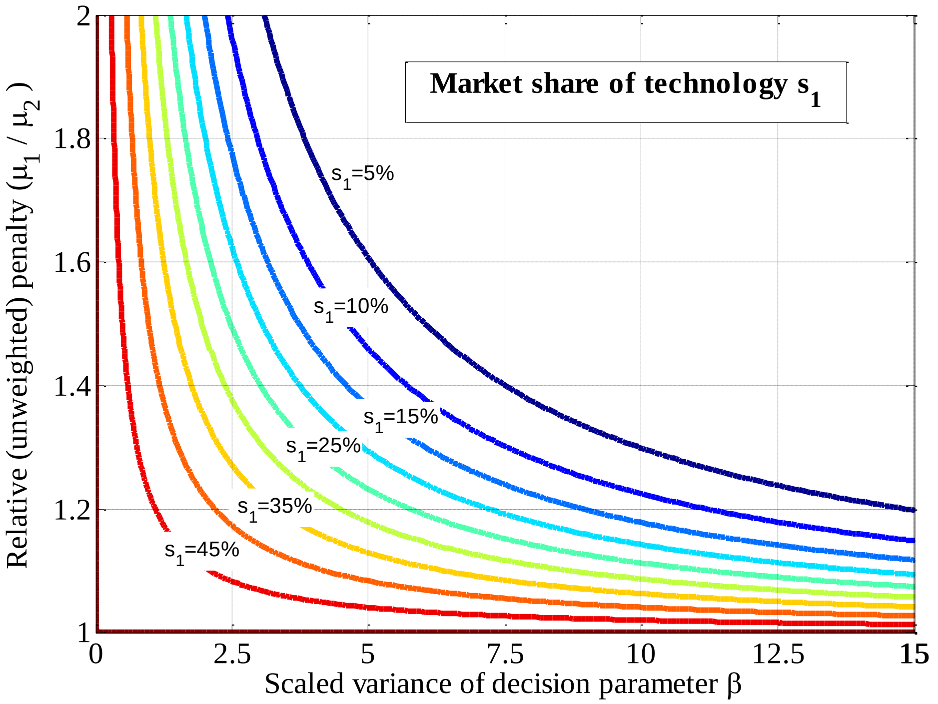

Figure 4.18 – Market share of a technology 1 against a technology 2 described by a multinomial logit model, based on penalty ratio 1 against 2 and the scaled variance of the decision parameter *β*.

The primary driver of the penalty function μ used to describe the investors' preferences are the total costs of heating and domestic hot water preparation (TCH), thus it is assumed that on average the total heat generation costs are the dominant variable. The TCH include the consumption-dependent (energy costs), consumption-independent annual operating costs (fixed annual tariffs, maintenance, etc.) and the levelized investment costs. In the decision process the TCH are augmented by monetary and non-monetary barriers for changing the type of heating systems, and intangible costs represented by consumer preferences (CP) of decision-makers. The consumption-dependent energy costs are defined by the final energy demand presuming the norm indoor temperature in buildings (20 °C in the case of Austria). Thus, in the decision-making process, behavioral aspects which influence the annual energy demand are not taken into account and different alternatives are compared on the same level of comfort level. This assumption seem reasonable, especially for building renovation activities where the information on future energy savings rather come from simple energy performance indicator calculations than from more complex methods that incorporate rebound effects[58].

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[58] A sensitivity analysis for this assumption is shown in section 5.2.1.

Bauermann (2011) provides empirical evidence that agents incorporate not only the current, but also the energy price of previous periods in their decision-making process. To account for this finding, the energy prices $c_{ec,t,decision}$ of an energy carrier *ec* used to calculate the adjusted total costs of heating and domestic hot water preparation are partly based on the energy price level of previous simulation periods:

$$c_{ec,t,decision} = \sum_{n=0}^{2} c_{ec,t-n} \cdot f_n \quad \forall ec,t \tag{4.37}$$

where

$c_{ec,t,decision}$ ... Price for energy carrier ec at time period t used in the decision process

$c_{ec,t-n}$ ... Observed price for energy carrier ec at time period t - n

$used:\ f_0 = 0.3,\ f_1 = 0.5,\ f_2 = 0.2$

Furthermore, it is assumed that the investor does not necessarily have full information about the impact of the supply line temperature of the heat distribution system on the annual efficiency of the heat supply system.

$$\kappa_{i,decision} = f_{\text{info},SL} \cdot \kappa_i \tag{4.38}$$

where

$f_{\text{info},SL}$ ... Information deficit factor with respect to supply line temperature effects

$used: f_{\text{info},SL} = 0.5$

κ_i ... Temperatur coefficient factor of heat supply technology i

$\kappa_{i,decision}$ ... Temperatur coefficient used in the decsion process

Three categories of barriers, related to changing the type of the heating systems, are considered in the model. The first are non-monetary barriers, basically associated with the comfort level the existing heating system provides. This means that a significant decrease of comfort level or degree of automation is not allowed:

- If a heat distribution system is available, single stoves are excluded.
- If a building central heating system is installed individual heating systems are excluded.
- Coal and wood log boilers are only allowed, if the existing heating system utilizes either coal or wood log.
- If natural gas or electricity are the main energy carriers, oil based heating systems are also excluded.
- If a district heating is used, all other energy carriers are excluded.

These non-economic barriers associated with the change of heating system types are summarized in a substitution matrix similar to Cost (2006), yet excluding the TCH.

The second category refers to the economic barriers that might occur when the energy carrier is changed. Such costs are e.g. natural gas connection costs, oil tank, biomass storage, drilling costs for the bore hole of heat pumps with vertical heat exchangers. Furthermore, it is assumed that decision-makers have a preference for the existing energy carrier. For energy carriers except for gas this preference is set to 0.9[59], for gas it is set to 0.8. The local availability of energy carriers constitutes the third barrier. It is discussed in detail in section 4.7.3 and 4.7.4.

In the Invert/EE-Lab model the MNLM approach, as described above, is extended by the mechanism described in the following section.

4.7.2 The nested logit model

The application of the MNLM is limited by the restrictive IIA assumption. However, if similar alternatives exist (e.g. gas boiler and gas condensing boiler, single stove versus central on-floor heating systems, different options of solar thermal collectors against no solar collectors, different options of buildings refurbishment compared to maintenance without effects on thermal losses) the independence from irrelevant alternatives (IIA) might not[60] hold and applying a nested logit model (NLM) is a more appropriated approach (see also Kwak et al., 2010). The nested logit model, which is the most widely used generalized extreme value (GEV) model, clusters similar alternatives in a so-called nest. If two alternatives are within the same nest, the IIA still holds also for GEV models. Thus, the nested logit models replace the IIA by an “independence of irrelevant nests” (IIN) hypothesis. If all correlations (“similarities”) are zero, the GEV converts to a standard logit model.

In the Invert/EE-Lab model, for the choice of heating systems a three-level NLM is applied. The top level nest defines whether or not thermal solar collectors are installed. The second level nest describes different heating system categories; on the third level subclasses of heating systems (e.g. condensing and non-condensing gas boilers) are grouped together.

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[59] 0.9 means that the penalty is reduced by 10%.

[60] Test if the IIA holds: Hausman test: (Hausman, 1978); McFadden test (Hausman, and McFadden, 1984), Wald test and likelihood ratio test.

Based on the nested logit model, a technology combination: primary technology *i*, belonging to heating system category *hscat* with a solar thermal system *sol* receives a market share as defined by equation (4.39).

$$s_{NLM,b,i,(hscat,sol),\mathrm{t}} = \frac{e^{\frac{\gamma_{b,\mathrm{i,t}}}{\sigma_{hscat}^{HSACT}}}\left(\sum_{i}^{I_{hscat}} e^{\frac{\gamma_{b,\mathrm{i,t}}}{\sigma_{hscat}}}\right)^{\frac{\sigma_{hscat}^{HSCAT}}{\sigma_{sol}^{SOL}}-1}\left(\sum_{l}^{HSCAT_{sol}}\left(\sum_{i}^{I_{hscat}} e^{\frac{\gamma_{b,\mathrm{i,t}}}{\sigma_{hscat}}}\right)^{\frac{\sigma_{l}^{HSCAT}}{\sigma_{sol}^{SOL}}}\right)^{\sigma_{sol}^{SOL}-1}}{\sum_{n}^{SOL}\left(\sum_{l}^{HSCAT_{n}}\left(\sum_{i}^{I_{k}} e^{\frac{\gamma_{b,\mathrm{i,t}}}{\sigma_{l}}}\right)^{\frac{\sigma_{l}^{HSCAT}}{\sigma_{sol}^{SOL}}}\right)^{\sigma_{n}^{SOL}-1}} \tag{4.39}$$

where

$s_{NLM,i,(hscat,sol),t}$	... Market share of technology *i* in building *b* in *t* based on the nested logit model, belonging to heating system category *hscat* combined with solar thermal system *sol*
SOL	... Set of heating system categories located in solar thermal nest *n*
$HSCAT_n$	... Set of heating systems located in $HSCAT_n$
I_k	... Set of technologies that belong to the same nest than technology *i*
$\sigma^{SOL}, \sigma^{HSCAT}$	... Indicator for similarity of options within a nest (indicator for direct substitutes), defined by the weighted standard deviation of the decision parameter (penalty function)
$\gamma = -\beta \cdot \mu$	

The similarity indicator for different options within a nest is defined by the market-share-weighted relative standard deviation of their penalty functions defined in (4.40) and using (4.41).

$$\sigma_{nest.R,b,t}{}^{2} = \sum_{i=1}^{I_{nest.R}}\left(s_{b,\mathrm{i},t}\cdot\left(\mu_{b,\mathrm{i},t}-\mu_{mean,R,b,t}\right)^{2}\right)/\left(\mu_{mean,R,b,t}\sum_{i=1}^{I_{nest.R}} s_{b,i,t}\right) \tag{4.40}$$

$$\mu_{mean,R,b,t} = \sum_{i=1}^{I_{nest.R}}\left(s_{b,\mathrm{i},t}\mu_{b,\mathrm{i},t}\right) \tag{4.41}$$

where

$\sigma_{nest,R,b,t}$	... Market share weighted standard deviation of penalty functions of options in nest *R*
$s_{b,i,t}$	... Market share of technology *i* in building *b* in time period *t*

Possible other discrete choice models

Even though the nested logit model is not restricted by the IIA, it still faces two limitations: it cannot deal with random taste variations—not all decisions makers have the same preferences (Hausman and Wise, 1978)—and it cannot be used if unobserved variables correlated over time for each decision-maker. Probit models can handle these limitations;

however they demand unobserved variables to be normally distributed. In contrast to lognormal distributions, which are the basis for logit and GEV models, the standard normal distribution is symmetric and has densities larger than zero on both sides of the ordinate. This implies for price correlations that some decision-makers prefer higher prices. This might be true in some cases, e.g. as more expensive technologies are often associated with better quality or more desirable features. Yet, this line of argumentation might not hold for energy prices. It is difficult to advocate that a significant share of a population has a positive preference for higher energy prices. Mixed logit models finally are able to cope with all mentioned limitations. In order to incorporate random taste variations, mixed logit models enhance the probability function for each alternative defined in logit models using (4.42) by introducing a density function for the decision coefficients $f(\lambda)$ as shown by equation (4.43).

$$s_{b,t,i} = \frac{e^{\lambda\mu_{b,i,t}}}{\sum_{j=1}^{N} e^{\lambda\mu_{b,j,t}}} \tag{4.42}$$

where

$s_{b,t,i}$ ... Probality of technology i in period t and building b

$\lambda\mu$ ... Density function for the decision coefficients μ

Thus, the probability function is defined by the integral over all possible decision-makers.

$$s_{b,t,i} = \int \left(\frac{e^{\lambda\mu_{b,i,t}}}{\sum_{j=1}^{N} e^{\lambda\mu_{b,j,t}}} \right) f(\lambda) d\lambda \tag{4.43}$$

Mixed logit models constitute a proper technique for implementing individual decision preferences[61]. Yet, based on the research briefly outlined in chapter 4.6, the author concludes that the empirical evidence is not sufficient to profoundly calibrate such a model extension.

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[61] Which is the case if the scaled variance λ depends on preferences of individual investors or the maturity (level of market penetration) of technology *i*.

4.7.3 Limitation of ultimate market shares based on non-tradable restrictions

Non-tradable restrictions are considered to be restriction which are associated with the location of the building and are independent from the actual users, decision-makers as well as the type of building. By estimating the ultimate market potential for each energy carrier in each sub region (*"energy carrier region",* e.g. urban, rural), non-tradable restrictions are taken into account. Such barriers are restrictions on the use of biomass and coal based heating systems in highly populated areas for reasons of transportation logistics and air emissions, the limited availability of grid-bounded energy carriers such as natural gas and district heat in specific areas or the installation of ground source heat pumps with shallow horizontal heat exchangers in urban regions. In the case of solar thermal systems, not only the share of suitable buildings is restricted (Novak et al., 2000) but also the maximum collector area per building is limited on the level of individual buildings. Currently it is defined that not more than 40% of the horizontally projected roof area of buildings can be used.

The limitation of the market penetration is implemented in the decision algorithm as follows. First it starts with the premise that the buildings, which define the building segment b, are, with respect to their region-specific properties, a randomly chosen, statistically independent subset of all buildings B_{ecr} located in a region ecr. Furthermore it is considered that the share of buildings $s_{measure,t} \cdot b$ which apply specific measures are again a randomly chosen, independent subset of b. Based on these assumptions, a restricted energy carrier ec is only available for a subset of $s_{measure,t} \cdot b$, unless the building segment b uses already this energy carrier. If the ultimate market penetration level of ec in a region ecr is limited to $S_{max,ec,ecr}$, then the share to which the energy carrier is available to $s_{measure,t} \cdot b$ can be defined by equation (4.44).

$$S_{adapt,\mathrm{max,ec},b,t} = \begin{Bmatrix} \dfrac{S_{\mathrm{max,ec,ecr}} - S_{ecr,ec,t-1}}{1 - S_{ecr,ec,t-1}} & b_{ec} \neq ec \\ 1 & b_{ec} = ec \end{Bmatrix} \tag{4.44}$$

where

$b \in B$ ... Building segment b

$b_{ec} = ec$ ... The building segment currently uses the energy carrier ec

$b_{ecr} = ecr$ ... The building segment is located in the energy carrier region ecr

$s_{\max,ec,ecr}$ ... Ultimate market share of energy carrier ec in energy carrier region ecr

$s_{ecr,ec,t\text{-}1}$ ... Market share of energy carrier ec in previous period t -1 based on on the building set $B_{ecr} \in B \mid b_{ecr} = ecr$

$s_{adapt,\max,ec,b,t}$ ... Adapted ultimate market share of energy carrier ec in building segment b in t

$0 \le s_{adapt,\max,ec,b,t} \le 1$

This implies that in those buildings where a different energy carrier than *ec* is used, the ultimate market share of *ec* is reduced, considering the previous market share of this *ec*. If the energy carrier *ec* is already applied in the building segment *b*, the ultimate market share is set to 1 and the whole set $s_{measure,t}$ *b* is allowed to reinstall the energy carrier again.

The upper market penetration level of a technology *i* is defined by the upper market penetration level of the energy carriers deployed by that technology (e.g. combination of main energy carrier with solar thermal collectors).

$$s_{adapt,\max,i,b,t} = \prod_{ec}^{EC_i} s_{adapt,\max,ec,b,t} \tag{4.45}$$

where

$s_{adapt,\max,i,b,t}$ ... Upper market share of technology i in building segment b in t

EC_i ... Set of energy carries used by technology i

$s_{adapt,\max,ec,b,t}$ ... Adapted ultimate market share of energy carrier ec in building segment b in t

Considering the ultimate market share for technologies, the market share, based on the NLM, for each technology *i* in building *b* and time period *t* is described in equation (4.46). The chosen approach only considers the first order combinations of the availability of energy carriers $s_{adapt,b,t,first.order}$ and not higher orders. Therefore the sum of first-order market shares is below 1. In a subsequent step, a normalization of the shares is performed[62], and the market share, adapted by the upper market penetration level, $s_{adapt,b,i,t}$ for technology *i* in building segment *b* at *t* is calculated (see Figure A.1 and A.2).

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[62] This procedure constitutes a simplification and does not correctly consider the ultimate market share of technologies, especially when the logit-model assigns very high market share to a highly restricted technology options. However, the approach massively reduces the calculation demand, as otherwise the calculation of the market shares of heating systems (which is responsible for about 50% of the calculation time) would need to be calculated $n_i!$, where n_i denote the number of available technology options, assuming statistically independently distributed restriction. If it becomes evident from the results that the ultimate market share variable cannot appropriately restrict a technology, then the building stock can be divided in two different region types (“energy carrier region”); one region in which the technology is allowed and a second region where it is prohibited.

$$s_{adapt,b,i,t,first.order} = s_{NLM,b,i,t} \cdot S_{adapt,\max,b,i,t} + \\ + s_{NLM,b,i,t} \cdot S_{adapt,\max,b,i,t}^{2} \sum_{k=1}^{K \in I: k \neq i} \left(\frac{\left(1 - S_{adapt,\max,b,k,t}\right) \cdot s_{NLM,b,k,t}}{\sum_{r=1}^{R \in I, r \neq k} S_{adapt,\max,b,r,t} \cdot s_{NLM,b,r,t}} \right) \tag{4.46}$$

$$s_{adapt,b,i,t} = \frac{s_{adapt,b,i,t,first.order}}{\sum_{j}^{I} s_{adapt,b,j,t,first.order}}$$

where

I ... Set of available options (technologies)

K ... Set of available options (technologies), $K \in I$: excluding i

R ... Set of available options (technologies), $R \in I$: excluding r

$s_{adapt,\mathrm{b,i},t}$ ... Market share of technology i in building segment b (at t) based on nested logit model considering the ultimate market for technology i in building segment b

$s_{\mathrm{NLM,b,i},t}$ ... Market share according to nested logit model

4.7.4 Market diffusion of technologies

The next enhancement of the decision process targets the change rate in market shares of technologies. Based on historical data, it is observed that in many cases the diffusion process of technologies shows specific patterns which can be described by market diffusion models. Such a well-known and widely applied model is the logistic diffusion process (Sultan et al., 1990; Grübler and Nakicenovic, 1991). According to the logistic diffusion model, the diffusion follows an S-shaped curve. This curve is described by three parameters: the (1) ultimate market potential S_{max}, the (2) midpoint (inflection point) of the growth trajectory t_m and a (3) parameter ΔT, the characteristic diffusion time, which defines the time span a technology needs to gain a market share of 90%, once it holds a market share of 10%.

$$s_{LDM,t,i} = \frac{S_{\max,i}}{1 + e^{-\ln(81)\frac{(t-t_m)}{\Delta T}}} \tag{4.47}$$

where

$s_{LDM,t}$ ... Share derived by logistic diffusion model in t

$S_{\max}$ ... Ultimate upper market limit

t_m ... Mid point, time where $S_{\max} / 2$ is reached

The big advantage of the model is its simplicity, as only three parameter needs to be estimated. The drawback of the model is that it completely predefines the diffusion process based on its parameters and that it is symmetric curve. To avoid this behavior, the diffusion process, as implemented in the Invert/EE-Lab model, only defines a valid corridor for the rate of change of market shares s for alternatives *i* in buildings segments *b*. Based on a logistic diffusion process, the limits for the change rate is defined by the previous share of an alternative *i* and its characteristic diffusion time.

Yet in opposite to the upper market penetration level, described above, the trajectories of the diffusion process define growth and decline rates on a top-level. Individual building segments are not restricted, as long as the total set of buildings remains within the corridor. Therefore in a first step, the average market share for a technology *i* has to be derived. This is done for three different types of building sets. The first set contains all buildings which belong to the same building category and energy carrier region (e.g. offices in urban areas). The second and third sets consist of all buildings which belong either to the same building category (e.g. offices) or same energy carrier region (urban areas). This is done to account for the fact that the penalty function of a specific technology *i* is compared to the average penalty and thus the previous market shares varies for different types of buildings (e.g. large versus small buildings) and regions (e.g. urban versus rural regions).

$$\begin{aligned} &B_{bca,ecr} \in \{B_{bca} \cup B_{ecr}\} \\ &B_{bca} \in \{b \in B \mid b_{bca} = bca\} \\ &B_{ecr} \in \{b \in B \mid b_{ecr} = ecr\} \end{aligned} \tag{4.48}$$

For these set of buildings the average market share is derived by equation(s) (4.49).

$$\begin{aligned} &s_{adapt,mean,\mathrm{b}ca.ecr,b,i,t} = \sum_{b=1}^{B_{bca,ecr}} s_{adapt,\mathrm{i},b,t} / n_{B_{bca,ecr}} \\ &s_{adapt,mean.bca,b,i,t} = \sum_{b=1}^{B_{bca}} s_{adapt\,\mathrm{i},b,t} / n_{B_{bca}} \\ &s_{adapt,mean.\mathrm{ecr,b},i,t} = \sum_{b=1}^{B_{ecr}} s_{adapt\,\mathrm{i},b,t} / n_{B_{ecr}} \end{aligned} \tag{4.49}$$

where

$s_{adapt,mean,bca.ecr,b,i,t}$ ... Average adapted market share for technology *i* of buildings within the Set $B_{bca,ecr}$ at time period *t*

$B_{bca,ecr}$ ... Set of buildings belonging to building category *bca*, located in *ecr*

$\mathrm{n}_{\mathrm{B}_{bca,ecr}}$ ... Number of buildings in set $B_{bca,ecr}$

The average market shares in previous simulation periods are used to estimate the current position on the logistic-diffusion curve (S-curve). For the upper diffusion corridor it is assumed that a high market share of the specific technologies *i* in similar buildings B_{bca} in different regions or different building types B_{ecr} in the same region support a higher market share.

$$s_{adapt,mean,b,i,t,\mathrm{inc}} = \sum_{n=1}^{t} \begin{pmatrix} s_{adapt,mean,bca.ecr,b,i,t-n} \cdot \left(1 - f_{bca} - f_{ecr}\right) + \\ + s_{adapt,mean,bca,b,i,t-n} \cdot f_{bca} + s_{adapt,mean,ecr,b,\mathrm{i},t-n} \cdot f_{ecr} \end{pmatrix}^{-n\cdot\delta} \tag{4.50}$$

where

f_{bca} ... Weighting factor building category only

f_{ecr} ... Weighting factor energy carrier region only

δ ... Decay rate of the exponential damping function

$f_{bca} + f_{ecr} < 1$

The following values are currently used:

$$f_{bca} = 0.2$$
$$f_{ecr} = 0.2$$
$$\delta = 0.4$$

This consideration is asymmetrical, as it does not mean that the market diffusion holds back if in other building types or regions the diffusion is slower than in the specific building segment.

$$s_{decision,b,\mathrm{i},t,inc} = \max \left\{ \begin{matrix} s_{adapt,mean,b,i,t,\mathrm{inc}} \\ \sum_{n=1}^{t} \left(s_{adapt,mean,bca.ecr,b,i,t-n,inc}\right)^{-n\cdot\delta} \end{matrix} \right\} \tag{4.51}$$

The estimated distance in time-units (years) in t to the mid point $t_{m,inc}$ of the rising trajectory is calculated based on market shares of previous simulation periods.

$$\left(t - t_{m,inc}\right) = n_{sim.step\ width} - \ln\left(\frac{S_{\max,i}}{S_{decision,b,i,t,inc}} - 1\right) \cdot \frac{2\varDelta T_{inc,i}}{2\ln(81)} \tag{4.52}$$

where

$S_{\max,i}$ ... Ultimate market share for technology *i*

$S_{decision,b,t,i,inc}$ ... Market share used for the inclining process at time t and technology *i*, based on the average market share of the set *B* of buildings ($b \in B$) in previous simulation periods

$\varDelta T_{inc,i}$ ... Characteristic diffusion time (10%-90%) for technology i of the inclining process [yr]

$n_{sim.step\ with}$ ... Simulation step width [yr]

Then the upper growth rate defined by this process for an alternative *i* in period *t* is given by

$$S_{\max,t,i} = \max\left(S_{\min}, \frac{S_{\max,i}}{1 + e^{\frac{-2\ln(81)}{2\varDelta T_{inc,i}}\cdot\left(t - t_{m,inc}\right)}}\right) \tag{4.53}$$

where

$S_{\mathrm{max,t,i}}$ ... Upper boundary of market share defined by the diffusion model for technology i at time t

$S_{\min}$ ... Lowest market share allways being allowed, currently used: $S_{\min} = 0.03$

S_{min} defines the lowest market share, which is allowed in any case and is needed by the model to start the diffusion process for new alternatives not holding shares in previous periods.

The lower boundary for the market share of an alternative i is defined in a similar way. Based on the estimated distance in time-units in t to the mid point $t_{m,dec}$

$$s_{decision,b,\mathrm{i},t,dec} = \sum_{n=1}^{t} \left(s_{mean,t-n,b,i,bca,ecr} \right)^{-n\cdot\delta} \tag{4.54}$$

$$\left(t - t_{m,dec}\right) = n_{sim.step\ width} - \ln\left(\frac{S_{\max,i}}{S_{decision,b,t,i,\mathrm{dec}}} - 1 \right) \cdot \frac{2\varDelta T_{dec,i}}{2\ln(81)} \tag{4.55}$$

where

$S_{decision,b,t,i,dec}$ ... Market share used for the declining process at time t and technology i, based on the average market share of the set B of buildings ($b \in B$) in previous simulation periods

$\varDelta T_{dec,i}$ ... Characteristic diffusion time (10%-90%) for technology i of the declining process [yr] Currently: $\varDelta T_{dec,i} = \varDelta T_{inc,i} / 3$ is used

the lowest share defined by the decreasing trajectory is calculates to

$$S_{\min,t,i} = S_{\max,i} \left(1 - \frac{1}{1 + e^{\frac{-2\ln(81)}{2\varDelta T_{dec,i}} \cdot \left(t - t_{m,dec}\right)}} \right) \tag{4.56}$$

$$\text{if } \left\{ S_{\min,t,i} < S_{\min} \mid S_{\min,t,i} = 0 \right\}$$

To adjust the market share based on the nested logit model (equation (4.46)) for the diffusion process described by the diffusion corridor (equations (4.53) and (4.56)), a correction factor f_{corrLD} is defined in equation (4.57).

$$f_{corrLDM,b,t,i} = \left\{ \begin{array}{ll} \min\left(f_{\max}, \dfrac{S_{\max,t,i}}{s_{adapt,mean,bca.ecr,b,i,t}} \right) & s_{adapt,mean,bca.ecr,b,i,t} > S_{\max,t,i} \\ \max\left(\dfrac{1}{f_{\max}}, \dfrac{s_{adapt,mean,bca.ecr,b,i,t}}{S_{\min,t,i}} \right) & s_{adapt,mean,bca.ecr,b,i,t} < S_{\min,t,i} \\ 1 & S_{\min,t,i} < s_{adapt,mean,bca.ecr,b,i,t} < S_{\max,t,i} \end{array} \right\} \tag{4.57}$$

where

$f_{\max}$ ... upper scaling limit, $f_{\max} > 1$

$s_{adapt,mean,bca.ecr,b,i,t}$ ... Average market share of technology i in region ecr and building category bca, adapted by upper market penetration limit

$f_{corrLDM,b,t,i}$ ... Correction factor accounting for trajectories defined by the logistic diffusion process

Finally, the shares are scaled again to account for the changed sum of market shares[63].

$$s_{b,\mathrm{i},t} = \frac{f_{corrLD,b,i,t} \cdot s_{adaptNLM,b,\mathrm{i},t}}{\sum_{r=1}^{I} f_{corrLD,t,r} \cdot s_{adaptNLM,b,r,t}} \tag{4.58}$$

where

$s_{b,i,t}$ ... Market share of technology i in building b at time t considering restrictions

$s_{adaptNLM,b,\mathrm{i},t}$ ... Market share of technology i in building b at time t not considering logistic diffusion model

By applying this procedure, shares reduced to meet the diffusion corridor are eventually scaled up again in this step and vice versa. This allows technologies to grow significantly faster than described by the diffusion model, if the logit model assigns them very high shares.

This behavior is shown in Figure 4.19 in the case of a simple two alternatives example, and different levels of upper market share in period $S_{max,t,i}$ as a result of the diffusion model for alternative i.

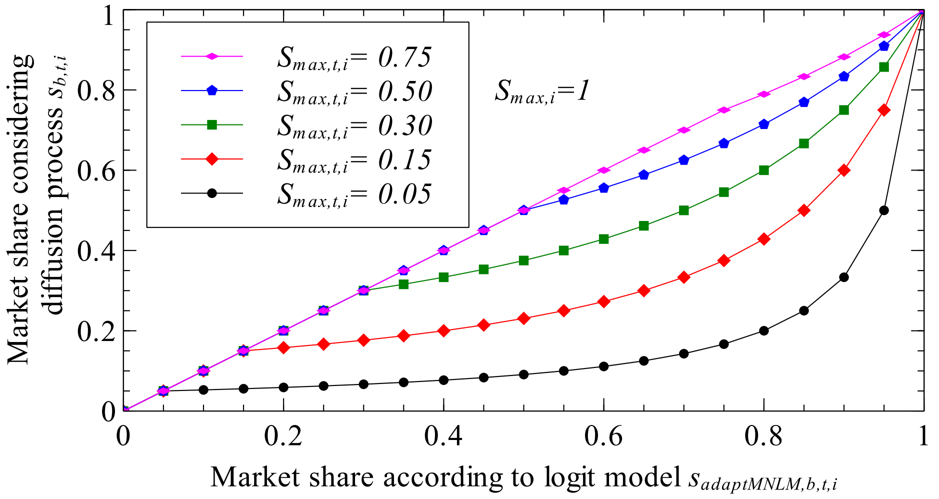

Figure 4.19. Market share $s_{b,t,i}$ of technology i against alternatives for different levels of upper market shares $S_{max,t,i}$ in t based on to the diffusion model.

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[63] Again, this procedure constitutes a simplification.

4.7.5 Limitation of the market share of technologies based on tradable restrictions

Tradable restrictions for the use of energy carriers are considered by applying cost-resource-potential-curves (CRPC). It is assumed that the market sets one single clearing price for each energy carrier. Therefore, new consumers of an energy carrier pay the same energy price as the existing consumers.

4.7.6 Calculating the weighted average penalty of all technology options per building segments

Based on the equations depicted above, the mean penalty function (4.35), used as reference technology (4.34) for each building segment and measure (changing heating system, domestic hot water system or part of the building envelopment), can be calculated from (4.58). Since the actual result of the process—the market shares of technologies—is needed as input for the calculation, this decision process runs in an iterative loop until the discrepancy between the mean values at the beginning and end of the calculation procedure is sufficiently small.

4.8 The decision algorithm for renovation activities

The market shares of different renovation measures are derived in a similar, but more simplified way. A two-level nested logit model is used. On the top level the decision of whether to perform a thermal renovation or to apply the non-thermal maintenance is taken. The penalty function for the thermal-renovation nest derives from the market-share-weighted penalties of the individual thermal renovation options. On the second level, the decision about the actual thermal renovation packages is taken. Neither diffusion restrictions with respect to the upper market penetration level nor the diffusion progress for emerging technologies are considered.

Furthermore, the decisions on the renovation packages are (currently) taken independently from the subsequently performed decision on the heating systems. Therefore, renovation measures are chosen based on the existing heating system, the current heating costs and the net renovation costs (levelized investment costs minus energy cost savings), while the decision on a heating system already considers the previously taken renovation measures.

Currently, each building segment can choose in each simulation step from a set of three different thermal renovation options plus the non-thermal maintenance option.

4.9 Decision tree structure and the calculation precision parameter $f_{min\ share}$

Throughout the simulation period, decisions anticipated by the model can be structured in a decision tree. For each building class and building segment, the share that undergoes some specific measures defines a new branch.

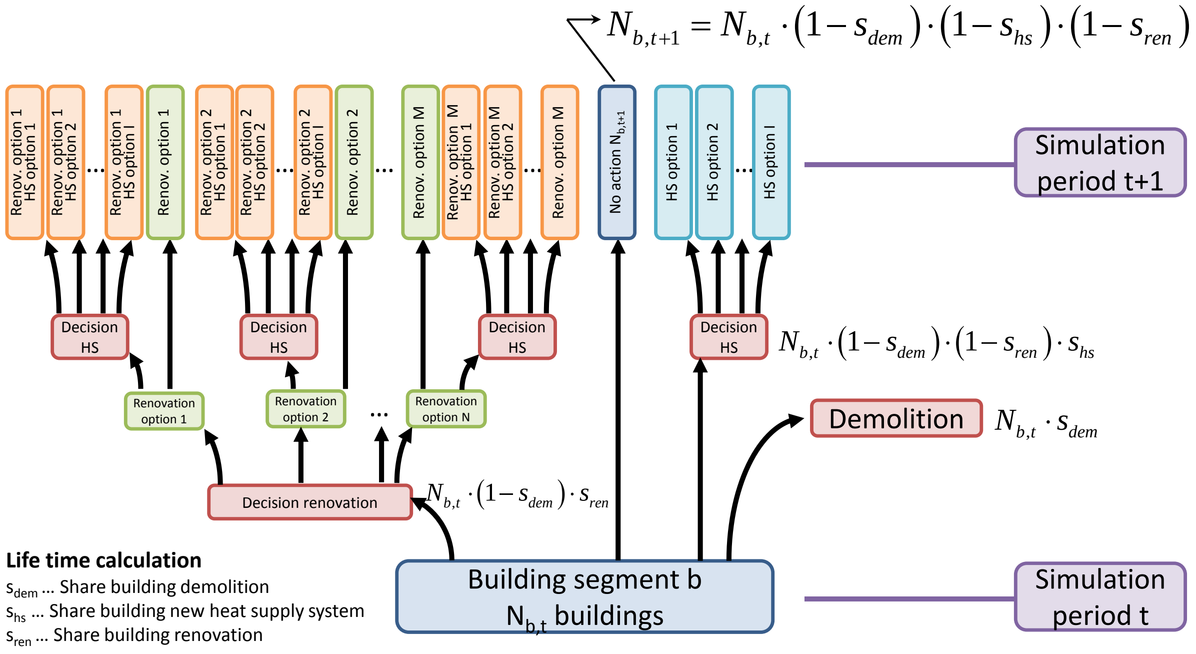

Figure 4.20 – Decision tree structure of the Invert/EE-Lab model.

Without any restrictions, the number of building classes and building segments would increase exponentially (see equation 4.59 and 4.60 for the case that no failure-free lifetime is considered). Given the large number of available options and their combinations, such a process would exceed the computing capacity of most computers within a few simulation periods.

$$n_{BC,t} = n_{BC,t-1} \cdot \left(1 + n_{renov\ options}\right) + n_{BCA} \cdot n_{CR} \cdot n_{new\ build\ options} \tag{4.59}$$

$$
\begin{aligned}
n_{BS,t} = n_{BS,t-1} \left(\begin{array}{l} 1 + n_{new\ hs\ options} + \\ + n_{renov\ options} \cdot \left(1 + n_{new\ hs\ options}\right) \end{array} \right) + & \quad \text{... Refurbished buildings} \qquad (4.60) \\
+ n_{BCA} \cdot (n_{CR} \cup n_{ECR}) \cdot n_{new\ build\ options} \cdot n_{new\ hs\ options} & \quad \text{... Newly constructed buildings}
\end{aligned}
$$

where

n_{BCA} ... Number of building categories

$n_{CR} \cup n_{ECR}$ ... Number of different regions

$n_{renov\ options}$ ... Number of available renovation options

$n_{new\ hs\ options}$ ... Number of available options for heat supply systems (and their combinations)

$n_{new\ build\ options}$ ... Number of available building shell options of new buildings

In order to control the number of additional building segments generated in each simulation period, new segments are only created if the heated floor areas of buildings that would belong to these segments exceed a predefined minimal share of the total heated floor area (see also Table A.1).

$$
n_{\min,BCA} = \frac{f_{\min\ share}}{10^6} \cdot \frac{A_{gfa,total} + 2 \cdot A_{gfa,BCA}}{3} \quad \forall BCA \qquad (4.61)
$$

where

$n_{min,BCA}$ ... Minmal number of buildings that must be exceeded to be split into different types

$n_{b,BCA}$ ... Number of buildings that belong to a specific building category BCA

$A_{gfa,total}$ ... Heated gross floor area of the total building stock

$A_{gfa,BCA}$ ... Heated gross floor area of buildings that belong to a specific building category BCA

$f_{\min\ share}$ ... Parameter defining the calculation precision (typically $1-10$)

Besides the defined parameter $f_{\min\ share}$ which is used to define the calculation precision of the deterministic part of the algorithm, the heated gross floor area that a segment must exceed in order to be newly created depends not only on the total gross floor area of the building stock but also on the gross floor area of buildings which belong to the same building category. This approach represents a compromise between the deterministic calculation precision for the total building stock and that for each building category, and it serves both requests at low computation costs.

Neglecting technology options which get a low share would mean that the model underestimates the potential market share of such alternatives. In this case, the final results would not be an unbiased approximation of the model core algorithm and results would shift with decreasing calculation precision. To avoid this, in each decision situation a stochastic algorithm randomly depicts an alternative out of all alternatives that do not meet the minimum floor space threshold.

Three decision situations are distinguished, in which a share of buildings does not meet the threshold limit and the minimum floor space threshold applies:

1. The share that undergoes measures does not meet the threshold
2. The share that does not apply any measures does not meet the threshold
3. The average of both does not meet the threshold

If the third case applies, the segment is not allowed to be split again. This means that the whole segment will perform a certain measure or none of it will. The segment switches if the share that is supposed to perform a measure exceeds a uniformly distributed random number $u_{b,x}$.

$$s_{measure,b} = \left\{ \begin{array}{ll} 1 & s_{measure,b} \geq u_{b,x} \\ 0 & s_{measure,b} < u_{b,x} \end{array} \right\} \quad \forall b \; where \; n_b \leq n_{\min,BCA}, b \in BCA \quad \forall BCA$$

where (4.62)

$u_{b,x}$ ... Uniformly distributed random number

If the first or second case applies, then at least $n_{min,BCA}$ buildings must change or remain unchanged.

$$s_{measure,b,t} = \left\{ \begin{array}{ll} \dfrac{n_{\min,BCA}}{n_b} & \dfrac{s_{measure,b,t} \cdot n_b}{2 \cdot n_{\min,BCA}} \geq u_{b,x} \\ 0 & \dfrac{s_{measure,b,t} \cdot n_b}{2 \cdot n_{\min,BCA}} < u_{b,x} \end{array} \right\} \quad \forall b \; where \; s_{measure,b,t} \cdot n_b \leq 2 \cdot n_{\min,BCA}, b \in BCA \qquad (4.63)$$

$$s_{measure,b,t} = \left\{ \begin{array}{ll} 1 - \dfrac{n_{\min,BCA}}{n_b} & \dfrac{1 - s_{measure,b,t} \cdot n_b}{2 \cdot n_{\min,BCA}} \geq u_{b,x} \\ 1 & \dfrac{1 - s_{measure,b,t} \cdot n_b}{2 \cdot n_{\min,BCA}} < u_{b,x} \end{array} \right\} \quad \begin{array}{c} \forall b \; where \, 1 - s_{measure,b,t} \cdot n_b \leq 2 \cdot n_{\min,BCA}, \\ b \in BCA \end{array} \qquad (4.64)$$

The random number $u_{b,x}$ is persistent to the building segment once it has been created. This ensures that the share at which a segment switches is randomly distributed for all building segments and does not change over time. This is a necessary precondition to guarantee that the results are independent from the number of draws and the chosen time step of the simulation.[64]

Besides defining the share that performs measures, also the number of chosen alternatives by the logit model is restricted in a similar way. For each segment, the relative shares of all alternatives that do not meet the minimum floor space threshold are used to define a distribution function for those options. Again a stochastic process depicts randomly an alternative for each segment which then gets the share $s_{b,t,small}$, which is the sum of all alternative not meeting the threshold within its own segment. The probability that a technology i that does not meet the threshold criteria gets chosen is defined by $s_{b,t,i} / s_{b,t,small}$.

$$s_{b,t,small} = \sum_{i=1}^{I} \left\{ \begin{matrix} s_{b,t,i} & \forall n_b \cdot s_{b,t,i} \leq n_{\min,BCA} \\ 0 & \forall n_b \cdot s_{b,t,i} > n_{\min,BCA} \end{matrix} \right\} \tag{4.65}$$

The algorithm described above ensures that model results are independent from the chosen calculation precision and simulation step. However, the model outcome is co-determined by a stochastic process. As a result, the model outcomes are not deterministic anymore; multiple model runs are required to define expectation value and variance of the results with respect to the stochastic model algorithm.

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[64] These random numbers are not draw in each simulation step, since this would bias the result depending on the number of drawings (and thus in dependence of the simulation step width and calculation precision parameter). To avoid such a behavior, three random number per building segment are draw which are then used for (1) demolition, (2) replacement of the heating system and (3) domestic hot water system (if a stand-alone technology is used) and one random number per building class (renovation). These numbers remain persistent until a corresponding measure is performed.

5 Uncertainties and sensitivities related to the model implementation

The calibration of the parameters used for the decision algorithm described above (nested logit model and diffusion restriction, see chapter 4) has significant impact on the stability of the model results. This section intends to analyze the impact of the most important input parameters on the stability of model results.

5.1 Uncertainties arising from the calculation precision parameter and the simulations step width

5.1.1 Calculation precision parameter $f_{min\ share}$

As described in section 4.9, without any restriction to the (deterministically derived) calculation precision, the computation demand would increase exponentially and would exceed available computation power within a few simulation periods. Thus, a control parameter $f_{min\ share}$ is introduced in the model which controls the share of decisions derived by the deterministic approach and thus the computation demand. The method implemented to cope with market shares below a certain threshold is based on a stochastic algorithm. This means that the model results are stochastic results as well and multiple model runs should be conducted to obtain meaningful results. From that a conflict arises: on the one hand, a reduced computation precision decreases the calculation needs per model run to some extent. On the other hand, it introduces additional uncertainties which lead to a higher number of model runs needed per scenario to obtain the similar low confidence interval of the model results. To get a first estimate of a rational level for the calculation precision parameter that keeps calculation time and uncertainties low, a series of model runs with different values of the calculation precision parameter $f_{min\ share}$ are performed, using the dataset of a baseline scenario for the Austrian built environment from 2009 until 2030.

A necessary precondition for the following analyses is that the statistical part of the results is “well” distributed. Therefore, it is tested whether model results coming from different runs using the same input data are distributed according to a normal distribution or not. This is done for the resulting energy demand per energy carrier after 22 simulation periods (2009-2030) using a $f_{min\ share} = 4$. The results are depicted in Figure 5.1 and suggest that this precondition is satisfied.

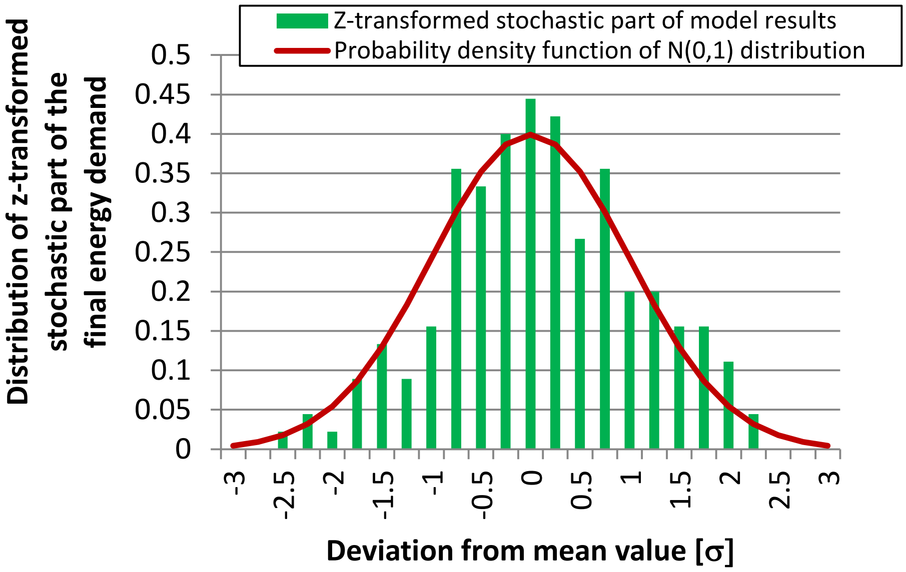

Figure 5.1 – Distribution of the for z-transformed stochastic part of model results (energy demand per energy carrier after 22 simulation periods, 12 simulation runs, 180 data points) compared to the probability density function of the standard normal distribution *N(0,1)*.

As estimators for the uncertainties arising from the stochastic algorithm two parameter ε_{EC} and $\varepsilon_{EC,\ BCA}$ were defined and their behavior analyzed. The parameter ε_{EC} is used as an estimator for the uncertainties of model results on a top level where only the total energy use per energy carrier is considered. In contrast, parameter $\varepsilon_{EC,\ BCA}$ is used to evaluate the uncertainties of results on a more detailed level and considers the energy use per energy carrier for each building category.

Based on the average energy use of an energy carrier *ec* after n_{simrun} simulation runs, calculate by

$$Q_{sys,Invert/EE-Lab,ec,f_{\min share},k} = \sum_{b}^{B_{ec}} Q_{sys,Invert/EE-Lab,f_{\min share},b,k}$$

$$\bar{Q}_{ec,f_{\min share}} = \sum_{k=1}^{n_{simrun}} \frac{Q_{sys,Invert/EE-Lab,ec,f_{\min share},k}}{n_{simrun}} \qquad (5.1)$$

where

$Q_{sys,Invert/EE-Lab,f_{min\,share},b.k}$ ... Energy use for heating and DHW per building b in simulation run k using a calculation precision parameter $f_{min\,share}$

$Q_{sys,Invert/EE-Lab,ec,f_{min\,share}}$ ... Total energy use of energy carrier ec for heating and DHW

B_{ec} ... Set of buldings deploying energy carrier ec for space heating $b \in B_{ec}$

n_{simrun} ... Number of performed simulation runs

$\bar{Q}_{ec,f_{min\,share}}$ ... Average total energy use of energy carrier ec for heating and DHW derived by using a calculation precision parameter $f_{min\,share}$

the relative standard deviations of the energy use for an energy carrier *ec* for n_{simrun} simulation runs can be calculated by

$$\sigma_{ec,f_{\min share}}{}^2 = \frac{1}{\bar{Q}_{ec,f_{\min share}}\left(n_{simrun}-1\right)} \sum_{k=1}^{n_{simrun}} \left(Q_{sys,Invert/EE-Lab,ec,f_{\min share},k} - \bar{Q}_{ec,f_{\min share}}\right)^2 \tag{5.2}$$

where

$\sigma_{ec,f_{min\,share}}$ ... Standard deviation of energy use for heating and DHW of energy carrier *ec*, based on n_{sim_run} simulation runs and a calculation precision parameter $f_{min\,share}$

The uncertainty parameter $\varepsilon_{EC,fminshare}$ is defined by the confidence interval calculated based on the total weighed sum of relative standard deviations for all energy carriers.

$$\varepsilon_{EC,f_{\min share}}{}^2 = \frac{1}{n_{ec}} \sum_{e=1}^{EC} \frac{\sigma_{ec,f_{\min share}}{}^2}{\bar{Q}_{ec,f_{\min share}}} \cdot t_{0.1,n_{simrun}-1}{}^2 \tag{5.3}$$

where

$t_{0.1,n_{simrun}-1}$ ... 5% quantile of the t-distribution

EC ... Set of available energy carriers

n_{ec} ... Number of energy carriers

The second uncertainty parameter $\varepsilon_{EC,BCA,fminshare}$ is defined the same way, yet considers the deviations of combination of energy carriers and building category.

$$\varepsilon_{EC,BCA,f_{\min share}}{}^2 = \sum_{bca=1}^{BCA} \sum_{ec=1}^{EC} \frac{\displaystyle\sum_{b=1}^{\forall \mathrm{B}_{\mathrm{ec,bca}} \in \mathrm{B}:\left\{\begin{matrix} b_{ec}=ec \\ b_{bca}=bca \end{matrix}\right\}} \sum_{k=1}^{n_{simrun}} \frac{\left(Q_{sys,Invert/EE-Lab,b,f_{\mathrm{minshare}},k} - \bar{Q}_{sys,\mathrm{ec,bca},f\,\mathrm{min}\,share}\right)^2}{\left(n_{simrun}-1\right)\bar{Q}_{sys,\mathrm{ec,bca},f\,\mathrm{min}\,share}{}^2}}{n_{BCA} \cdot n_{EC}} \cdot t_{0.1,n_{simrun}-1}{}^2 \tag{5.4}$$

where

$Q_{sys,ec,bca,f_{minshare},k}$ ... Energy use of energy carrier ec in building category bca and simulation run k, using a calculation precision parameter $f_{min\,share}$

$Q_{sys,ec,bca,f_{minshare},k}$ ... Average energy use of energy carrier ec in building category bca based on n_{simrun} simulation runs

B ... Set of all buildings

$B_{ec,bca}$ ... Set of all buildings which belong to building category bca and use the energy carrier ec

b_{ec} ... Energy carrier used in building b

b_{bca} ... Building category type of building b

BCA ... Set of available building categories

n_{bca} ... Number of building categories

The results of this analysis are drawn in Figure 5.2. An obvious outcome of this analysis is that the confidence interval describing the uncertainties related to the stochastic process increases with a higher degree of details. However the figure also reveals that for a specific level of uncertainties on a more disaggregated level, the computation time tends to decrease with an increasing calculation precision parameter f_{minshare}[65] and a higher number of simulation runs.

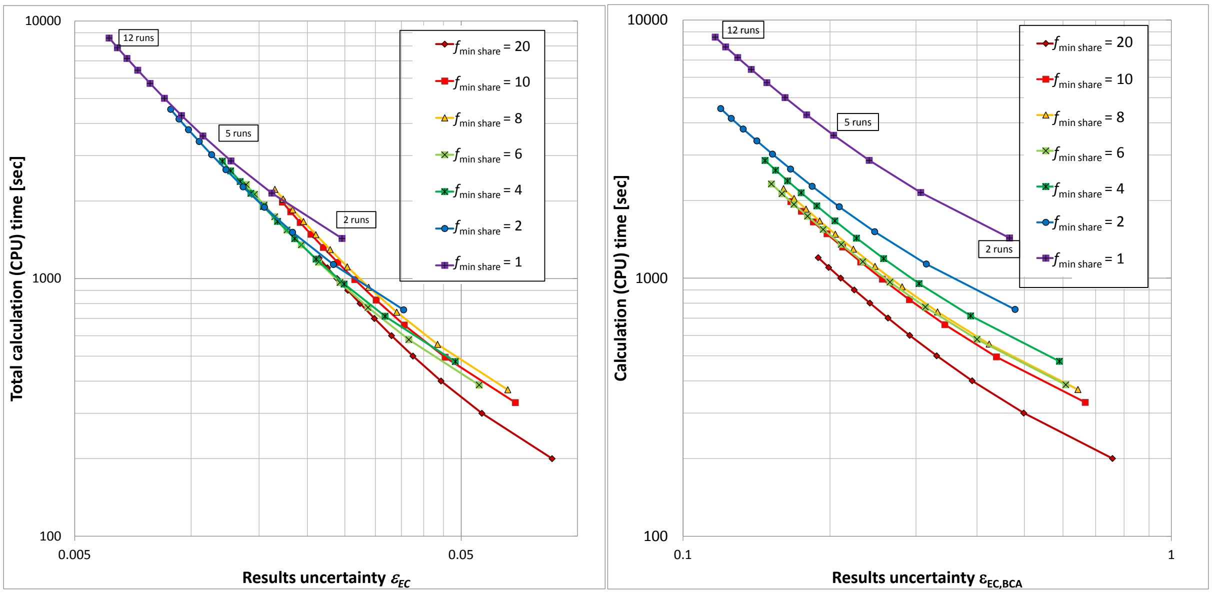

Figure 5.2 – Calculation time against the uncertainty indicator $\varepsilon_{EC,fminshare}$ (left graph) and $\varepsilon_{EC,BCA,fminshare}$ (right graph) of results as measured described above for the results after 22 simulation periods.

In a further test, the model behavior is analyzed to determine whether or not, and if, to which degree, the results vary with the calculation precision, indicating that the stochastic

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[65] As this parameter increases, the threshold for splitting segments increases and a higher number of decisions are based on the stochastic and not the deterministic algorithm.

algorithm introduces some systematic bias. To do so, the average results, based on 12 simulation runs, for a simulation using different values for the $f_{\text{min share}}$ parameter are compared with each other. The behavior of the resulting energy use per energy carrier is shown in Figure 5.3. It can be observed that there appears to be some systematic bias. Yet, when using a parameter $f_{\text{min share}}$ of 10 or less, the discrepancy for relevant energy carriers is in a range of 3% or less und thus negligible. Furthermore, it has to be noted that, when performing 12 simulation runs per scenario, results do not tend to stay within the 90%-confidence interval, spanned by runs with a different $f_{\text{min share}}$. This is to say that the confidence interval derived might underestimate the uncertainties associated with the implemented decision-making approach (with respect to changing input parameters)[66].

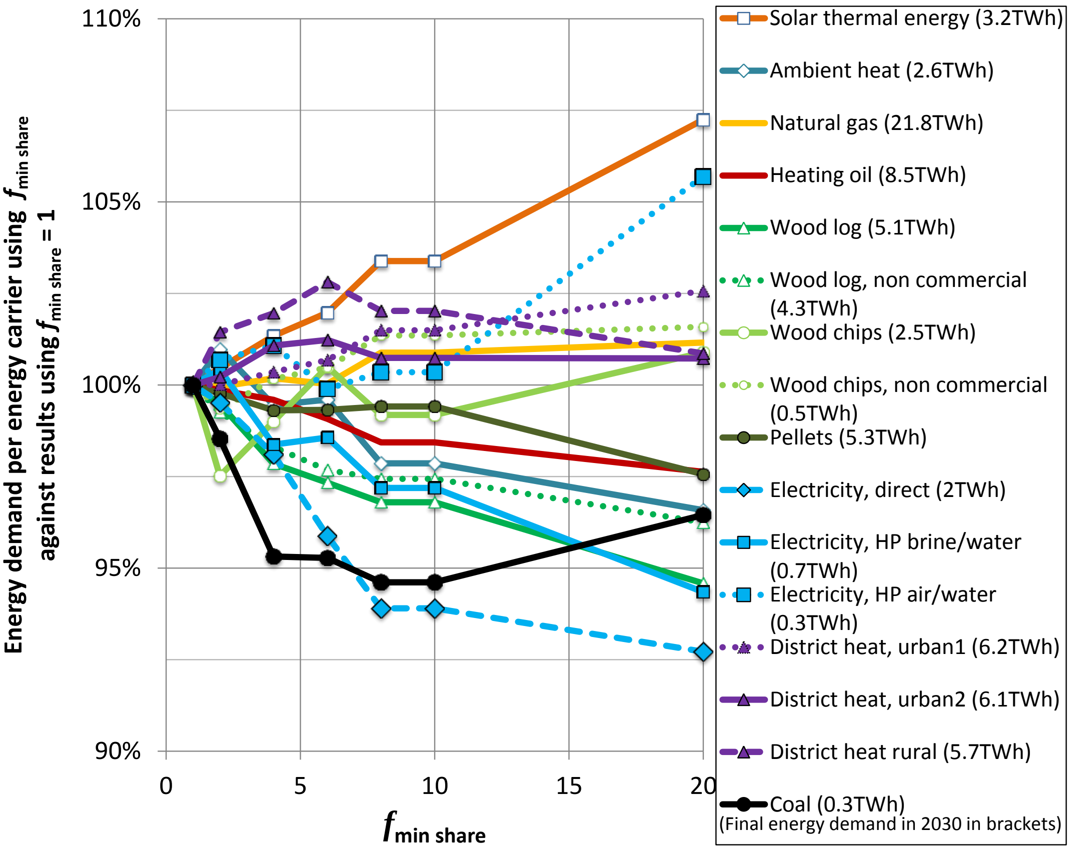

Figure 5.3 – Average energy consumption (after 22 simulation runs) per energy carrier against the results of simulation runs with $f_{\text{min share}} = 1$.

In Table 5.1 the results shown above are compared to a simpler, deterministic algorithm, which allows building measures only, if either the number of buildings exceeds $n_{\text{min,BCA}}$ or more than half of the buildings within a segment ($s_{\text{measure,b}} > 0.5$) perform such a

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[66] The standard deviation of the model results tend to be very small, thus the confidence interval is also very narrow (see Table 5.2 - Table 5.4).

measure. As can be seen from this table, the described deterministic algorithm fails to derive a similar high quality model behavior and the more comprehensive implemented stochastic approach is superior.

Table 5.1 – Comparison of results derived from the implemented stochastic algorithm against a simpler deterministic algorithm.

Energy carrier (final energy demand in 2030 in brackets)	**Energy consumption in 2030 using deterministic approach ($f_{\text{min share}} = 4$) compared to stochastic algorithm using $f_{\text{min share}} = 1$**
Solar thermal energy (3.2 TWh)	70%
Ambient heat (2.6 TWh)	65%
Natural gas (21.8 TWh)	96%
Heating oil (8.5 TWh)	118%
Coal (0.3 TWh)	167%
Wood log (5.1 TWh)	103%
Wood chips (2.5 TWh)	51%
Pellets (5.3 TWh)	59%
Electricity, direct (2 TWh)	147%
Electricity, HP brine/water (0.7 TWh)	53%
Electricity, HP air/water (0.3 TWh)	114%
District heat, urban2 (6.1 TWh)	103%
District heat rural (5.7 TWh)	104%
District heat, urban1 (6.2 TWh)	101%
Wood log, non-commercial (4.3 TWh)	92%
Wood chips, non-commercial (0.5 TWh)	46%

A similar analysis is performed for the variable: *number of buildings undergoing some sort of thermal renovation*. Again, the model results should not shift significantly, if the calculation precision parameter changes. In this case, the algorithm fully meets the requirement, as can be seen in Figure 4.4. In addition, the results of a simpler, deterministic algorithm are drawn (dashed lines), which again allows measures only if either the number of buildings exceeds $n_{min,BCA}$ or more than half of the buildings within a segment ($s_{measure,b} > 0.5$) perform such a measure. As can be seen, the behavior of the second algorithm strongly depends on the calculation precision parameter, with results eventually converging (close?) to the stochastic algorithm.

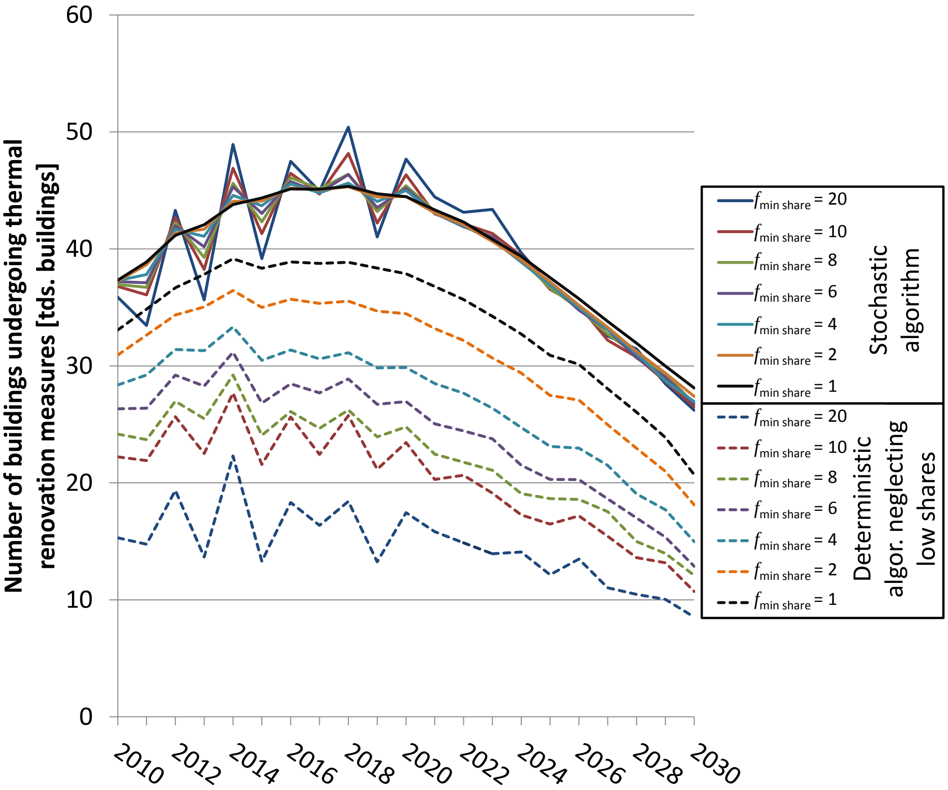

Figure 5.4 – Number of buildings performing thermal building renovation. Model results obtained using various calculation precision parameter $f_{\text{min share}}$. The solid lines represent the implemented stochastic model algorithm. The dashed lines show results using a deterministic algorithm in which measures are only performed, if the number of buildings exceeds $n_{min,BCA}$ or $s_{measure,b} > 0.5$.

5.1.2 Simulation step width $n_{sim.step\_width}$

A different way of decreasing the simulation time is to increase the simulation step width. This means that results are not calculated and obtained for each simulation year but for e.g. every second, third or fifth year only. To validate the results it needs to be shown that the systematic errors resulting from such a simplified calculation tend to be within a tolerable range. Again, the average energy consumption per energy carrier (with a market share of 1% (0.8 TWh) or more in 2030), using 12 simulation runs, is compared to the average energy consumption using $f_{\text{min share}} = 1$ and a simulation step width = 1 year (Figure 5.5).

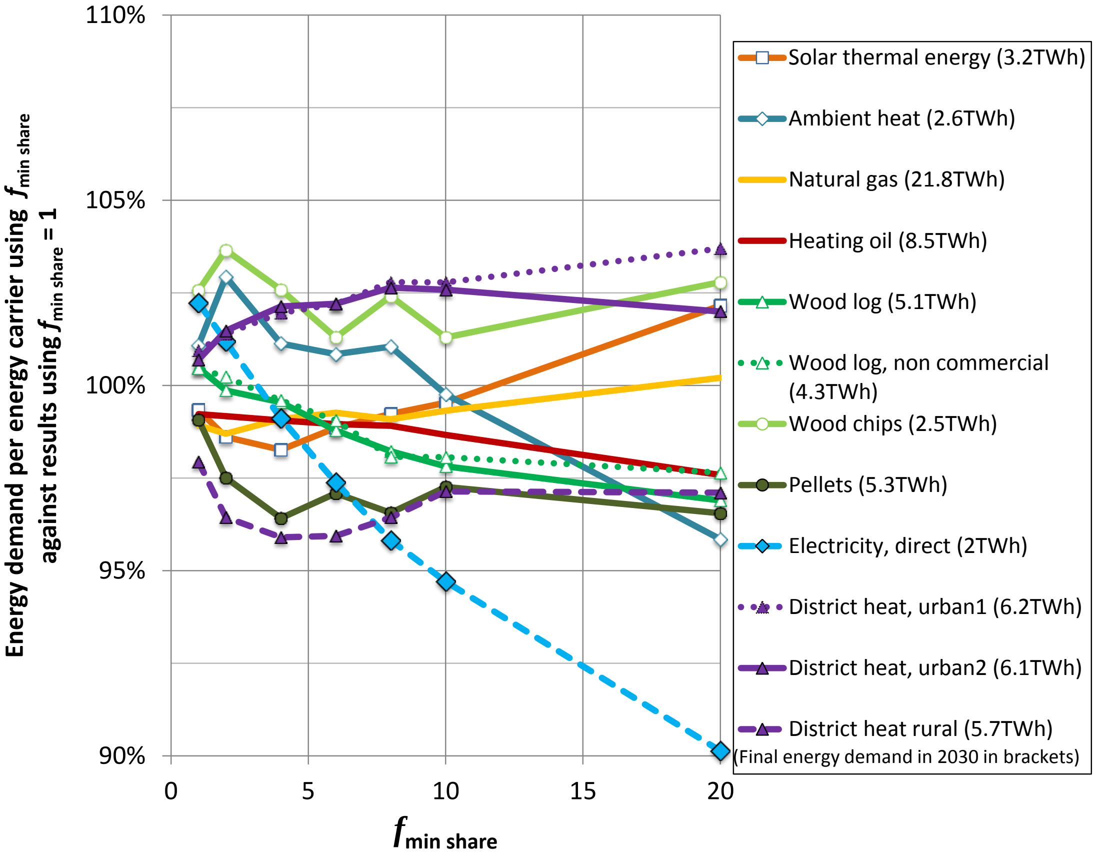

Figure 5.5 – Average energy consumption (after 22 simulation runs) per energy carrier using a simulation step width of 2 years against the results of simulation runs with $f_{\text{min share}} = 1$ and simulation step width = 1.

Results obtained from this analysis indicate that the model algorithm delivers data, which basically do not shift with an increasing $f_{\text{min share}}$. The systematic bias (for the scenario analyzed) compared to scenario runs using an annual step width are in the range of about 4% or lower, if an $f_{\text{min share}}$ of 10 or less is used. The comparison of the level of uncertainties against the simulation time reveals that using a simulation step width of 2 reduces the computation time by more than 50% compared to a simulation step width of 1 (see Figure 5.6).

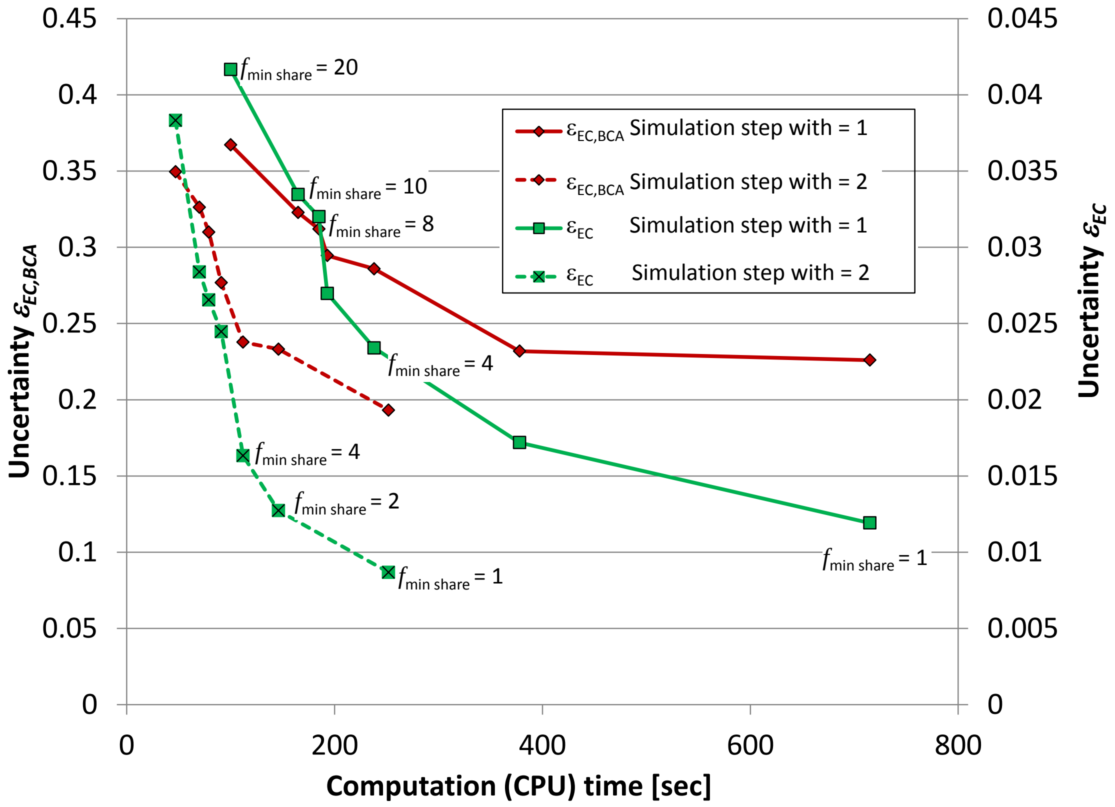

Figure 5.6 – Comparison of results uncertainties against simulation time using a simulation step width of 1 (solid lines) and a step width of 2 (dashed lines).

5.2 Uncertainties of results arising from non-observed model variables

5.2.1 The nested logit model

Scaled variance β of the decision algorithm

The β-value (scaled variance) of the logit model is responsible for the slope of the selectivity and therefore important to the outcome of the scenarios (see section 4.7). To test the sensitivity of the results on this (unobserved) value, the derivatives of the share of energy carriers with respect to the scaled variance β are calculated. An indicator $\varepsilon_{t,\beta}$ was defined which calculates the sum of squared derivatives for all energy carriers.

$$\varepsilon_{t,\beta} = \sqrt{\sum_{ec=1}^{EC}\left(\frac{\bar{Q}_{sys,ec,t,\beta+\Delta\beta/2} - \bar{Q}_{ec,sys,t,\beta-\Delta\beta/2}}{\Delta\beta}\right)^{2}} \tag{5.5}$$

where

$\varepsilon_{t,\beta}$	... Sensitivity of model results after t periods with respect to a small variation of $\Delta\beta$
$\bar{Q}_{ec,sys,t,\beta\pm\Delta\beta/2}$	... Average energy use of energy carrier ec derived using a scaled variance $\beta \pm \Delta\beta$ in simulation periods t
β	... Scaled variance of the decision parameter

Results derived for the Austrian base line scenario after 22 simulation periods (2008-2030), considering all restrictions, indicate a (local)[67] minimum of the $\varepsilon_{t,\lambda}$ parameter (for the Austrian built environment) for a β-value in the range of 8-10 (see Figure 5.7). For the scenarios calculated within this thesis, a $\beta_{hs} = \beta_{ren}$ of 8 is used.

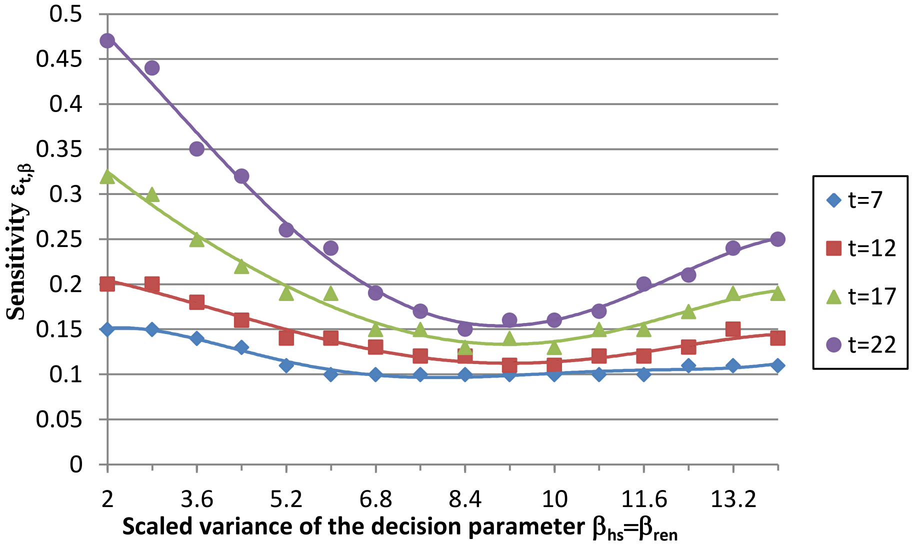

Figure 5.7 – Sensitivity $\varepsilon_{t,\beta}$ of the model results (share of energy carriers on the final energy demand) with respect to the scaled variance ($\beta_{hs}=\beta_{ren}$) of the decision parameter.

The following table compares the installed nominal thermal boiler capacity after the 22nd simulations period (2008 – 2030) under different assumptions regarding the scaled variance β_{hs} with the reference scenario[68] using a β_{hs} -value of 8. While the results for some energy carriers (natural gas, direct electric heating, heat pumps and biogenic energy carriers) seem to be more or less robust with respect to very wide variation of this parameter, the outcomes for two energy carrier groups, heating oil products and district heating, are heavily impacted. If the parameterization is changed to more winner-takes-it-all behavior, heating oil based boilers loose market shares, while district heating gains shares.

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[67] The global minimum of this function can be found at very high β values (the winner takes it all) with $\varepsilon \sim 0$.

[68] As reference scenario, the WEM-scenario (see chapter 1) was chosen.

The long tail-behavior of district heating at high β-value is caused by the algorithm according to which the technology diffusion restrictions are incorporated in the model. The high selectiveness of logit-model at high β-value leads to market share $s_{adaptNLM,b,t,i}$ close to 1 for the technology with the highest utility (or lowest penalty = costs). In such cases, however, the implemented algorithm does not consider diffusion restriction properly. As can be seen from Figure A.2, even if the upper market share $S_{max,t,i}$ of technology i is restricted to a low value (which is the case for district heating networks with high heat densities in rural areas (see Müller et al, 2014)), the actual market share $s_{b,t,\mathrm{i}}$ of the technology can be well above its upper market limit if no other technology with a considerable market share $s_{adaptNLM,b,t,i}$ is available. Although at this point, this behavior is somewhat unpleasant, it should be rather seen as a problem related to the winner-takes-it-all behavior at really high β-values, than with a shortcoming of the implementation of technology diffusion algorithm.

Table 5.2 – Sensitivity of cumulated installed capacity per energy carrier cluster after 22 simulation periods with respect to the scaled variance (β_{hs}) of the decision parameter.

	Cumulated installed boiler capacity [GW] (95% confidence interval in brackets)**					**Difference compared to reference scenario**			
	β_{hs}								
	4	**8***	12	24	30	4	12	24	30
Natural gas	11.4 (±0%)	**10.2 (±0%)**	9.4 (±0%)	8.8 (±0%)	8.8 (±0%)	12%	-7%	-14%	-13%
Heating oil	4.1 (±0%)	**3 (±0.7%)**	2.4 (±0.5%)	1.8 (±0.9%)	1.3 (±0.9%)	36%	-20%	-42%	-56%
Electricity, direct	1 (±3.2%)	**0.9 (±0.8%)**	0.8 (±2.4%)	0.8 (±1.5%)	0.8 (±0%)	13%	-6%	-13%	-13%
Electricity, HP	2.8 (±0.6%)	**2.9 (±0.6%)**	3 (±0%)	2.9 (±0%)	2.5 (±0%)	-3%	3%	-2%	-15%
Biomass	10.7 (±1.2%)	**10.8 (±0.2%)**	10.3 (±0.6%)	9.4 (±0.1%)	9.2 (±0.2%)	-1%	-5%	-13%	-15%
District heating	2.6 (±0.4%)	**5.6 (±0.5%)**	7.7 (±0.6%)	10.7 (±0%)	12.4 (±0%)	-53%	38%	92%	121%

* Reference scenario
** 95% confidence interval based on 5 model runs using $f_{\mathrm{min\_share}} = 4$
HP … Heat pumps

A similar sensitivity analysis was done for the scaled variance used for building-envelope related renovation activities β_{ren}. Again, for the reference scenario a β-value of 8 was chosen. As can be seen in Table 5.3, the results are not influenced to a high degree with respect to this parameter. A steeper, more cost-based parameterization leads to additional renovation activities in the multi-family residential building sector and reduced activities in residential buildings with not more than 2 households per buildings.

Table 5.3 – Sensitivity of cumulated renovated gross floor area per building type cluster after 22 simulation periods with respect to the scaled variance (β_{ren}) of the decision parameter.

	Cumulated renovated GFA [million m²] (95% confidence interval in brackets)					Difference compared to reference scenario			
	β_{ren}								
	4	**8***	12	24	30	4	12	24	30
Small residential buildings	49 (±0.3%)	**46.7 (±0.4%)**	46.4 (±2.4%)	44.5 (±0.6%)	44.6 (±1.2%)	5.1%	-0.5%	-5.3%	-4.4%
Residential build. with more than 2 households	26.7 (±0.1%)	**27.4 (±0.3%)**	28.6 (±1%)	29.2 (±0.6%)	29.4 (±0.7%)	-2.8%	4.1%	5.7%	7.1%
Non-residential buildings	24.1 (±0.6%)	**23.4 (±0.7%)**	23.4 (±3.1%)	23.3 (±0.7%)	23.4 (±0.6%)	3.1%	0.4%	-0.8%	0.3%

* Reference scenario
** 95% confidence interval based on 5 model runs using $f_{\text{min\_share}} = 4$
GFA … Heated gross floor area

Sensitivity of the model results related the penalty function $\mu_{b,t,i}$

The decision algorithm of the logit model assigns market shares of newly installed systems based on penalty function $\mu_{b,t,i}$. This variable derives from annual heating costs, adjusted for the estimated[69] consumer preferences for each alternative. Thus, it is assumed that, on average, the heat generation costs are the dominant decision criteria. As described in section 4.6, the author couldn't find profound evidence for Austria to reject this assumption and calibrate parameters for additional decision criteria. However, analyses done by researches indicate that costs are not the only decision parameter. In order to analyze the effects of such an altered penalty function, a sensitivity analysis is performed, This is done by modifying the penalty for one alternative i, while the penalties for other technology options j remain as they are.

$$\begin{aligned} r_{b,t,i,sens} &= \frac{\mu_{b,t,i} + f_{sens} \cdot \mu_{b,t,mean}}{\mu_{b,t,mean}} \\ r_{b,t,j,sens} &= \frac{\mu_{b,t,j}}{\mu_{b,t,mean}} \qquad j \in I : j \neq i \end{aligned} \tag{5.6}$$

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[69] Calibrated on a macro level by comparing the model results for the period 2000-2011 with installation data taken from literature.

where

$r_{b,t,i,sens}$ ... Adopted relative penalty of measures i compared to weighted average utility of all available options

$r_{b,t,j,sens}$ ... Relative penalty of other measures than i

$\mu_{b,t,mean}$ ... Weighted average utility of all available options

f_{sens} ... Sensitivity parameter

The results of the variance for the major energy carriers are shown in Figure 5.8. They indicate that especially emerging (heat pumps, pellet heating systems) and vanishing (heating oil) technologies and energy carriers are sensitive to changes in the penalty function.

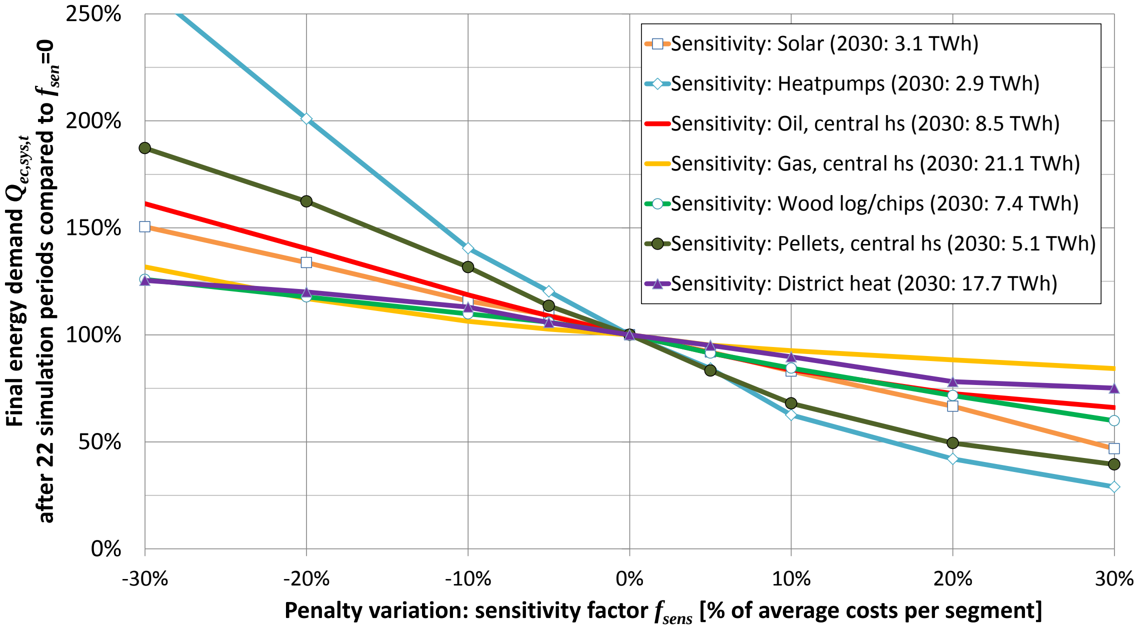

Figure 5.8 – Sensitivity of the final energy demand after 22 simulation periods (2009 – 2030) of different energy carrier clusters to changes in the penalty function used by the decision process.

Sensitivity of the penalty function $\mu_{b,t,i}$ with respect to the consumption-dependent energy costs

As described in section 4.4.4, the energy demand considering the user behavior might differ considerably from the one calculated according to the calculation standard. This is especially the case for buildings with a very poor energy performance. Depending on the perception of energy costs by the investment-decision-maker, the importance of investment costs versus energy costs is expected to change as well. Thus, the dependency of the results on the decision process – whether to consider energy costs based on the user-behavior-adjusted energy needs (which reflect the real energy costs), or the energy needs without behavioral aspects (which reflect the energy performance of the building at the same comfort level) – are analyzed and shown in Table 5.4.

Table 5.4 – Sensitivity of the model results with respect to the decision variable: annual energy demand with (alternative case) or without (reference case) user behavior.

	Reference case		**Alternative case**		**Difference**	
	In 12th	In 22nd	In 12th	In 22nd	In 12th	In 22nd
	simulation period					
	Final energy demand [TWh] (95% confidence interval**)					
Natural gas	25.3 (±0.1%)	21.8 (±0.1%)	25.2 (±0.3%)	21.7 (±0.1%)	-0.2%	-0.5%
Heating oil	16.1 (±0.2%)	8.8 (±0.4%)	16.4 (±0.3%)	9 (±0.2%)	1.5%	2.2%
Coal	0.5 (±0.3%)	0.1 (±2.7%)	0.5 (±1.9%)	0.1 (±9.2%)	0.0%	-5.0%
Electricity, direct	5.1 (±0.5%)	2.4 (±1.2%)	5.2 (±1.2%)	2.4 (±0.7%)	0.7%	0.0%
Electricity, heat pumps	1.1 (±1%)	1.6 (±0.6%)	1.1 (±0.7%)	1.6 (±0.5%)	1.3%	-0.6%
Ambient Heat	2.6 (±0.9%)	3.8 (±0.5%)	2.6 (±0.7%)	3.8 (±0.3%)	0.7%	-1.3%
Biomass	22.1 (±0.2%)	20.5 (±0.1%)	21.6 (±0.1%)	20.1 (±0.3%)	-1.9%	-1.7%
District heating	19.8 (±0.1%)	20.8 (±0.1%)	19.8 (±0%)	21 (±0.2%)	0.1%	0.5%
Solar thermal energy	2 (±0.3%)	2.9 (±0.1%)	1.9 (±0.4%)	2.9 (±0.3%)	-0.8%	-0.7%
	Renovated gross floor area [million m²]					
Small residential buildings	26.2 (±1.3%)	46.7 (±0.4%)	26.7 (±2.5%)	47.3 (±0.3%)	1.1%	1.5%
Res. build. with 3+ apartments	13.1 (±0.8%)	27.4 (±0.3%)	13.3 (±2.4%)	27.3 (±0.3%)	1.1%	-0.3%
Non-residential buildings	11.5 (±2.7%)	23.4 (±0.7%)	11.9 (±5.8%)	23.7 (±0.6%)	2.2%	1.8%
	Cumulated installed nominal thermal boiler capacity [GW]					
Natural gas	4.9 (±0%)	10.2 (±0%)	4.9 (±0%)	10.2 (±0%)	-0.6%	-0.3%
Heating oil	1.2 (±1.7%)	3 (±0.7%)	1.4 (±0.8%)	3.2 (±0.6%)	12.7%	7.0%
Electricity, direct	0.6 (±0.7%)	0.9 (±0.8%)	0.7 (±0%)	0.9 (±0%)	5.0%	3.5%
Electricity, heat pumps	1.4 (±1.5%)	2.9 (±0.6%)	1.4 (±0.8%)	2.9 (±0.6%)	1.1%	-1.1%
Biomass	4.8 (±0.5%)	10.8 (±0.2%)	4.6 (±1.5%)	10.5 (±0.5%)	-5.4%	-2.7%
District heating	2.9 (±1.1%)	5.6 (±0.5%)	2.9 (±0%)	5.7 (±0%)	-0.1%	1.1%

** 95% confidence interval based on 5 model runs using $f_{\mathrm{min\_share}}$ = 4

In case decision-makers do not consider the energy demand of the building under reference conditions but rather use the user behavior adjusted final energy demand (which is closer to the real consumption), it is expected that heating systems with higher consumption-dependent energy costs should get a higher share than they would get in the reference case. The model, as shown in Table 5.4, exhibits this behavior. In the alternative case, where the user behavior adjusted energy demand is used as decision criterion, heating oil based boilers receive a higher share, while heating systems with low running energy costs get lower shares. However, the results also indicate that the model results are quite robust in terms of this uncertainty. The final energy demand of most energy carriers as well as the cumulated renovated gross floor area does not deviate significantly from the reference case.

5.2.2 Cost-based adoption of refurbishment activities

As described in section 4.5.1, the number of buildings being renovated per simulation period do not only depend on the age of the building components and the distribution parameters of their lifetimes, but also on the weighted average penalty ("adjusted costs") of available refurbishment options. Although, to the author's knowledge, this combination of the economic and the distribution-based approach has not been quantified and published directly, it appears to be plausible that this behavior exists to some degree.

To understand the impact of this calibration, a sensitivity analysis for this parameter is shown in the following. For this analysis, the parameter $f_{scale,base}$ (see equation (4.26)) is varied between 0.5 and 1[70]. This is done for four settings: first, (a) a reference scenario, based on the WEM-scenario described in Chapter 7.1, yet without unlimited subsidy budgets. When using a $f_{scale,base}$ of 0.5, the thermal renovation activities are reduced on average by about 10%-15% (see Figure 5.9) compared to the non-cost-sensitivity approach ($f_{scale,base} = 1$), which relies only on the historical observed lifetime data and derived parameter for the Weibull distribution for building components (see section 6.1). Under these scenario settings, non-thermal renovation activities (maintenance option) decrease by 30% to 35% for $f_{scale,base}$ of 0.5 compared to $f_{scale,base} = 1$.

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[70] $f_{scale,base} = 1$ stands for a cost elasticity of 0;
$f_{scale,base} = 0.5$, corresponds roughly to a cost elasticity of about -1 in case the average total costs of heating after measure > 1.2 x current marginal (consumption-dependent) costs for heating, and a cost elasticity of about -0.5 when total costs of heating costs < 0.8 x current marginal heating costs.

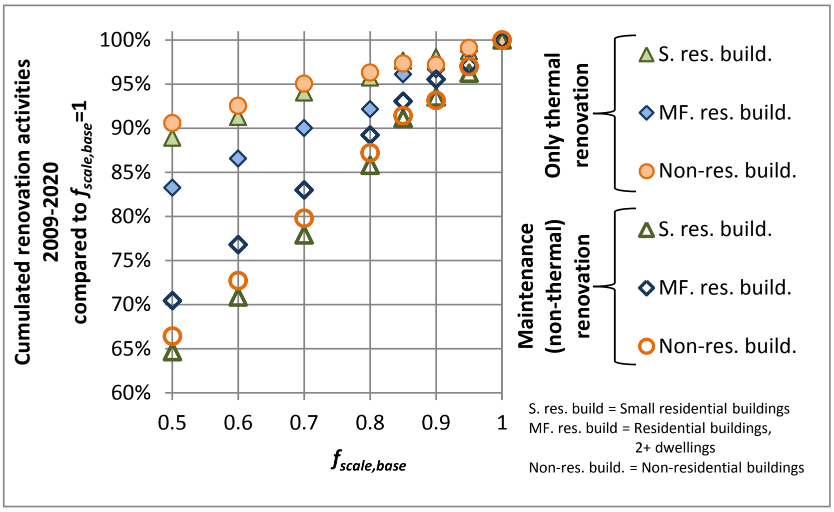

Figure 5.9 – Sensitivity of the model results: renovated gross floor area after 12 simulation periods (2009 – 2020) with respect to cost sensitivity parameter $f_{scale,base}$.

The other three sensitivity settings analyze scenarios where only the renovation option 3 is available (see Figure 6.12). This is done for (b) a scenario with the investment costs shown in Figure 6.13, (c) a scenario with twice the investment costs for renovation type 3 and (d) a scenario with half of the investment costs for renovation option 3 (Figure 5.10).

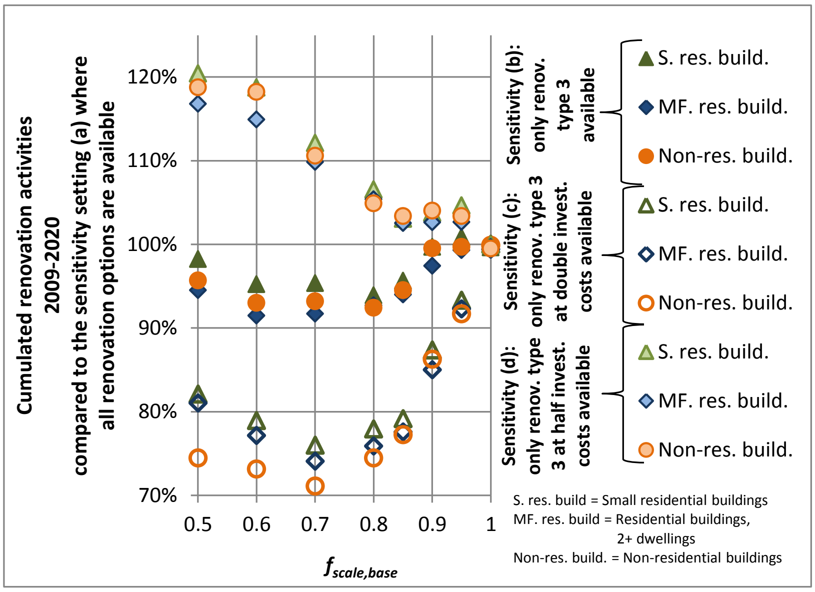

Figure 5.10 – Sensitivity of the model results: renovated gross floor area after 12 simulation periods (2009 – 2020) with respect to cost sensitivity parameter $f_{scale,base}$.

Under settings (b) where only renovation option 3 is available to the model (also no maintenance option), the cumulated refurbished gross floor area between 2009 and 2020 decreases by about 5% for a $f_{scale,base}$ in the range of 0.5 and 0.85 compared to the renovated gross floor area[71] of the sensitivity setting (a) (see Figure 5.9). Under the sensitivity setting (c) the doubled renovation investment costs results in decreasing renovation activities. For a $_{\text{fscale,base}}$ between 0.5 and 0.85, the activities are reduced by about 20%-30%. On the other hand, reducing the investment cost (d) increases the renovation activities. For a setting of $f_{scale,base} = 0.5$, the renovated gross floor area increases by almost 20%, again when compared to scenario setting (a) with $f_{scale,base} = 0.5$.

5.2.3 The logistic diffusion process

Upper market penetration level of energy carriers

The sensitivity of the model result with respect to the estimated upper market penetration level S_{max} of energy carriers is tested by varying this parameter for the most-restricted energy carriers: district heating, natural gas and biomass. The results indicate that the energy carriers: natural gas and biomass do not respond a lot to the variation of their upper market penetration level within +/- 20 percentage points. The results for district heating are quite sensitive to such a variation. A *ceteris paribus* increase of the upper market penetration level by 20 percentage points increases the cumulated installed thermal capacity of district heating between 2009 and 2030 by more than 35%. One of the main reasons for the high sensitivity of district heating is its low upper market penetration level S_{max} in rural areas, which on average is in the order of about 5%.

Table 5.5 – Sensitivity of the model results after 22 simulation periods with respect to a ceteris paribus variation of the upper market penetration level of (a) district heating, (b) natural gas and (c) biogenic energy carriers.

	Cumulated installed boiler capacity (95% confidence interval in brackets)**					**Difference compared to reference scenario RS**			
	-20%	-10%	**RS***	10%	20%	-20%	-10%	10%	20%
District heating	4.4 (±1.2%)	4.9 (±0.9%)	**5.6 (±0.5%)**	6.7 (±1%)	7.6 (±0%)	-21%	-12%	19%	36%
Natural gas	9.7 (±0%)	9.9 (±0%)	**10.2 (±0%)**	10.4 (±0%)	10.5 (±0%)	-5%	-2%	2%	3%
Biomass	9.7 (±0%)	10.4 (±0.5%)	**10.8 (±0.2%)**	11.1 (±0.1%)	11.2 (±0%)	-10%	-4%	2%	4%

* Reference scenario

** 95% confidence interval based on 5 model runs using $f_{\text{min\_share}} = 4$

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[71] Including the non-thermal maintenance option.

Characteristic diffusion time of technologies $\Delta T_{inc,i}$

The concept that diffusion processes, on a macro-scale, often show an S-shaped pattern has been established for many decades and is underlined in many scientific publications (e.g. Nakicovic and Grübler, 1991; Grübler, 1998). This behavior is introduced in the decision algorithm and is steered by an exogenously defined variable: the characteristic market penetration time $\Delta T_{inc,i}$. Since this variable cannot be observed directly and needs to be estimated based on comparable diffusion processes, the question arises to which extent the model results are determined by this variable and thus influenced by possible false estimations. A sensitivity analysis, in which this variable is in a range of +/- 50%, is used to test the stability of the results. The outcome indicate that the results for 12 and 22 period simulation runs are robust with respect to this variable and that the final energy demand of the individual energy carriers changes by 5% or less after 12 simulation periods (2008-2020) and less than 2% after 22 simulation periods (2008-2030).

For the scenarios subsequently shown in this work, a characteristic diffusion time (10%-90%) of 15 years[72] for the positive growth and a characteristic diffusion time of 5 years for the negative growth process are used.

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[72] 30 years for 1%-99%.

6 Assumptions on the historical and future development of the Austrian built environment, energy supply technologies and climate change

This chapter summarizes the implementation of the Austrian building stock data in the Invert/EE-Lab model and the exogenously defined assumptions on the developments of future framework conditions. It starts with the historical calibration of renovation activities, and continues with the estimated future growth of the building stock, energy price scenario data and assumption settings for new buildings, refurbishment options and heat supply systems. Furthermore, it discusses and presents the implemented assumptions on the scale of changing climate conditions.

6.1 Calibration of renovation activities based on historic data

The data on historical renovation activities in Austria are discussed in chapter 3.4. In this section these data are applied to calibrate the historical renovation activities in the model Invert/EE-Lab. This approach builds on the service lifetime module of the Invert/EE-Lab model and its distribution-based approach as described in section 4.5. However, while the typical use of this module is for determining future renovation activities, in the subsequent step it is instead used for calibrating the historical renovation activities.

6.1.1 Estimating the distribution parameters for the service lifetime of building components

This section elaborates on the calibration the Weibull distributions used to define the service lifetimes of building components. The data provided by Meyer et al. (1995) are used to define reasonable values for the two parameters of the Weibull distributions for three different components: façade, windows and heating systems and different installation periods (shown in Figure 6.1 - Figure 6.3). In these figures, the grey area below the black bold line represents the observed share of components (according to Meyer et al., 1995) which survived a specific age (survival rate). The red dotted line and the green line display the fitted Weibull curves. The red dotted line represents the best fit for each construction period. In order to increase the stability and reduce the number of estimated Weibull curves, the data for different construction periods are clustered. The first cluster contains components of the installation period from 1933 to 1953 (for heating systems: 1933 to 1943), the second cluster components which were installed afterwards. The green line in the following figures depicts the estimated Weibull curves for the clustered data.

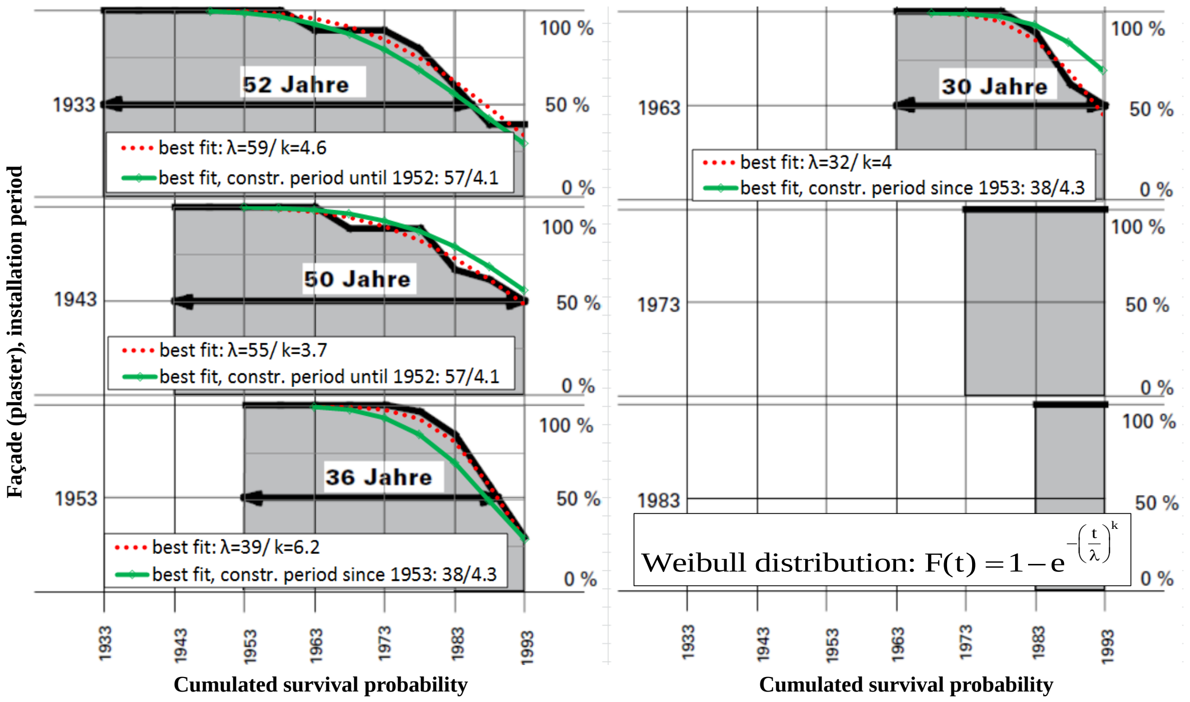

Figure 6.1 – Observed cumulative survival rate of facades (plaster) by Meyer et al. (1995) based on Swiss building data (black line, grey area) and modeled survival rate based on estimated Weibull distributions (red dotted line: best fit for individual construction periods, green line: best fit for construction period clusters: installed before 1953 and since 1953).

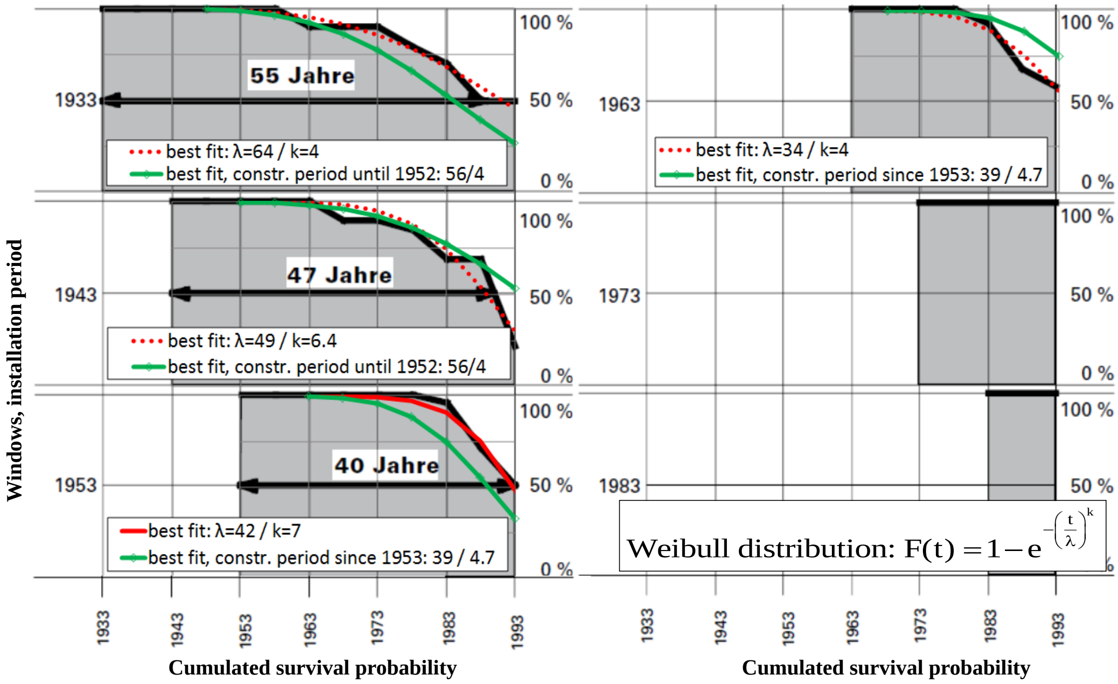

Figure 6.2 – Observed cumulative survival rate of windows by Meyer et al. (1995) based on Swiss building data and modeled survival rate based on estimated Weibull distributions (red dotted line: best fit for individual construction periods, green line: best fit for construction period clusters: installed before 1953 and since 1953).

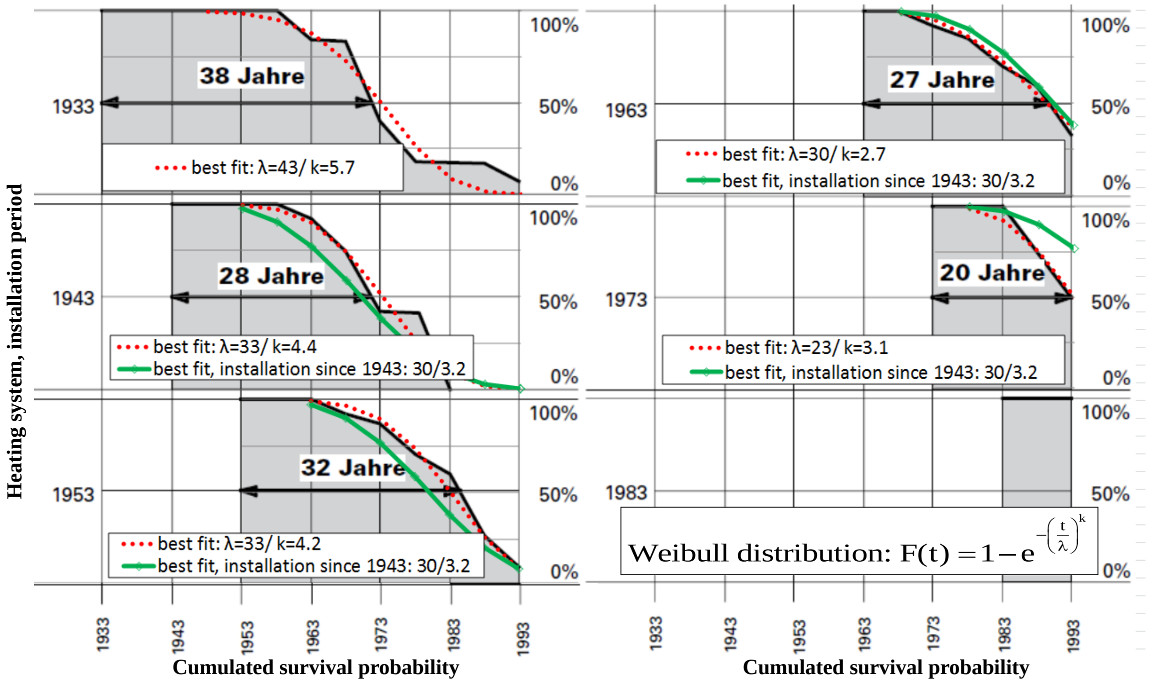

Figure 6.3 – Observed cumulative survival rate of heating systems by Meyer et al. (1995) based on Swiss building data and modeled survival rate based on estimated Weibull distributions (red dotted line: best fit for individual construction periods, green line: best fit for construction period clusters: installed before 1943 and after 1953).

In Figure 6.4, the derived distribution for the survival rate of facades and windows, estimated based on Meyer et al. (1995) for buildings constructed after 1953, is compared with data about the age of building of the Austrian social housing sector, at which major renovations were performed (Bauer, 2013). It shows that both datasets match very well. Furthermore, both datasets display the tendency that components in older buildings have a longer average lifetime than those in newer buildings. Thus, it is concluded that the estimated component lifetimes are in reasonable range.

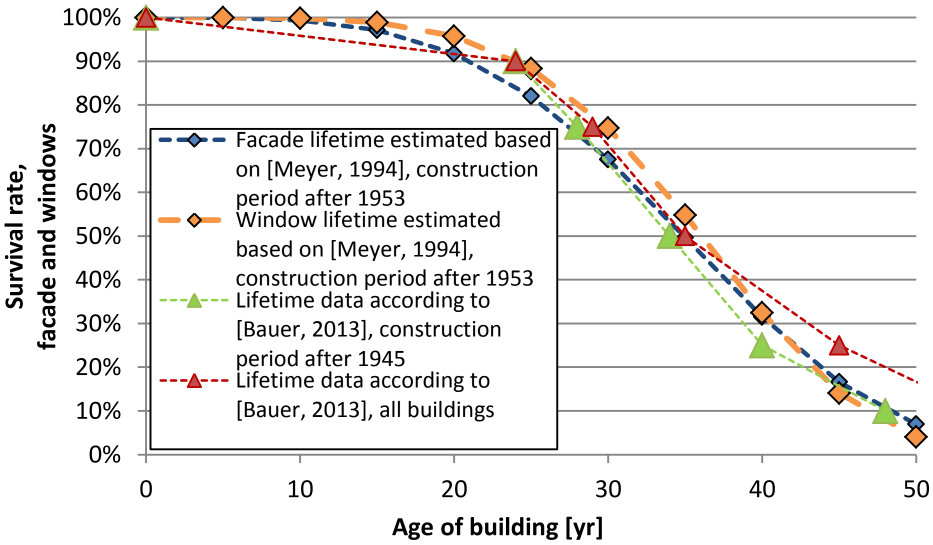

Figure 6.4 – Comparison of observed survival rate according to Bauer (2013) and estimated survival rate based on Meyer et al. (1995).

The service lifetime data used in the simulation runs are depicted in the Appendix A.3

6.1.2 Estimating the historic renovation activities based on the lifetime of building components

In this section the building renovation algorithm is applied to the historic Austrian residential building stock for the period of 1890 to 2008 (only buildings that have survived until 2006 are considered). The algorithm shown in section 4.5.1 is used to calculate the historical replacement of installed components. The estimated distributions of the service lifetimes of building components shown in the previous section are applied to the Austrian residential building stock of the year 2006. The left diagram in Figure 6.5 displays the number of dwellings per construction period in buildings existing in 2006 in which the original windows have not been replaced over time according to the model. The right diagram in Figure 6.5 depicts the number of dwellings which have undergone a first window replacement cycle (2nd-generation components), a second or third cycle (3rd/4th-generation components) according to the applied model.

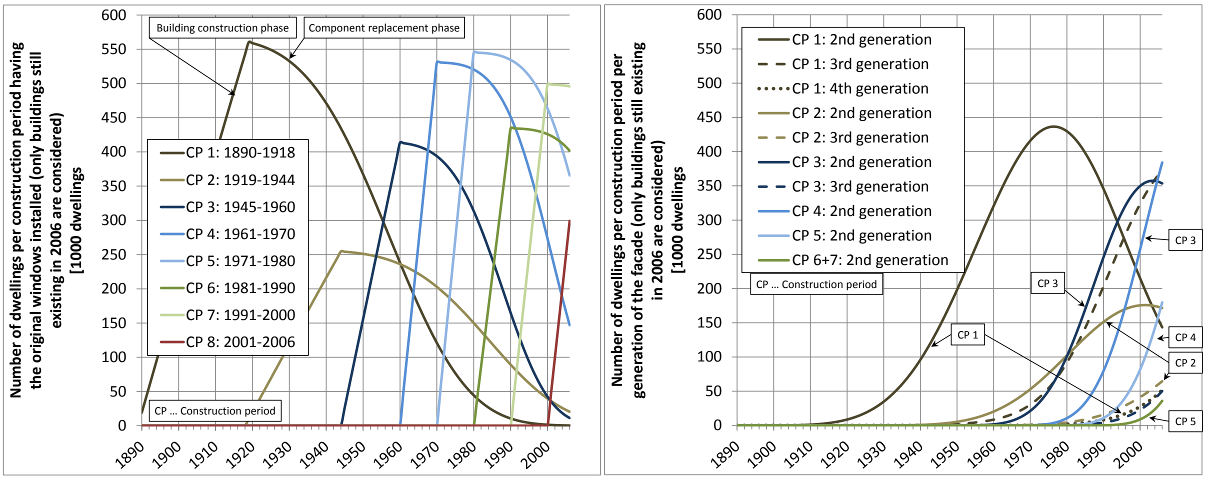

Figure 6.5 – Number of dwellings in Austrian residential buildings per construction period having the original windows installed (left) and a 2nd or 3rd generation windows based on the lifetime algorithm implemented in the Invert/EE-Lab model.

The results of the same analysis performed on façade elements are shown in Figure 6.6. In contrast to windows, it is assumed that the lifetime of measures done on facades equals the lifetime of the original elements.

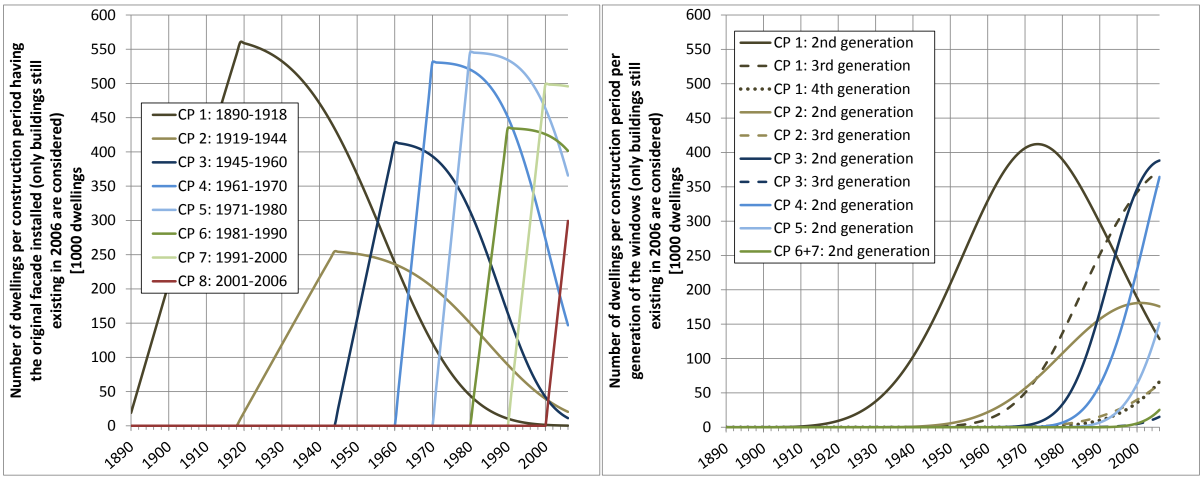

Figure 6.6 – Number of dwellings in Austrian residential buildings per construction period having the original facades (left) and a 2nd or 3rd generation facades based on the lifetime algorithm implemented in the Invert/EE-Lab model.

For the upper ceiling and base floor, data on the service lifetime are not explicitly available. But it can be assumed that the upper ceiling (but not the roof) and the base floor basically last as long as the masonry of the building. Therefore, in principle, no measures need to be set on these components throughout the lifetime of the building.

Historical data on façade-related measures and window-replacements are available for the period 1991-2000 (Statistik Austria 2004a-i). To estimate the accuracy of the (service-lifetime-based) replacement cycle model, these numbers are calculated for the period 1991-2000 considering dynamics between 1890 to 2000 as shown above. Table 6.1 compares the model results and statistical data.

Table 6.1 – Comparison of building renovation (facades and windows) activities for the period 1991-2000 in Austria.

	Number of buildings			**Number of dwellings**		
	Statist. data	**Model results**	**Deviation**	**Statist. data**	**Model results**	**Deviation**
	[tds. buildings]		[%]	[tds. dwellings]		[%]
Façades	255	289	**13%**	674	642	**-5%**
Windows	286	288	**1%**	721	640	**-11%**

The calculated aggregated results for the number of windows replaced match the empirical data for the period 1991-2000 provided by Statistic Austria quite well. The model underestimates the number of dwellings by 11%; the deviation for buildings is below 1%. For façades, the differences between the data calculated by the model and those provided by Statistik Austria (2004a-i) are slightly larger. The model overestimates the number of buildings on which façade-related measures were taken by 13% and underestimates the number of dwellings by 5% for the analyzed period. This implies that the lifetime of façade elements differs for buildings that are single and double family houses and those that are apartment buildings. Yet, since data for a more disaggregated analysis are not available, this bias has not been compensated up to now.

A sensitivity analysis on the impact of different lifetime parameters for façades and windows is shown in Figure 6.7. Within a variation of the Weibull distribution parameter λ[73] in the range +/- 10%, the number buildings applying façade related measures increase by about 1.4% (395 Buildings or 875 Dwellings) per a 1%-reduction of λ. The effect of shorter service lifetimes of windows on the number of buildings and dwellings replacing their

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[73] "Characteristic lifetime": Average lifetime of components at which a cumulated failure rate of 63.2% occurs.

windows is slightly lower than that for façade-related measures. On average, a decrease of the lifetime of windows by 1% increases the replaced windows in the model by 1%.

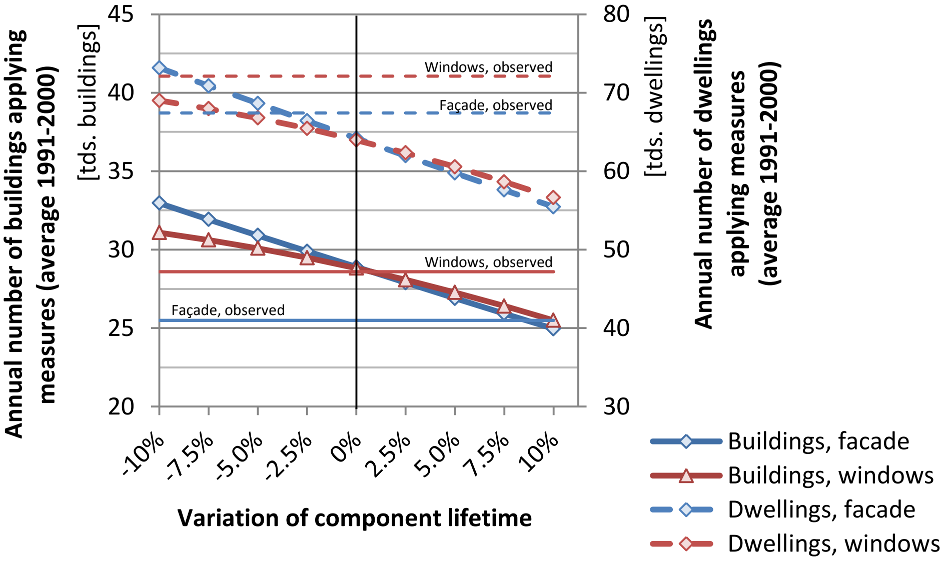

Figure 6.7 – Sensitivity of the annual number of buildings and dwellings in Austria performing façade- and window-related measures for the period 1991 – 2000 according to the replacement cycle model. (0% is equal to the service lifetime values described above).

For the period from 2001 to 2006 the model estimates an increase of replacement activities compared to the average activity in the period 1991-2000. According to the model, the average annual number of buildings undergoing renovation activity increases by 7%-16%, the number of dwellings increases by about 15%-19%. This means that the share of large buildings performing façade related measures increases disproportionally in the model.

Table 6.2 – Comparison of the model results for building renovation (facades and windows) for the period 1991-2000 and 2001-2006.

	Number of buildings			**Number of dwellings**		
	1991-2000	**2001-2006**	**Increase**	**1991-2000**	**2001-2006**	**Increase**
	[tds. buildings p.a.]		[-]	[tds. dwellings p.a.]		[-]
Façade-related measures	28.9	30.9	+7%	64.2	76.3	+19%
Replacing windows	28.8	33.5	+16%	64.0	73.8	+15%

These numbers imply that every year about 2%-2.5% of buildings and dwellings did some façade-related measures within the analyzed period. Under the assumption that the share of thermal renovation to non-thermal renovation did not change significantly compared to the period 1991-2000, the model's result leads to a buildings renovation rate of about 1.2% for the period 2000-2006.

The actual thermal renovation rate of the past 10-15 years in Austria is not very well documented. The author of this thesis discussed in various projects the actual thermal renovation rate[74] expressed in deep-renovation-equivalents for the last decade with experts from the Umweltbundesamt, members of the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management, energy officers of the Austrian federal states[75] and experts from the funding bodies "Wohnförderung". Based on the results of these discussions, the average annual *deep-renovation-equivalents* renovation rate for the period 2005-2012 is set to 0.8% of the conditioned gross floor area of the total building stock, which is lower than the rates suggested by UBA (2012) or IIBW (2013).

Assumptions on the building stock in 2008 and its historic renovation status

Based on the data described above, the historic renovation status of the Austrian building stock in 2008 is estimated. The results are given by Table 6.3.

The status of the building stock in 2008 is implemented as the starting point and base year for the scenarios developed later on. With respect to the thermal quality of renovations performed before 2008 the simplified assumption is made that all renovation activities done before 1995 include only minor thermal improvements (windows), while renovation activities performed since 1995 are associated with improved windows (quality standard of new buildings in 2000) and 35% of the energy reductions compared to thermal renovations performed in 2008[76] with respect to the façade elements, upper ceiling and base floor.

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[74] For the scenarios the preferences for renovation activities (compare to maintenance activities) need to be calibrated based on observed renovation rates.

[75] In German: " Energiebeauftrage der Bundesländer".

[76] In order to simplify the data, it is assumed that all façade-related measures performed between 1995 and 2008 improved the thermal quality and not just 50%, as indicated by the Building and Household Census 2001. To compensate for the bias, the estimated thermal improvement of facades, upper ceiling and base floor (~70% of the energy savings compared to 2008 renovation) was lowered by 50% compared to the actual estimated improvements.

Table 6.3 – Estimate of the number of residential buildings and households per construction year and renovation status in 2008.

	Buildings [1000 #]	Dwellings
Construction period, before 1945, buildings with additional renovation barriers [1)]		
Original thermal quality	77	198
Thermal improvements before 1995	-	-
Thermal improvements since 1995	50	127
Construction period, before 1945		
Original thermal quality	97	208
Thermal improvements before 1995	53	117
Thermal improvements since 1995	96	208
Construction period 1945 - 1980		
Original thermal quality	409	834
Thermal improvements before 1995	39	87
Thermal improvements since 1995	307	648
Construction period, 1981 - 2008		
Original thermal quality	604	1134
Thermal improvements before 1995	-	-
Thermal improvements since 1995	-	-

1) e.g. cultural heritage, stucco façade, etc.

6.2 Assumptions on the future growth of the building stock

The forecasts commissioned by the Austrian Conference on Spatial Planning (ÖROK)[77] are a commonly acknowledged estimation of the development of the residential buildings stock in Austria. Developed by the Statistics Austria, major updates are released periodically every 10 years. The latest forecast, released in 2011 (Hanika, 2011) covers the period until 2050 subdivided into 124 regions in Austria. The forecast provides data for the development of the population, labor force, the number of private households and the households' size (in terms of persons per households).

For the estimated number of residential buildings per building size, within this work, the author uses the regional data of the existing building stock for the 2640 municipal regions[78]. In a second step, the historical developments of the inhabitants of these 2640

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[77] In German: "Österreichische Raumordnungskonferenz".

[78] In German: "Gemeinden".

regions are analyzed and used to estimated the future development of the individual municipal regions. This is done in such a way that the 124 regions, as defined in the ÖROK forecast 2011, meet their forecast targets. The development of the residential buildings per building size results from scaling the initial share of buildings per building size by the development of the number of buildings for each municipal region. For the scenarios conducted by the Invert/EE-Lab model, the data are grouped according to the defined 73 regions (see 3.3).

For non-residential buildings, to the author's knowledge, no consistent forecast is available. Thus, an approach is used where the non-residential floor areas develop according to the growth of the sector specific value added in the period until 2020 (Kratena et al., 2013). Afterwards the growth rate of the floor area decreases to the annual development of the residential buildings until 2030.

In the Invert/EE-Lab model, individual relative growth rates can be defined separately for *"climate regions"* (in this work: 10 types) and *"energy carrier regions"* (in this work: 8 x 3 +2 (Vienna) types). However, they cannot be defined for each combination of climate region and energy carrier regions. As a consequence, the development of the buildings per region cannot exactly meet the forecast data provided by the ÖROK forecast. The following figure compares the growth of households for the period of 2010 to 2050 according to the ÖROK forecasts for the 9 federal states and 10 climate zones against the resulting model data. For Carinthia, the model underestimates the number of households in 2050 by 16% and those of Styria and Burgenland by 10%. For Vorarlberg and Tyrol the number of households is overestimated by 5%.

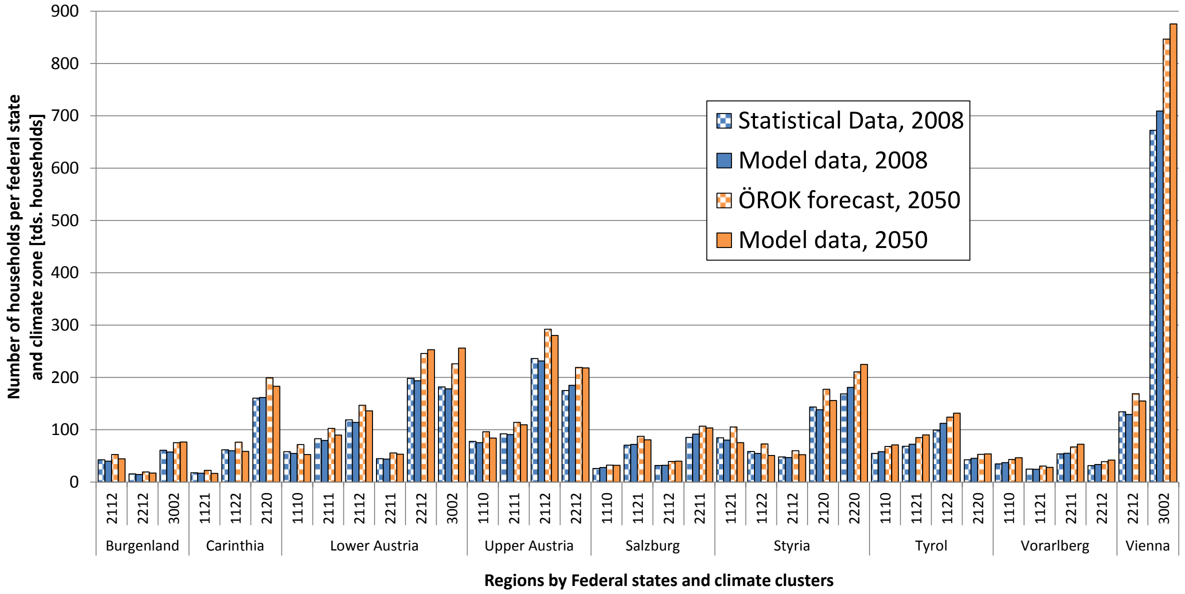

Figure 6.8 – Development of the household number per federal states and climate zones. Comparison between ÖROK forecast and data applied in the scenarios.

6.3 Energy price scenario

Energy prices are based on Müller et al. (2014a). In this energy price scenario, retail consumer prices for gas and oil increase between 2012 and 2030 by 19% and 25%. The prices of biogenious energy carriers and district heating rise by 12% and 14%; that of electricity by 8%.

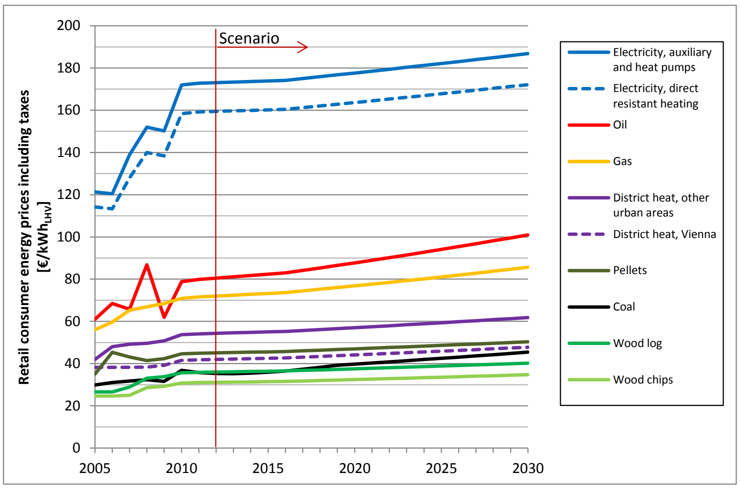

Figure 6.9 – Energy prices until 2030.

Cost-resource-potential curves are implemented for biogenic energy carriers to consider the limited but tradable biomass resources (Figure 6.10). For wood log it is assumed that resources are decreasing over time. The reason behind this assumption is that a significant share of wood log used for space heating purposes are currently harvested more or less non-commercially by final end users, since fully commercial forest management and wood forwarding is not economical for a large share of the existing forest. It is expected that with an increasing deployment of biomass potential and increasing biomass prices, the share of non-commercially harvested wood for heating purposes will decrease. On the other hand, it is expected that the biomass fractions, wood chips and pellets, will increase. Biomass, available for the building stock at the reference price level (Figure 6.10), increase in the scenarios from 32 TWh in 2010 (of which 24 TWh are used in 2010) to 35 TWh in 2020 and finally 36 TWh in 2030.

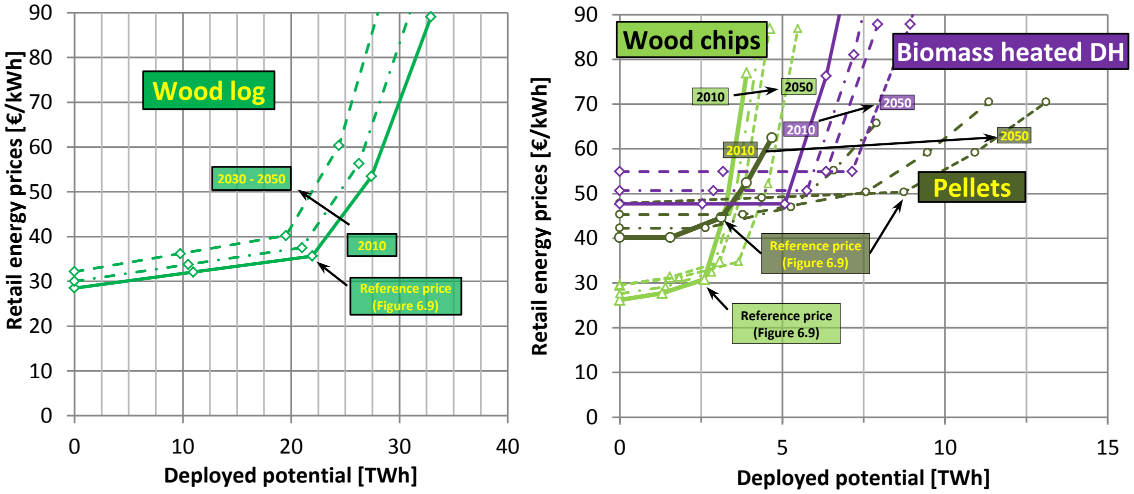

Figure 6.10 – Applied biomass cost-resource-potential curves for 2010, 2020, 2030 and 2050.

6.4 Scenario settings for new buildings, refurbishment options and heat supply systems

6.4.1 New buildings

Cost data

Cost data for new buildings are given in Bauer (2013), Leutgöb et al. (2013), Schulz et al. (2011) or Enseling and Loga (2013). In her publication, Bauer analyzes the cost-efficiency of energy efficiency measures for the Austrian social building stock[79]. This building stock

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[79] In German: “Gebäudebestand der gemeinnützigen Bauvereinigungen“.

comprises mainly large residential buildings, with an average surface-to-volume ratio of about 0.45. For this building stock, construction costs (excluding garage, solar collects, elevator in small buildings, corrected by apartment size) range between 1551 €/m² and 1779€/m² (price level 2011). According to her analysis, costs increase by 10% for a building with an energy need $q_{H,nd,gfa}$ of 17 kWh/GFA m² compared to one with an $q_{H,nd,gfa}$ of 68 kWh/ GFA m². For a building with an $q_{H,nd,gfa}$ of 9 kWh/GFA m² costs increase by 15% compared to a low thermal quality building.

Leutgöb et al. (2013) analyze the cost efficiency of different energy performance standards for new constructions. According to their data, initial investment costs[80] for typically residential buildings (cost data for Vorarlberg, 2013) range between 2050-2100 €/m²BGF for single family houses (220 m^2_{BGF}), 1500-1550 €/m²BGF for multifamily houses (700 m^2_{BGF}) and 1450 €/m^2_{BGF} for large apartment buildings (2030 m^2_{BGF}). This publication identifies additional investment costs for passive house standard buildings in the range of 140-220 €/m^2_{BGF} (average about 150 €/m^2_{BGF}) for single family houses, 115-150 €/m^2_{BGF} (average about 135 €/m^2_{BGF}) for multifamily houses and 75-95 €/m^2_{BGF} (average about 90 €/m^2_{BGF}) for large apartment buildings. The ventilation system is responsible for about 50 €/m^2_{BGF} of the additional investment costs, the more efficient building envelope causes about 90 €/m^2_{BGF} for single family homes and 30-50 m^2_{BGF} for larger residential buildings. The remaining differences result from additional solar thermal collectors and savings due to smaller heating systems.

In the project "Erarbeitung einer Integrierten Wärme- und Kältestrategie"[81] (Henning et al., 2013; Schulz et al., 2011) additional investment costs for more efficient buildings are also analyzed. According to their results, a decrease of the surface-to-volume ratio corrected energy needs $q_{H,nd,norm,gfa}^{+new}$ (equation (6.1)) from 14 to 11 kWh/m² $_{BGF}$ comes along with an increase of investment costs of about 145 €/m^2_{BGF} (large apartment buildings) to 170 €/m^2_{BGF} for single family homes. A further reduction towards passive house standard increases the specific investment costs by 260-300 €/m^2_{BGF} compared to the reference construction type. While for the two less ambitioned energy performance standards, a ventilation system with

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[80] Construction costs (in German: "Bauwerkskosten") according to ÖNORM 1801-1:2009 (cost categories 2, 3 and 4). The corresponding cost groups of the CEEC Code (Wright and Stoy, 2008) are: A-G and K.

[81] Translates to: "Development of an integrated heating and cooling strategy".

heat recovery is not necessary, for the last type such a system is considered. Solar thermal collectors are already included in this costs data.

Enseling and Loga (2013) publish initial investment cost data for new single family homes and multifamily homes. According to their analysis, additional investment costs (excluding heating system and solar thermal collectors) of about 50 to 100 €/m² occur for the “Energieeffizienzhaus 55” standard, compared to the EnEV 09 standard. For the cost optimal configuration which reaches “passive house” standard, the additional investment cost are about 150 €/m².

In the Invert/EE-Lab model new buildings can choose at each point of time from three different thermal quality standards. While the quality standards increase over time (see Figure 6.11) it is assumed that the investment costs remain constant. For the period until 2012, the envelope type “Construction period 2009-2012” constitutes the option with the lowest thermal quality, “Construction period 2013-2015” the medium quality type and “Construction period 2016-2019” the type with the highest thermal quality. After 2015, the type “Construction period 2016-2019” represents the low-quality option, while the best-quality option is represented by the “Construction period post 2020, B” type. The investment costs are shown in Table 6.4

Table 6.4 – Investment costs for new buildings.

Building size [m²]	**Lowest Quality**	**Medium Quality** [€/m²]	**Best Quality**
150	1600	1635	1750
400	1500	1495	1590
2000	1165	1205	1280
3000	1150	1185	1255

Thermal quality

The thermal quality of new buildings is set based on the national document which defines the pathway toward “Nearly Zero Energy Buildings” until 2021 (OIB, 2012). After 2020, an additional increase of the thermal quality of new buildings is considered in the scenarios and refers to the type: “Construction Period post 2020, B” (Figure 6.11). The data in this figure are shown for the indicator $q_{H,nd,norm,gfa/gv}^{+new}$. This indicator represents the specific energy needs for heating of a building, corrected by the characteristic length l_c of the building.

$$q_{H,nd,norm,gfa/gv} = q^{+new}_{H,nd,norm,gfa/gv} \cdot \left(1 + 3/l_c\right) \qquad (6.1)$$

where

$q_{H,nd,norm,gv}$ ... Specific energy needs per heated gross floor area [kWh/m²yr]

$q_{H,nd,norm,gfa}$ ... Specific energy needs per heated gross volume [kWh/m³yr]

$q^{+new}_{H,nd,norm}$ .. Volume-to-surface specific energy needs [kWh/m³yr]

l_c ... Characteristic building length (volume-to-surface ratio)

The energy needs for heating per building type and implemented efficiency levels are depicted in Figure 6.11

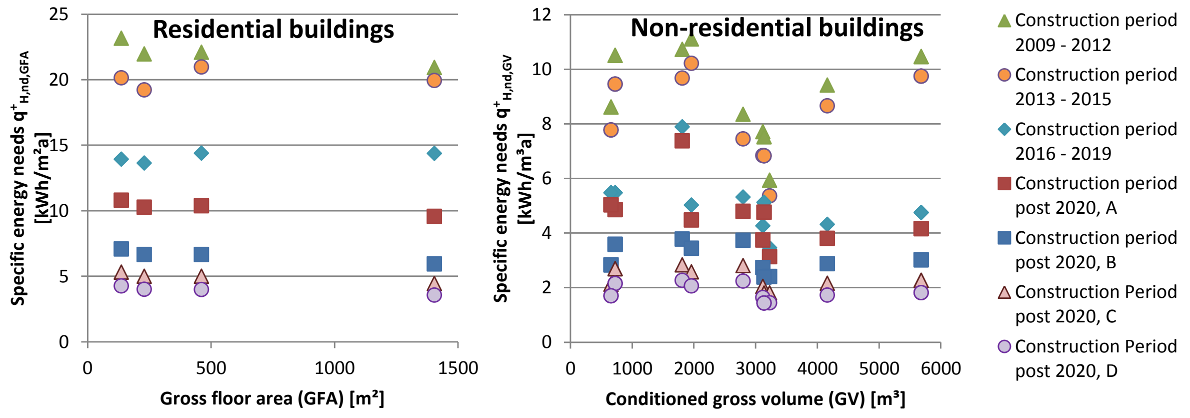

Figure 6.11 – Specific energy needs for heating of new buildings, as defined in the applied scenarios.

Regulations for the energy needs for cooling are given in OIB (2011). This document defines that the cooling needs of new non-residential buildings, caused by external gains under the assumption that the internal gains are zero, must not exceed 1 kWh/m³yr. Considering a room height of 2.5 to 3 meters, this refers to floor area-specific energy need of 2.5 to 3 kWh/m²yr. These range is significantly higher than the average energy need for cooling of the current Austrian building stock. Therefore, in the scenarios shown below, new buildings are defined in such a way that the average energy needs for cooling, caused by external gains, is close to 1 kWh/m²a, which is lower than the regulatory upper level by the factor of almost 3.

One has to be aware that the externally caused energy needs for cooling are highly sensitive to the effective heat storage capacity of the buildings and thus the building construction type. By changing the assumptions about the internal heat storage capacity, the defined reference values can easily change in a wide range. The cooling needs including internal gains, which then define the actual cooling needs, are less sensitive to the effective heat storage capacity.

6.4.2 Refurbishment of existing buildings

Cost data

Bauer (2013) reports average investment costs for a (standard) thermal renovation of the analyzed building stock are between 170 and 190 €/m^2_{NFA} (127-135 €/m^2_{GFA}). However, she points out that for smaller objects the renovation costs are likely to exceed 200 €/m^2_{NFA}. Such renovations reduce the average energy consumption by 34 kWh/m^2_{GFA} (45 kWh/m^2_{NFA}a), resulting in an average final energy consumption for these buildings of 58 kWh/m^2_{GFA}a. The average final energy consumption of buildings for which a very high thermal quality standard renovation was applied is 40 kWh/m^2_{GFA}a. In these cases additional costs of 110 €/m^2_{NFA} (110 €/m^2_{GFA}) for a ventilation system, better insulation and windows as well as additional planning costs occur. She also points out that in case of comprehensive refurbishments, additional (non-energy related) costs of 100-150 €/m^2_{NFA} usually occur.

Bohnenschäfer et al. (2013) analyze the economics of climate change mitigation option and social effects of extending the German Renewable Heat Law[82] to the existing building stock in Germany’s federal state Sachsen-Anhalt. According to their data, insulating non-refurbished (energy need of 145 kWh/m²) or partially refurbished (energy need of 95 kWh/m²) single family homes to 50 kWh/m² energy need standard costs between 125 and 171 €/m². For apartment buildings with a net floor area of 530 m² investment costs range from 92 €/m² (already partially refurbished) to 127 €/m². For non-residential buildings, the specific investment costs are reduced by an additional 10 €/m². In the Entranze project, investment costs for several kinds of building refurbishments are gathered. The data are documented in Boneta (2013).

The cost data used in this study are depicts Figure 6.13.

Thermal quality

In this work a set of five different renovation standards per building type is defined (see Figure 6.12). The energy needs for space heating of buildings constructed after 1945, corrected by the characteristic building lengths (see (6.2)), of the least ambitious renovation types (refurbishment type 1) under average Austrian climate 2005 conditions are set to

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[82] In German: “Erneuerbare Energien Wärme Gesetz”.

$q^{+renov}_{H,nd,norm,gfa}$=25 kWh/m²a. This is slightly higher than the upper limit, as specified in the OIB (2012a) document of $q^{+renov}_{H,nd,norm,gfa}$=24 kWh/ m²a allowed until 2014. The energy needs for the most efficient refurbishment type (type 5) are set to $q^{+renov}_{H,nd,norm,gfa}$=15 kWh/m²a, which is somewhat lower than the allowed upper limit of $q^{+renov}_{H,nd,norm,gfa}$=17 kWh/m²a as specified by OIB (2012a) for comprehensive refurbishments performed after 2020. Furthermore, it is considered that this value is corrected by the room height.

$$q_{H,nd,norm,gfa} = q^{+renov}_{H,nd,norm,gfa} \cdot \left(1 + 2.5 / l_c\right) \cdot (h_{room} / 2.6) \qquad (6.2)$$

where

$q_{H,nd,norm,\mathrm{gfa}}$	... Specific energy needs per heated gross floor area [kWh/m²yr]
$q^{+renov}_{H,nd,norm,gfa}$	... Volume-to-surface specific energy needs per heated gross volume [kWh/m³yr]
l_c	... Characteristic building length (volume-to-surface ratio)
$h_{room} =$	... Net room height

Residential buildings: $h_{room} = 2.6$

For buildings constructed before 1945 as well as warehouse and mall style buildings[83], larger technical, economic and social restrictions are assumed. Therefore, the (characteristic building length-corrected) energy needs for space heating $q^{+renov}_{H,nd,norm,gfa}$ (under average Austrian climate 2005 conditions) are defined in a range of 45 to 21 kWh/m²a. The resulting site-specific energy needs for space heating are shown in Figure 6.12.

The relative energy savings, considering the user-behavior and thus the rebound effect, are in a range of 10% to 50% for the refurbishment type 1. For the refurbishment option 5 the energy savings are between 45% and 65%. Without considering the rebound effect, energy savings would increase by 10% to 15% (~7 percentage points).

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[83] Non-residential prefab constructions.

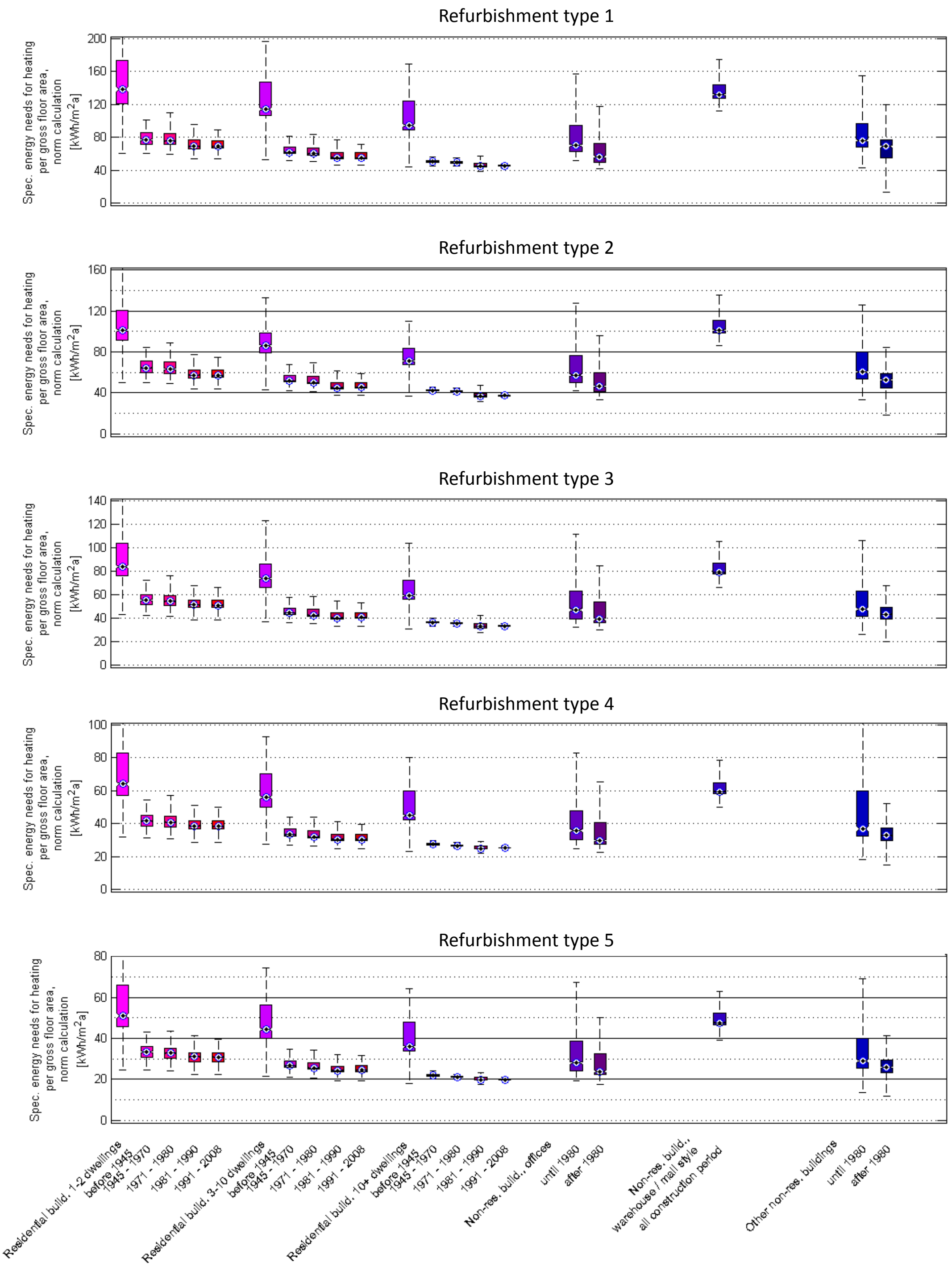

Figure 6.12 – Defined refurbishment options: specific energy needs for space heating per building type and construction period cluster.

The additional investment costs, compared to the maintenance option without any energetic improvements are shown in Figure 6.13. The existing large residential and office buildings constructed after 1980 almost meets the energy needs of refurbishment type 1, therefore additional investment costs are as low 50 €/m² per conditioned gross floor area. For other buildings, additional investments range from 100 to 400 €/m² per conditioned gross floor area.

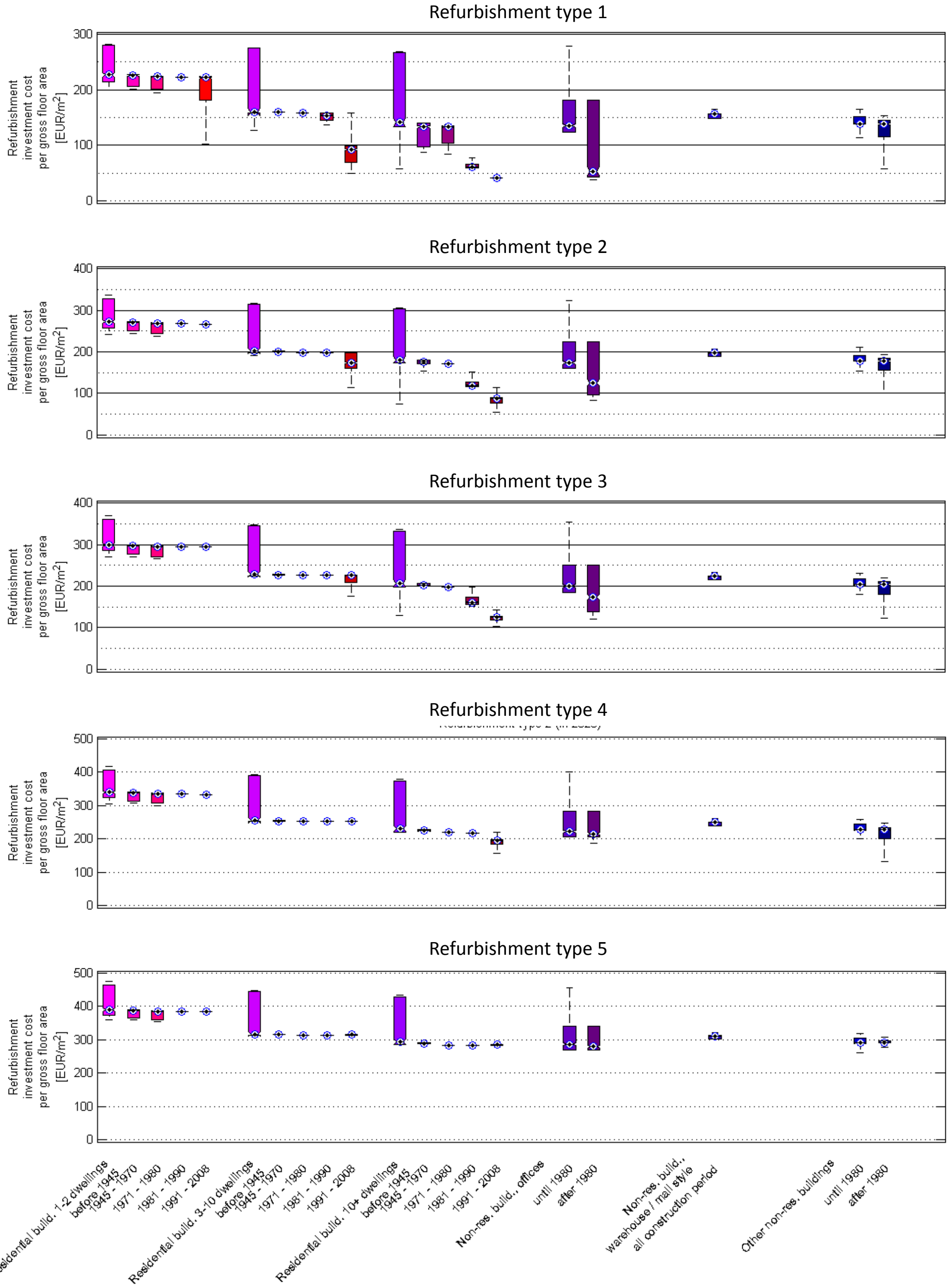

Figure 6.13 – Defined refurbishment options: associated additional investment costs compared to a non-thermal maintenance at the end of the lifetime cycle of major components (windows and façade).

6.4.3 Heat supply systems

For this analysis, 21 different heating systems are defined, of which 11 can be combined with solar thermal systems. Four different sizes of solar thermal collectors per apartment are considered: 6 m², 15 m², 20 m² and 30 m². The assumptions about investment costs of heating systems and their efficiencies as well as the upper market penetration rate of different energy carriers are shown in Appendix A.2.

6.5 Climate scenarios and deriving semi-synthetic climate data

In the PRESENCE project (Schicker and Formayr, 2012) climate data on a regional level were derived to estimate the future effects of climate change on the heating and cooling demand of buildings. This was conducted by the Department of Metrology of the University of Life science[84]. A brief description of the approach and applied data derived by the team of the Department of Metrology is given in the next two paragraphs.

On a global level, climate models are quite consistent when assessing the effects of climate change. On a regional level data can differ quite considerably. To get better insights into the effects of climate change on a region level as well as into the uncertainties of the forecasts, a set of three different regional climate models, (RCMs) driven by two global climate models applying a A1B scenario, is used. The first selected RCM is the Aladin model (Déqué and Piedelievre, 1995), operated by CNRM and driven by the ARPEGE global climate model (GCM) (Déqué et al, 1995), the second is the REMO model (Jacob and Podzun, 1997), operated by MPI and driven by ECHAM5 (Roeckner et al., 2003), and the third is the RegCM3 model (Giorgi et al., 1993), operated by ICTP and also driven by the ECHAM5 GCM.

For the daily and sub-daily parameters such as temperature and solar radiation, a bias correction for all three models using the EOBS 1981-2006 data (Haylock et al. 2008) is applied. A localization of the 25 x 25 km grid from the RCM data to a 1 x 1 km grid was carried out, using the Austrian INCA dataset (Haiden et al., 2011). These data were also used to estimate the spatial variability of climate variables such as temperature and solar radiation on a monthly basis. For future climate conditions, hourly semi-synthetic climate datasets

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[84] And not by the author of this thesis.

(SSCD) were calculated based on the bias-corrected and localized RCM data. To be able to properly represent the Austrian climate conditions, January and July temperatures are used and radiation clusters are defined (Kranzl et al, 2014b). For every cluster a representative observation site is selected. These (hourly) data were then used for the generation of the hourly SSCD for the past. For the future hourly SSCDs the localized and bias corrected scenario datasets for three future time slices, 2011 – 2040, 2036 – 2065 and 2051 – 2080 are derived.

Using the SSCD, the author of this thesis derives monthly temperatures for 1995 (EOBS 1981 – 2006) as well as climate model specific monthly temperatures for 2025 (SSCD 2011 – 2040), 2050 (SSCD 2036 – 2065) and 2065 (SSCD 2051 – 2080). Furthermore, a common climate reference year (2005) is calculated based on a linear path between 1995 and the averaging climate conditions for 2025 as derived by the three climate models using the SSCD 2011 – 2040 datasets. The climate change between 2065 and 2080 is extrapolated based on the development of the national heating degree days until 2080 (also derived in the PRESENCE project). These monthly climate datasets are used by the Invert/EE-Lab model to calculate the energy demand changes on an annual basis.

The Austrian population-weighed monthly temperatures for the period 1981 – 2006, and the derived data for the climate in 7 decades from now (2080) are shown in Figure 6.14. Based on the EOBS data, an annual mean temperature of 8.5 °C in Austria is calculated. Assuming that this was the climate corrected mean temperature in 1995, an average increase between 1995 and 2005 (common reference climate 2005) of 0.3 °C is calculated. Between 1995 and 2065 (SSCD 2051 – 2080) the average temperature increases by about 2.1 °C to 2.2 °C, which corresponds to 0.31 °C per decade temperature increase. For the period until 2080 an additional temperature increase of 0.5 °C to 0.6 °C is calculated, resulting in a total increase of 2.6 °C to 2.8 °C, compared to the observation period 1981 – 2006 (0.3 °C – 0.32 °C increase per decade).

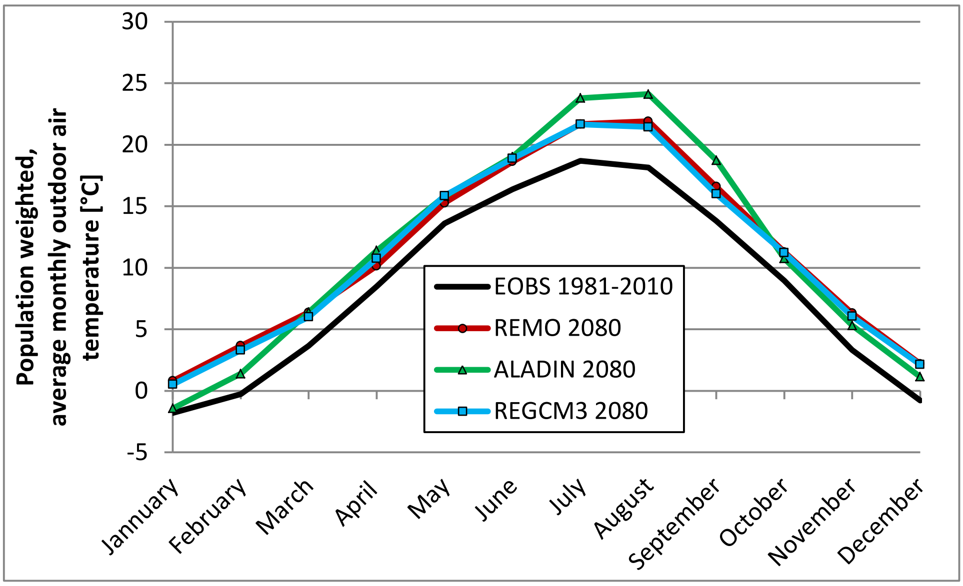

Figure 6.14 – Population weighted monthly outdoor air temperature in Austria for the period 1981 to 2010 and the results of SSCDs for 2080.

The originally developed set of 19 different climate zones for Austria distinguishes between regions according to their winter and summer temperatures, as well as their winter and summer solar radiation. In order to keep the size of the dataset the Invert/EE-Lab model has to process to a minimum, these 19 climate regions are summarized into 10 regions.

7 Scenarios for future energy demand of the Austrian building stock

This chapter presents the results as derived by the developed and applied Invert/EE-Lab model. The analysis covers a set of different scenarios. In the first part, the energy needs and final energy consumption until 2030 are analyzed in three policy scenarios. Two policy scenarios focus on current energy policy settings. The third incorporates more ambitious policy measures by 2021 and reflects the ongoing discourse between energy economists from the Umweltbundesamt and the Energy Economics Group and members of the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management on how to foster climate change mitigation and energy conservation strategies. These scenarios are based on the work done by Müller and Kranzl (2013a, 2013b).

The second part of this chapter focuses on the impact of the climate change on the energy needs for heating, cooling and domestic hot water until 2080. The scenarios shown in this section are based on the work done within the PRESENCE project (Müller et al., 2014a). Only those tasks of the projects which were performed by the author of this thesis are included in this section.

All monetary units (cost and price data) given in this chapter represent inflation adjusted units on the price level of 2010.

7.1 Development of energy needs and final energy consumption with existing policies until 2030: the WEM scenario

The following scenario is based on the policy settings for the WEM scenario (with existing measures) outlined in Müller and Kranzl (2013a). The idea of this scenario is to analyze the development of the final energy demand and the share of renewable energy carriers used to supply that demand until 2030 considering the policy framework conditions as implemented by spring 2012.

In Austria, many regulations which have an impact on the energy demands of and the energy carriers used in buildings (building code, level of subsidies and compliance conditions such as share of renewable energy carriers or upper limit for energy needs) are defined on the level of federal states. Implementing the detailed set of policy measures would push this kind of analysis beyond available resources. Therefore average levels of energy policy measures for Austria are estimated. The applied policies are described in the following sections.

7.1.1 Scenario assumptions

Investment subsidies for heating systems

Investment subsidies are given for alternative heating systems, mainly heating systems which deploy some share of renewable energy carriers. The subsidies given approximate the current average level in Austria. As discussed above, subsidy schemes vary between the federal states, while in this work a common policy set for all Austrian regions is applied. Therefore, the implemented subsidies do not exactly meet the current Austrian policy schemes.

Table 7.1 – Investment subsidies for heating systems in the WEM scenario.

Heating system	Subsidies	Upper limit per building
Wood log boiler	20%	2300 €
Wood chips boiler	20%	3000 €
Pellets boiler	23%	2800 €
District heating in urban regions	15%	
District heating in rural regions	23%	
Heat pumps, air-water	5%	1000 €
Heat pumps, brine-water	15%	2500 €
DHW-Solar thermal system, res, buildings	25%	3500 €, but max. 2000 € / dwelling
Solar thermal combi-system, res, buildings	25%	3500 €
Solar thermal collectors, non-res. buildings	15%	2100 €

An annual national subsidy budget for promoting alternative heating systems is applied in the scenario. For residential buildings the available budget amounts to inflation-adjusted €$_{2010}$ 100 million per year. Non-residential buildings have an annual cap of €$_{2010}$ 10 million.

Additionally to the subsidies shown above, it is implemented that newly installed oil boilers receive a support through the "Heizen mit Öl"[85] campaign. The support, given by the Austrian mineral oil industry, is limited until 2016 and does not contribute to the implemented national cap for subsidies given for heating systems.

Building refurbishment

In case buildings are refurbished or energetically relevant building components are replaced, the new components have to meet specific requirements with respect to the heat transmission coefficient. Furthermore, OIB (2012a) defines a dynamic pathway for the development of the specific energy needs, corrected by the characteristic buildings length. In the existing policy scenario the least efficient refurbishment type (see section 6.4.2) which, considering technical and social-economic barriers, corresponds to the requirements set before 2015, as defined in OIB (2012a).

Table 7.2 – Subsidies for building refurbishments and newly constructed buildings in the WEM scenario.

Building type	refurbishment type	Upper limit per building
Existing building	1-3	30%
New residential building	2-3	23%
New non-residential building	2-3	15%

The annual financial support for refurbishment measures and additional efficiency standards for new buildings is also limited by a cap. For residential buildings the total budget mainly consists of the "Wohnbauförderung" given by the federal states, and the "Sanierungsscheck" and "Sanierungspacket Bund", both granted by the federal government. Non-residential buildings receive support from the "Wohnbauförderung", the "KMU-Scheck", the "Sanierungspaket Bund" and the "Umweltförderung im Inland (UFI)". This scenario assumes that the annual support budget for new buildings remains on the level of 2012 for the whole period afterwards. For residential buildings, the total budget, and thus also the budget for refurbishing existing buildings, declines between 2011 and 2030 (Figure 7.1). The refurbishment budget for residential buildings in 2013 amounts to inflation-adjusted $€_{2010}$ 290 million. Until 2030 the budget declines to $€_{2010}$ 120 million. Non-residential buildings are confronted with a steep decline in the refurbishment budget between 2012 and 2014. For

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[85] Translates to: "heating with oil".

these building categories, the annual budget restriction remains at €$_{2010}$ 38 million per year between 2014 and 2030.

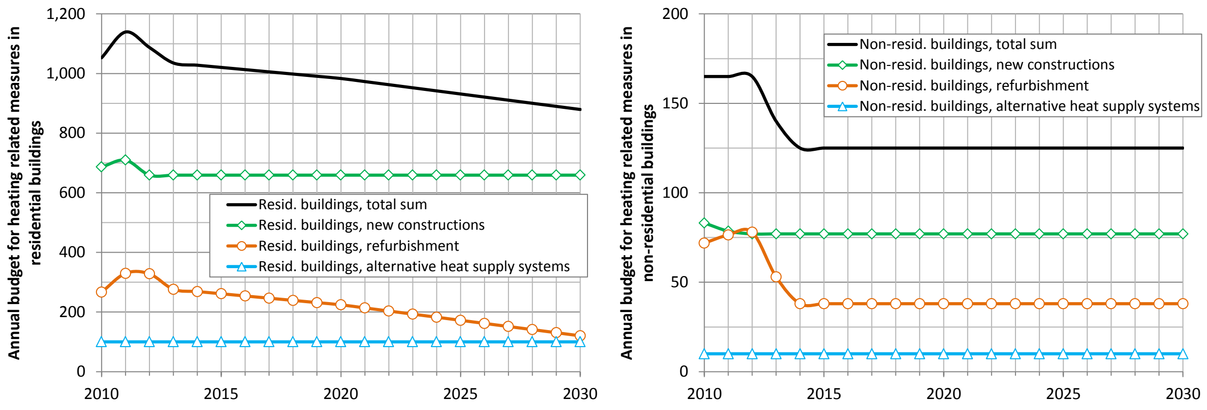

Figure 7.1 – Annual inflation-adjusted subsidy budget cap for heating related measures in buildings.

7.1.2 Scenario results

Development of conditioned floor area until 2030

Based on the development of the number of dwellings per building type and the value added of the service sector, the total net floor area increases from 455 million m² in 2008 to 550 million m² in 2030 (Figure 7.2). The floor area of non-residential buildings increases by 28% resulting in a conditioned net floor area of 145 million m². The annual growth rates until 2020 is about 1%p.a. for residential buildings, while non-residential buildings are assumed to increase by about 1.5%p.a. Between 2020 and 2030 the average growth rates decline to 0.8%p.a. for residential buildings and 1.1%p.a. for non-residential buildings. The resulting annual average demolition rates are 0.43% for buildings constructed before 1945, 0.18% for buildings constructed between 1945 and 1981 and 0.07% for buildings constructed afterwards.

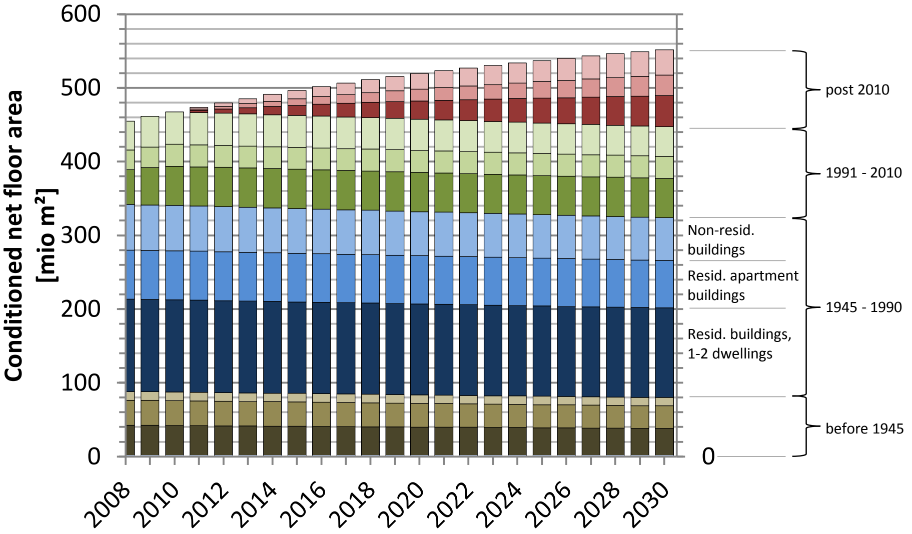

Figure 7.2 – Development of the conditioned net floor area per three building category types and four construction periods until 2030.

Figure 7.3 depicts a closer look at building envelope-related measures. In this figure, a breakdown of these measures per net floor area for the existing building stock is given. The shares of the three primary types of measures are shown: (1) keeping the status quo and applying no measures, (2) applying maintenance measures without thermal improvements, and (3) applying thermal renovations which improve the energy performance of the buildings. This is done for three building construction periods and shown for the years 2010, 2020 and 2030. In this scenario, the share of buildings (per construction period cluster) that conduct any building envelope related measures between 2010 and 2030 ranges from 43% for cluster 2 (construction period 1991-2010) to 70% for cluster 3 (buildings of the construction period 1945-1990). The share of buildings constructed before 1945 (cluster 1) which undergo a building-envelope related refurbishment sums up to 47%. There are two reasons why the share of this cluster is significantly lower than that of cluster 2. First, a large share of buildings constructed before 1945 is associated with “additional renovation barriers” (see Table 6.3), as such are raised by cultural heritage, stucco façades, etc. To account for the additional barriers, longer service lifetimes are defined for the façade (plaster) and windows of these buildings. The second reason is that within this cluster the share of buildings, which replaced building components before 2010, is higher than the share in younger buildings (Table 6.3). This leaves cluster 1 with a higher share of recently installed components. The share of thermal renovations on all building envelope related measures (thermal renovations plus maintenance) is between 40% and 45% for clusters 1 and 2 within the period of 2010-

2020 and about 35% for cluster 3 and decreases over time. This is in fact reasonable; buildings with low energy performance indicators are more likely to set measures earlier than newer buildings with better energy performance indicators.

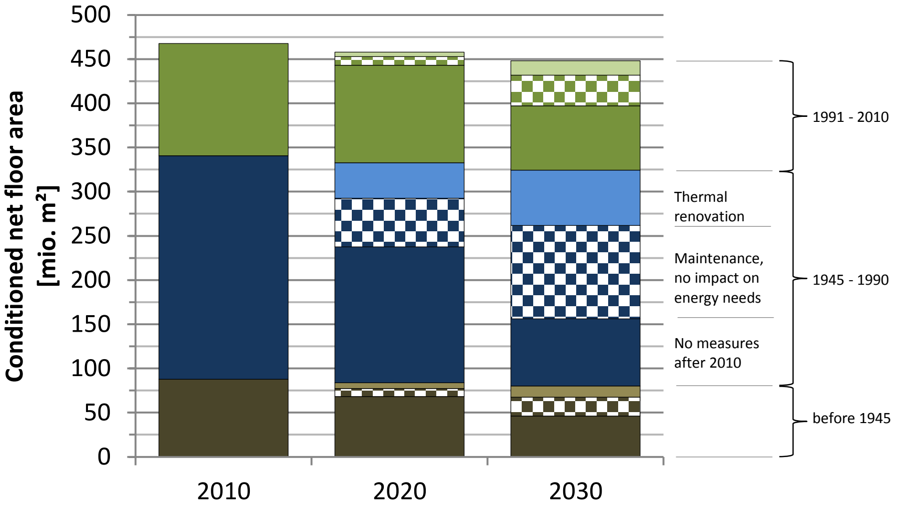

Figure 7.3 – Renovation and maintenance activities in the existing policy (WEM) scenario: conditioned net floor area by construction period and type of renovation measure.

In the following, the development of the energy needs for space heating, air conditioning and domestic hot water until 2030 according to the existing policy (WEM) scenario are shown.

Energy needs for space heating

The development of the energy needs for space heating is driven by four variables. Thermal renovation and building demolition reduce the energy needs, while the increasing heated floor area curb the demand for space heating. Finally, the extent of the impact of the user-behavior changes. Increasing energy prices lead to decreasing user-behavior-corrected energy needs, while the increasing household income and the shift towards heating systems with lower annual energy-consumption-depended costs increase the calculated need. The net effect of these four input factors is negative, meaning that the energy needs for space heating decrease by about 11%. The user-behavior-corrected energy needs for space heating amount to 62 TWh in 2030. As can be seen from Figure 7.4, the energy needs of buildings constructed after 2010 cause only 6.6% of the energy needs for space heating in 2030, even though they represent almost 20% of the heated floor area.

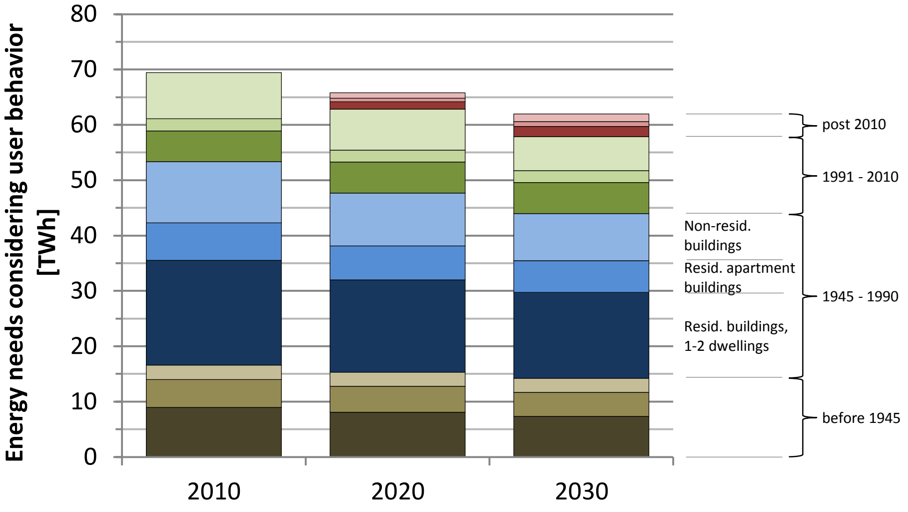

Figure 7.4 – Development of the energy needs for space heating in the existing policy scenario until 2030.

Energy needs for cooling

The four drivers for the development of the energy needs for cooling are, in principle, the same as for heating. However, thermally refurbished and newly constructed buildings have, on average, higher energy needs for cooling, if the ability to reduce solar or internal gains during hot weather periods was not directly addressed in the construction or renovation process. This is because in the case of cooling, thermal energy has to be dissipated into the environment[86], which is hampered by better thermal insulation. Furthermore, newly constructed buildings tend to have a higher share of transparent façade areas than older buildings and are less massive constructed, which also tends to increase the cooling needs.

In the existing policy scenario (WEM) the energy needs for cooling increase from 10.9 TWh in 2010 to 13.6 TWh in 2030. Buildings constructed after 2010 (~20% of the gross floor area in 2030) cause more than 25% of the total energy needs for cooling (Figure 7.5).

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[86] This is valid as long the temperature, averaged over more or less one to a few days, depending on the heat storage capacity of building, does not exceed the desired indoor temperature. This precondition is valid for virtually all regions in Austria throughout the year, except for so-called *“heat periods”*. In a climate such as in Seville (see Figure 4.6), the average daily temperature in summer exceeds 26°C, which means that the energy flow related with cooling conditions is reversed and insulation on opaque surfaces areas tends to reduce the cooling needs.

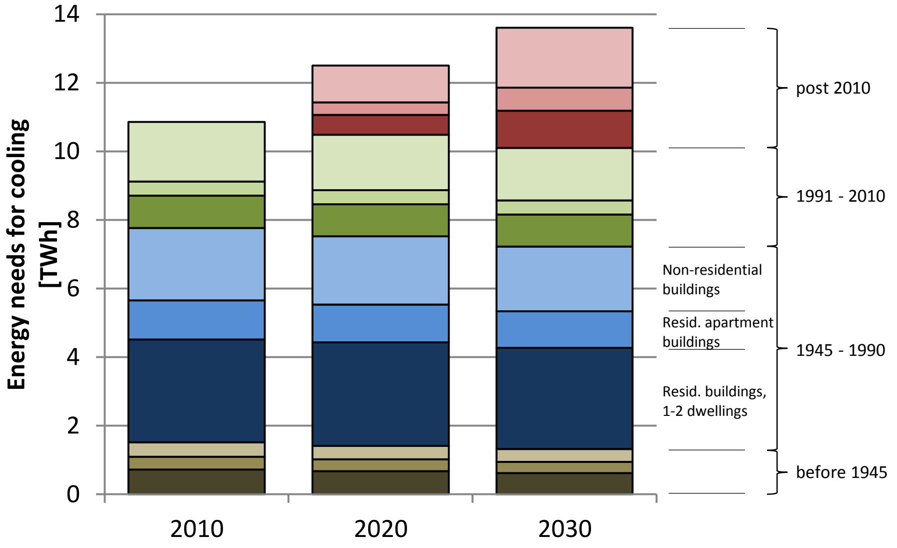

Figure 7.5 – Development of the energy needs for cooling in the existing policy scenario (WEM) under constant climate conditions until 2030.

Energy needs for domestic hot water

The applied method calculates the energy needs for domestic hot water as a function of the conditioned gross floor area and the specific energy needs per floor area, which vary for different building type categories. For the scenarios shown in this thesis, the default specific energy needs are used according to ÖNORM B 8110-5. Exceptions to this are made for residential apartment buildings. For this building usage category, the default value is raised from 35 Wh/m²d to 46 Wh/m²d. The reason for this is the considerably lower conditioned floor area per inhabitant than in single family houses[87]. If the same specific energy need for DHW were applied, this would mean that the hot water demand of people living in apartment buildings is significantly lower than that of those living in single family homes. Discussions in the course of the project "Solargrids" (Müller et al., 2014c) with experts of the Fernwärme Wien GmbH revealed that the 35 Wh/m²d default value underestimates the average energy demand for this purpose of their supplied residential customers. Increasing the default value by 1/3 leads to a person-specific hot water demand that is approximately equal for residential buildings with less than three dwellings and those with more than three dwelling per building.

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[87] See also EN ISO 13790:2008, *Table G.12 - Example of conventional input data related to occupancy*: Single-family houses: 27.4 kWh / (m² d), apartment blocks: 54.8 kWh / (m² d).

Table 7.3 – Energy needs for domestic hot water supply in the WEM scenario.

	2010	**2020** [GWh]	**2030**
Residential buildings	6495	7134	7562
Non-residential buildings	753	855	906
Total	**7248**	**7989**	**8469**

The calculated energy needs for domestic hot water in 2010 amount to 7.3 TWh, of which residential buildings hold a share of about 90%. Between 2010 and 2030 the energy needs increase by 17%.

Development of the final energy demand in the WEM scenario

The total final energy demand under constant climate conditions (using the reference climate conditions of 2005) is shown in Figure 7.6. Historical values for the final energy consumption in buildings are given by the national energy balance, released by Statistic Austria (Statistic Austria, 2014). Based on these data, the HDD-corrected delivered energy of non-electrical energy for space heating and DHW of the Austrian built environment is estimated for the period 2000-2012. The energetically contributions of solar thermal and ambient energy since 2005 are taken from the energy balance. The contributions of these energy carriers for the period 2000 to 2004 is estimated based on installed area and devices respectively. A similar approach is used to estimate the electricity consumption for space heating and DHW production since the national energy balance reports the electricity consumption per sector, yet does not distinguish between the different applications. Therefore electricity demand for space heating and DHW for the period 2000 to 2012 is estimated by the author based on the information on installed heating systems in 2001 (Statistik Austria, 2004a-i) and the assumption that the stock decreases by about 1%p.a. for the period 2000 to 2012 (Haas et al., 2011, see also results from the Microcensus "energy consumption of households"[88], Statistik Austria, 2013a). The observed final energy consumption of the analyzed sector—not considering the estimated electricity consumption—amounted to 90.5 TWh (99.4 TWh including electricity) in 2000 and has decreased to 83.8 TWh (90.7 TWh) in 2013. In the existing policy scenario the final energy consumption decreases to 80 TWh in 2030, starting on a level of 95 TWh in 2008. The role of electricity decreases constantly in the scenario, even though heat pumps gain increasing shares. The decreasing

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[88] In German: "Energieeinsatz der Haushalte".

net-effect is triggered by the replacement of direct resistance heating system in buildings with high energy needs for space heating and the increasing replacement of electricity for DHW production, either by solar thermal heat or by combined heating/DHW heat supply systems.

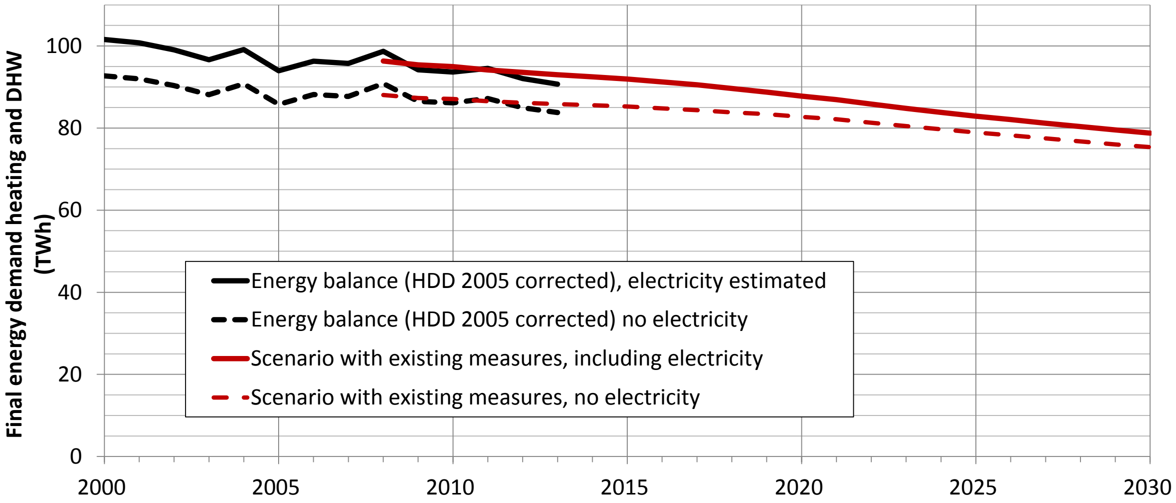

Figure 7.6 – Total final energy demand for space heating and DHW in the existing policy scenario (WEM scenario).

The development of the final energy consumption per energy carrier is shown in the next two figures. Figure 7.7 depicts the top-five energy carriers for the past decades: heating oil, natural gas, district heating, wood log and electricity. Until the early 2000s, heating oil (light and extra light heating oil and LPG) constituted the most applied energy carrier for space heating in Austria. After its steady decline since then, natural gas had taken over as the top energy carrier by 2004. In the existing policy scenario, district heating is the only energy carrier, out of these five, which increases its absolute delivered energy level until 2030. However, as can be seen in the figure, the model is not able to reproduce the steep consumption increase between 2009 and 2010, but increases the level steadily. A similar behavior can be observed with heating oil. While the observed consumption of heating oil decreased by almost 40% (9 TWh) between 2008 and 2013, the model reproduces a much slower decline.

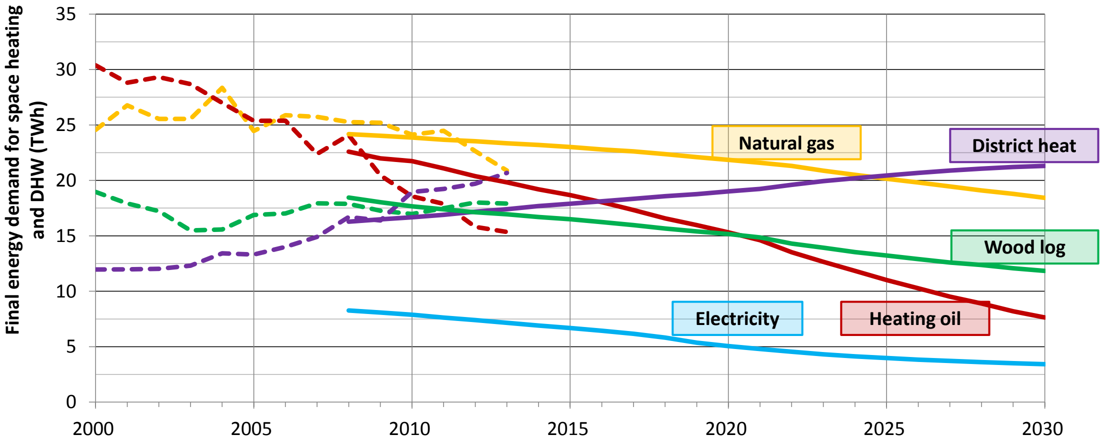

Figure 7.7 – Final energy consumption in the existing policy scenario of the main energy carriers used for space heating and DHW production: natural gas, district heat, wood log, heating oil and electricity in the existing policy scenario.

The final energy consumption of the remaining five energy carrier clusters, wood pellets, wood chips, ambient heat utilized by heat pumps, solar thermal energy and coal, are shown in the next figure. The utilization of coal in this sector has declined for more than 4 decades and plays only a most modest role anymore. The other four energy carrier groups in this cluster are among the “new renewable energy carriers” and are steadily increasing in share as well as in absolute consumption level. In this scenario, the final energy demand of ambient and solar thermal energy more or less triples between 2008 and 2030. However, starting from a low level, these energy carriers can just barley surpass the declining energy carrier electricity (used for space heating and DHW production). The usage of wood chips levels at about 3.3 TWh in 2022. The reason lies in the implemented cost-resource-potential curves for biogenic energy carriers. At this utilization level the energy price of wood chips increases to 45-50 €/MWh (see 6.3 and Figure A.3) and other technologies such as wood pellets become more economically efficient. The final energy consumption of wood pellets in 2030 is somewhat above 5 TWh. At this level, the cost-potential-curve for this energy carrier is still rather flat. Therefore, this energy carrier is not restricted in terms of supply but of demand.

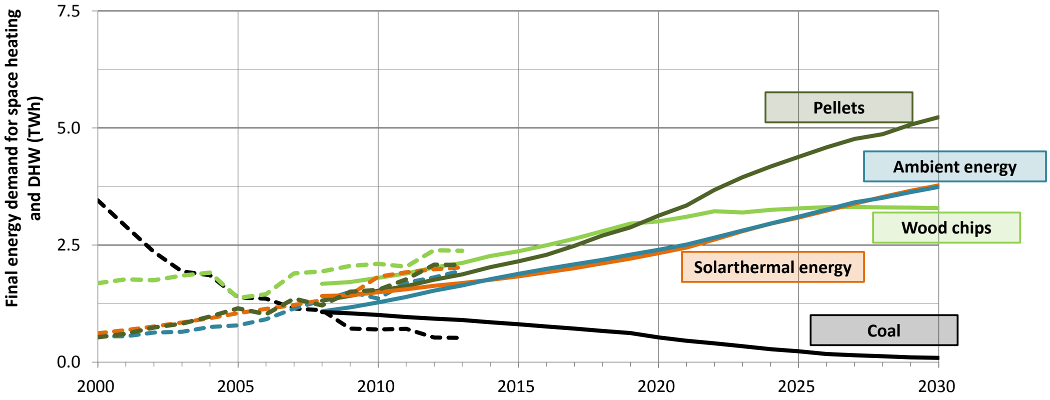

Figure 7.8 – Final energy consumption of the remaining energy sources: pellets, wood chips, ambient and solar energy and coal in the existing policy scenario.

Solar collector distribution

In the following figure the utilization of available roof areas by solar thermal collectors is shown. The filled rectangular represents the total (horizontal projected) roof area available in the model, calculated by using the number of buildings and their (simplified modeled) geometry. Based on these data, a total roof area of about 290 million m² is available in the model by 2030. However, as shown in section 4.7, restrictions are implemented which prohibit the full utilization of this area. First, the solar thermal option is only available for about 65% of the buildings, accounting for the estimate that 35% of buildings (see Müller et al., 2014c) are placed unfavorably in terms of the energy yield of solar thermal collectors. The remaining ~65% of buildings cannot use the full roof area either, as they also face restrictions. For these buildings it is defined that only 40% of the calculated, horizontal projected roof area is usable. This means that the upper limit for the installation of solar thermal collectors in 2030 is 115 million m²[89]. About one third of the buildings which could in principal install solar thermal, have a heating system installed (single ovens, apartment central gas boilers, district heating, direct electric convectors) which cannot be combined with solar thermal energy (orange area).

The area checkered in red shows the calculated final solar collector deployment on a roof-by-roof level in 2030. As can be seen from the figure, only a very low share of buildings have installed solar thermal collectors above 2/3 of the restricted technical potential

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[89] Streicher et al. (2010) consider a total roof area of buildings with flat roofs of 155 km² and 479 km² for buildings with span roofs, which gives a total roof area of 634 km². However, they assume more stringent restrictions with respect to the technical applicability of solar thermal collectors or PV. Their technical potential for solar thermal and PV on roofs for the existing building stock amounts to 35+79=114 km².

considering the available roof area in the existing policy scenario. The majority of solar thermal adopters use about 30% of the roof area available for solar thermal collectors. Furthermore, it can be seen that about 30% of the buildings have no solar thermal collectors installed. Thus, it can be concluded that in this scenario the available roof area for solar thermal does not significantly limit the deployment of solar thermal energy.

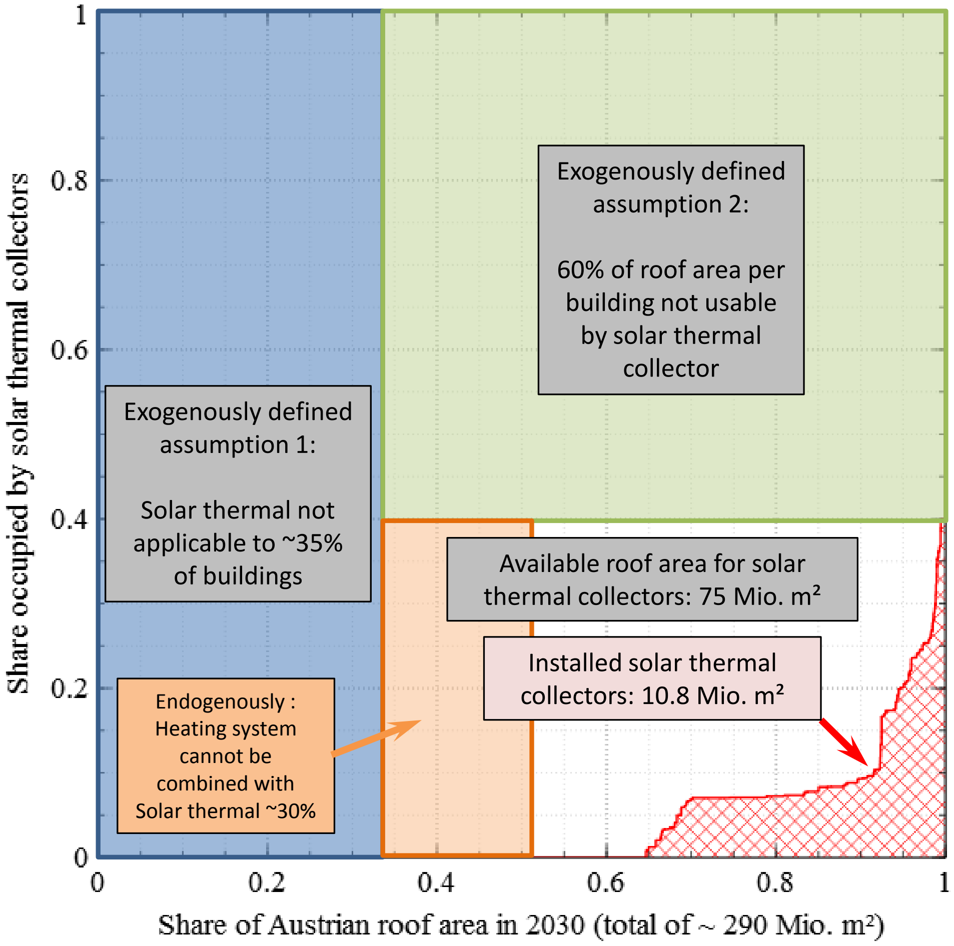

Figure 7.9 – Distribution of solar thermal collectors in the existing policy scenario.

A further decomposition of the decision-dynamics in the WEM scenario is given in Figure 7.10. In this figure the gross floor area of the building stock in 2010 is divided by energy carriers. In 2010, heating oil (extra light and light heating oil and LPG) was the energy carrier which supplied the largest gross floor area (~150 million m²) with energy for space heating, followed by district heating (~115 million m²), natural gas and wood log (~85-90 million m²). The second column represents the share of buildings with respect to building envelope-related measures. The black bar on the bottom indicates the gross floor area of buildings which do not perform any envelope related measures. The white bar on the top represents the area of the buildings which get demolished in the existing policy scenario. Both are primarily influenced by the age of the associated buildings. The cost efficiency of measures (see equation (4.26)) has a minor influence on the share of buildings performing any envelope related measures, which then also slightly influences the building demolishing rate (see equation (4.28)). The two remaining bars depict the floor area which undergoes some maintenance measures (grey checkered area) and thermal building renovation (blue area). The ratio between these two measures is heavily influenced by the cost efficiency of the thermal building renovation. The existing heating system and the associated energy-consumption-depending running costs have a large impact on the cost efficiency of thermal building renovation. This is reflected by the ratio of maintenance and thermal building renovation per energy carrier as shown in Figure 7.10. Heating systems with rather low energy-consumption-depending running costs such as wood log, district heating and heat pump will apply the maintenance technology option to a much higher degree than it is the case for heating systems with high running energy costs such as heating oil and direct electric heating.

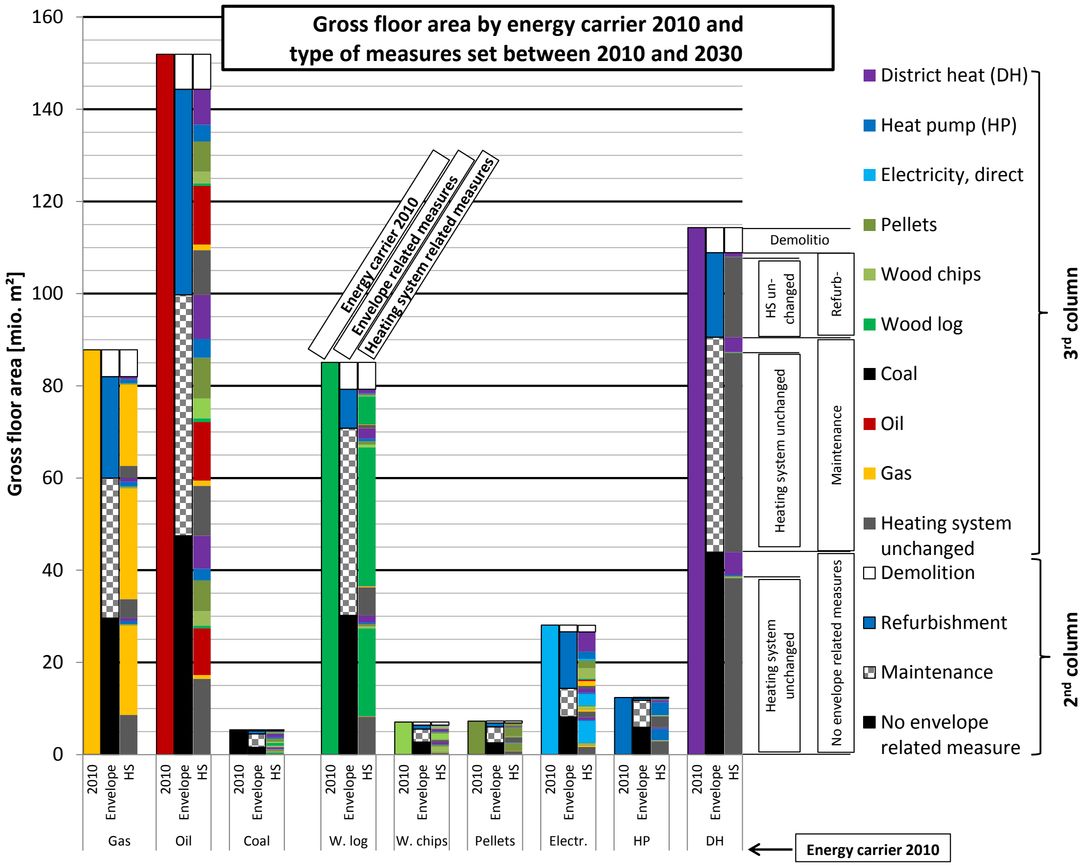

Figure 7.10 – Decomposition of the development until 2030 in the existing policy scenario of the gross floor area of buildings existing by 2010 by energy carrier in 2010 and type of envelope and heat system related measure.

The third column depicts the changes in the scenario related to the heating system. The gray area represents the share of buildings which keep the existing heating systems. In case an existing heating system (in 2010) is replaced by a newer system, the energy carrier of the new system is shown color-coded. In the scenario, buildings which are connected to district heating mostly do not change their heating system. This is implemented in the model by assuming a longer service lifetime for this type of heating system (thus, the column is dominated by the gray bar) and a high preference for the existing heating system. Buildings with heating systems deploying natural gas are also very likely not to change the energy carrier. In contrast to the district heating, this is not as strictly exogenously defined as it is the case for district heating. In fact, it is triggered by the very low preference for switching from natural gas towards solid energy carriers (for comfort reasons), however switching to other energy carriers to heating systems like heat pumps or district heating is not directly restricted. Yet compared to gas, other energy carriers do not offer significantly higher advantages to overcome the preference of keeping the existing energy carrier in this scenario. The same holds for biogenic energy carriers and heat pumps. Once installed in the building, these heating systems are likely to be kept if the existing heating systems need to be replaced by new ones.

For direct electric heating and heating oil, the situation is different. Buildings which are currently heated by direct electric heating systems mostly do not have a heat distribution system installed. Therefore the installation of another different heating system is restricted and the direct electric heating (mostly) remains in the building. In the analyzed scenario it is assumed that a building-central (high temperature) heat distribution system is installed (if it does not exist yet) in case a thermal building refurbishment is performed. This implies that once buildings are thermally renovated in the scenario, switching to a building-central heating system is not restricted any more. While direct electric heating remains in unrefurbished buildings, almost all refurbished buildings switch from direct electric heating to a different, more cost-efficient, heating system (Figure 7.10).

Buildings which use heating oil as energy carrier to supply space heating are also likely to change the energy carrier if the existing heating system has reached the end of its service lifetime. In this case, almost 50% (47.3%) of the floor area switch to biogenic energy carriers, and about 35% (33.8%) to district heating. Heating pumps rank at third place (14.3%).

7.2 Development of energy needs and final energy consumption with additional policies: the WAM scenario

This scenario assesses the effects of some additional policy measures which are under discussion in Austria and are most likely to be applied within the upcoming years.

7.2.1 Policy settings

This scenario enhances the existing policy scenario by four measures aiming for a higher share of renewable energy carriers and a lower final energy demand:

- Additional financial budget for supporting refurbishments is given.
- Higher refurbishment standards are required after 2020.
- For newly constructed and comprehensively refurbished buildings[90], a minimum share of the final energy demand has to be supplied by renewable energy carriers.
- The condensing boiler technology is demanded in case natural gas or oil boilers are installed.

First, the annually available budget for building refurbishments is increased in the WAM scenario compared to the existing policy scenario. While in the scenario shown above the available budget decreases over time, an increase is assumed in this scenario. Starting at a subsidy level of about €405 million in 2012, it increases to €540 million until 2020 and remain at this level afterwards. The financial budgets for supporting new constructions or alternative heating systems remain unchanged. The second assumption demands an increasing refurbishment standard for buildings renovated after 2020. In the existing measures scenario the refurbishment types 1-3 (Figure 6.12) are available throughout the simulation period, in the WAM scenario only the refurbishment types 2-4 are installable after 2020. The specific investment subsidies given in the WEM scenario are not sufficient to exploit the total annual refurbishment budget available in WAM scenario. Therefore, the specific subsidies are adopted in this scenario. For the refurbishment type 2 specific subsidies increase gradually to 40% in 2020 and remain constant afterwards. For the refurbishment types 3 and 4 subsidy levels increase to 45% until 2025 and stay on this level for some time afterwards.

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[90] Measures targeting the building envelope as well as the heat supply system.

The third measure regulates that in new or comprehensively refurbished buildings renewable energy carriers or district heat need to supply a minimum proportion of the final energy demand. For new residential and publicly owned buildings the target share is set to be 15% by 2015; a level that can be fulfilled by installing thermal solar combisystem. Residential buildings, which are comprehensively refurbished after 2014, need to install at least 6 m² of solar collector area per dwelling or another RES-H system (once they replace their heating system). For newly constructed non-residential buildings the minimum share of renewable energy carriers is set to 5% of the total final energy demand, again starting with 2015. Especially in new buildings legislative measures to increase the penetration rate of renewable energy carriers are implemented. Financial instruments (subsidies) are not the main instruments for this purpose anymore and their level can be reduced. Thus, in this scenario the specific investment subsidies for renewable energy carriers are reduced by 50% for new residential buildings. Finally, the fourth assumption demands that gas and oil boilers installed after 2015 must be equipped with a condensing boiler technique.

7.3 Introducing ambitious energy policies: the WAM+ scenario

7.3.1 Policy settings

The third scenario represents a scenario with ambitious policy settings beyond 2020. The scenario is based on the discussions and work done within the “WAMplus – Szenario” project (Müller and Kranzl, 2013b). It incorporates four additional policy elements:

(1) The obligation to refurbish buildings within a suitable time frame if a substantial potential for cost effective measures is identified and/or the upper limits defined within the current OIB RL 6 (OIB, 2011) are exceeded. If buildings do not have an energy performance certificate, then default data based on the building age and type and the refurbishment status should be used.

(2) The (2a) obligation to replace old, fuel based decentral heating boilers in IG-L regions. The replacement has to be done within a suitable time frame. (2b) Heating systems using renewable energy carriers or district heating should be used if technically and economically feasible.

(3) The usage of natural gas is restricted, if the building has a central heating system and the building is not located in an IG-L region. In regions other than IG-L regions

installing natural gas boilers is prohibited if heating systems using renewable energy carriers or district heating are available and are technically and economically feasible.

(4) The introduction of a CO_2 tax of 70 €/t CO_2 by 2021. Biogenic energy carriers are assumed to be carbon neutral and thus CO_2 tax exempt. Furthermore, it is assumed that the CO_2 tax is incorporated in the retail electricity and district heating prices.

7.3.2 Implementation of WAM+ specific measures

(1) The obligation to refurbish buildings within a suitable time frame.

It is assumed that this policy consists of three sub-measures:

- Better energy performance indicators are required if thermal refurbishment is applied. In the applied scenario only refurbishment types 3-5 are available after 2020.
- If building shell related measures are taken and the building does not fulfill certain energy performance requirements, these measures need to reduce the energy needs. This means that the maintenance option is not available any more by 2021 (except for energy-efficient buildings).
- The obligation to refurbish buildings increases the renovation rate, due to the temporarily accelerated renovation cycle. The term “substantial potential for cost effective measures” in the chosen interpretation depends on the energy performances indicator and on the age of the building and its building components while the actual economics of renovation measures are not directly considered. With respect to the age of the building envelope, it is assumed that the refurbishment obligation targets only buildings once the components surpass 90% of the characteristic façade lifetime, which is about 40-55 years (see section 4.5). The limit of the energy performance indicator that must be exceeded in order to be covered by the obligation is set in accordance with the OIB (2012a) document to $q_{H,nd,\min}^{+renov}$ =25kWh/m² (see equation (6.2)). Finally, a calibration parameter $f_{\text{ren\_inc}}$ is introduced which scales the effect of accelerated renovation cycles on a global level and reflects the vague term “suitable time frame”.

$$s_{measure\_inc,b,t} = s_{measure,b,t} \cdot \left(1 + f_{age} \cdot f_{H,nd} \cdot f_{ren\_inc}\right) \tag{7.1}$$

$$f_{age} = \min\left(1, \frac{\max(0, t_{age} - t_{\min})}{t_{\max} - t_{\min}}\right) \tag{7.2}$$

$$f_{H,nd} = \min\left(2, \frac{\max(0, q^{+renov}_{H,nd,norm,build} - q^{+renov}_{H,nd,\max})}{q^{+renov}_{H,nd,\max} - q^{+renov}_{H,nd,\max}}\right) \quad (7.3)$$

where

$s_{measure\_inc,b,t}$ ... Increased renovation rate

$s_{measure,b,t}$ ... Renovation rate according to equation (4.27)

t_{age} ... Age of envelope

$t_{\min}$ ... $0.9\lambda_{envelope}$ (characteristic lifetime of envelope ~0.9 × 40-55 yr)

$t_{\max}$ ... $1.5\lambda_{envelope}$ (characteristic lifetime of envelope ~1.5 × 40-55 yr)

f_{ren_inc} ... Calibration factor for the sharpness of term "suitable time frame"

$q^{+renov}_{H,nd,norm,build}$ ... Specific l_c-corrected energy needs of the building [kWh/(m²a)]

$q^{+renov}_{H,nd,\min}$ ... 25 kWh/m²yr

$q^{+renov}_{H,nd,\max}$ ... 55 kWh/m²yr

The calculated increase rate of envelope measures is shown in Figure 7.11.

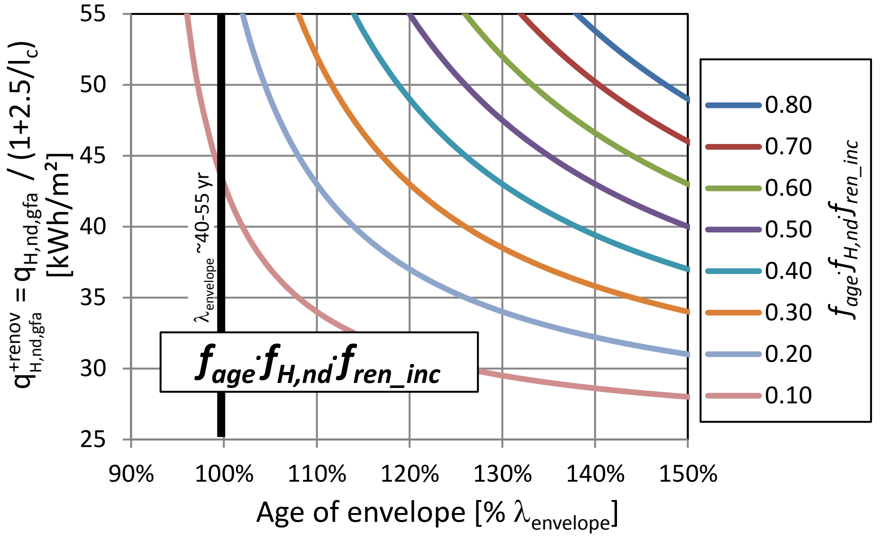

Figure 7.11 – Increase of renovation measures rate in dependence on the age of the façade and the characteristic building length-corrected specific energy needs.

(2a) The obligation to replace old, fuel-based decentral heating boilers in IG-L regions.

This measure leads to an accelerated replacement cycle of heating systems in buildings located in IG-L regions. Their estimated share on the energy demand for heating and domestic hot water is shown in chapter 3.2.5. This measure is implemented similarly to the previous measure; again the age and the (boiler) efficiency, as well as a factor $f_{\text{boiler\_inc}}$ which translates the term “suitable time frame” into a mathematical form, are considered. The increased replacement rate factor is set on top of the “natural” boiler replacement rate as calculated by the lifetime distribution based approach (see section 4.5, 6.1.1 and Appendix A.3).

$$s_{measure\_boiler\_\mathrm{inc},b,t} = s_{measure\_boiler,b,t} \cdot \left(1 + f_{age,hs} \cdot f_{boiler\_\mathrm{inc}}\right) \tag{7.4}$$

$$f_{age,hs} = \min\left(1, \frac{\max(0, t_{age,hs} - t_{\min})}{t_{\max} - t_{\min}}\right) \tag{7.5}$$

where

$s_{measure\_boiler\_inc,b,t}$	... Increased boiler replacement rate
$s_{measure\_boiler,b,t}$	... Boiler replacement rate according to equation (4.27)
$t_{age,hs}$	... Age of heating system
$t_{\min}$	... $0.9\lambda_{hs}$ (characteristic lifetime of envelope ~0.9 × 28-35 yr)
$t_{\max}$	... $1.2\lambda_{hs}$ (characteristic lifetime of envelope ~1.2 × 28-35 yr)
f_{boiler_inc}	... Calibration factor for the sharpness of term "suitable time frame"

Furthermore it is implemented that owners are only obligated to replace an existing natural gas fired boiler if a newly installed boiler would increase the annual efficiency by more than 6%. This assumption incorporates that existing condensing boilers are excluded from this measure.

(2b) Privileged usage of heating systems using renewable energy carriers or district heating if technically and economically feasible.

The expression *"usage of heating systems using renewable energy carriers or district heating"* is interpreted in the sense that the share of heating systems utilizing fossil and electric energy is reduced compared to the share based on the logit-diffusion process. The expression *"if technically and economically feasible"* is implemented by considering the economics of different alternatives. Thus, the reduction of the market share of non-renewable and non-DH systems depends on the cost relation between these heating systems and, considering the ultimate market share of energy carriers (see section 4.7), the cost of the least expensive heating system utilizing a higher share of energy coming from renewable energy resources or district heating.

The cost relation between different heating systems is described by the ratio $r_{hs,i,j}$ of their TCH (total cost of heating).

$$r_{hs,i,j} = c_{hs,i} / c_{hs,j} \tag{7.6}$$

where

$r_{hs,i,j}$ ... Cost ratio between heating system i and heating system j
$c_{hs,i}$ ... Total costs of heating (TCO) of heating system i
$c_{hs,j}$ ... Total costs of heating (TCO) of heating system j

Furthermore, *economically feasible* is expressed by two threshold levels. If the cost ratio surpasses a certain level $f_{\mathrm{c,max}}$, then it is assumed that technology i is not economically feasible. If on the other hand the cost ratio $r_{hs,i,j}$ is lower than a specific threshold $f_{\mathrm{c,min}}$, then technology i is fully economically feasible compared to option j.

$$f_{hs,i,j\_econ\_feas} = \frac{r_{hs,i,j} - f_{c,\min}}{f_{c,\max} - f_{c,\min}} \qquad (7.7)$$

$$0 \leq f_{hs,i,j\_econ\_feas} \leq 1$$

where

$f_{c,\min}$ ... Cost relation between heating system i and alternative heating system j, which, if $c_{hs,i} / c_{hs,j}$ remains lower, marks an economical feasability of 100%
$f_{c,\max}$ ... Cost relation between heating system i and alternative heating system j, which, if exceeded by $c_{hs,i} / c_{hs,j}$, marks an economical feasability of 0%
f_{hs,i,j_econ_feas} ... Factor describing the economical feasibility of technology i compared to j

A heating system i is only restricted by an alternative option j if the share of renewable energy carriers utilized by option j is larger than the share utilized by system i.

$$f_{non-res} = \begin{pmatrix} 1 & \forall\ s_{hs,i,\,fossil} > s_{hs,j,\,fossil} \\ 0 & \forall\ s_{hs,i,\,fossil} \leq s_{hs,j,\,fossil} \end{pmatrix} \qquad (7.8)$$

where

$s_{hs,i/j\_fossil}$ ... Share fossil and electric energy on total delivered energy using heating system i / j

The technical feasibility is defined by considering the ultimate market penetration of energy carriers per energy carrier region utilized by each technology. It is assumed that the restriction of market shares is independently distributed. The factor $x_{hs,i}$ describing the reduction of the market share (of the fossil and electric energy) of a technology i considering the *technical and economical feasibility* is defined in the next equation.

$$x_{hs,i,\,fossil} = 1 - \sum_{j}^{I} \left(1 - \max \begin{pmatrix} 0, \\ f_{hs,i,j\_econ\_feas} \cdot f_{non-ren} \cdot \left(\sum_{k}^{K} S_{\max,t,k} - \sum_{l}^{L} S_{\max,t,l} \right) \end{pmatrix} \right) \qquad (7.9)$$

$$0 \leq x_{hs,i} \leq 1$$

where

$S_{\max,t,k}$ ... Upper market penetration level of techology k in t

K ... Set of available heating system technologies $K \in I$, for which $s_{hs,j,fossil} \geq s_{hs,k,fossil}$ is true

L ... Set of available heating system technologies $L \in K$, for $l \neq j$ is true

By considering the share of renewable energy carriers (and district heating) utilized by each technology

$$f_{reduction\_hs,i,b,t} = \max\left(0,1-\left(1-x_{hs,i,fossil}\right)s_{hs,i,fossil}\right) \tag{7.10}$$

where

$f_{reduction\_hs,i,b,t}$ ... Reduction factor for share of heating system i after privileging non-fossil energy carriers

s_{hs,i_fossil} ... Share fossil and electric energy on total delivered energy using heating system i

the market shares for an technology i is adjusted and normalized (=setting the sum of all market shares to 1)

$$s_{hs,i,b,t} = \min\left(1, \frac{s_{hs,i\_\log it\_diffusion,b,t} \cdot f_{reduction\_hs,i,b,t}}{\sum_{j=1}^{I} s_{hs,i,b,t}}\right) \tag{7.11}$$

where

$s_{hs,i,b,t}$ ... Share of heating system i after privileging non-fossil energy carriers

$s_{hs,i\_\log it\_diffusion,b,t}$ ... Share of heating system i according to the logit-diffusion approach

The following illustrates the implemented approach with two simple examples: A hypothetical building can chose from three hypothetical alternative heating systems with identical costs ($c_{hs,i}$=$c_{hs,j}$), current market penetration and user preferences ($\mu_{hs,i}$=$\mu_{hs,j}$): a (1) biomass fueled boiler, a (2) natural gas boiler with solar collectors and a solar energy contribution of 30% and a (3) monovalent natural gas boiler.

In the first case, the ultimate market penetration limit of all alternatives is set to 1, $f_{c,\max}$=1.1, $f_{c,\min}$=0.9. Without privileging renewable energy carriers all technologies would get a share $s_{hs,i\_logit\_diffucion,b,t}$ = 33.3%. Since the privileged usage of renewable energy carriers is demanded, in a first step the share of technology (3) is reduced by 50%, the share of technology (2) by 50%x70% = 35%. The missing share of 28% that is accordingly derived is added to the technologies according to their reduced market shares (= normalizing market shares). Thus, we get market shares $s_{hs,i,b,t}$ of 46.5% for technology (1), 30.2% for technology (2) and 20.3% for technology (3).

In the second example, the ultimate market share of technology (1) is limited to 40% and that of technology (2) to 75%. In this case, the logit/diffusion process would result in a market share of 18.6% for technology (1), 34.9% for technology (2) and 46.5% for alternative (3). The implemented approach of demanding a privileged installation of heating systems utilizing alternative energy carriers would reduce in a first step the market share of technology (2) by 50%x70%x40% = 14%, and the share of technology (3) by 50%x(1-(1-0.4).(1-0.75) = 42.5%. Before the normalizing of the market shares, technology (1) receives a share of 18.6%, technology (2) of 30% and technology (3) of 26.7%. The difference between the sum of these shares and 100% is 24.7%. After normalization the final market shares are 24.7% for technology (1), 39.8% for alternative (2) and 35.5% for technology (3).

(3) Restricted usage of natural gas.

For all buildings located in IG-L regions, the installation of natural gas fueled boilers is allowed without restriction to the privileged usage of alternative energy carriers for heating and domestic hot water supply. For buildings not located in IG-L regions, the installation of natural gas fueled boilers is allowed only if (a) the building is not equipped with a central heating system (e.g. apartment central gas heating systems) or (b) no economically feasible heating systems are available (see section above).

IG-L regions are defined as such, because air pollution is particularly high in these areas and a special focus is put on emission reductions. From this point of view, installing wood log boilers, which usually have rather high emission rates, seems counterproductive with respect to air quality. Therefore, the effect of prohibiting wood log boilers in these regions is calculated in an alternative sensitivity run applying a very broad interpretation of economic feasibility. This interpretation of economic feasibility basically means that most heating systems utilizing alternative energy carriers are economical ($f_{c,\min}$=$f_{c,\max}$ =3) and thus the installation of fossil heating systems prohibited in most cases. A default assumption of the shown scenarios is that wood log boilers are allowed in rural regions only. By prohibiting the installation of wood log in such a scenario setting, the usage of wood log in IG-L regions is reduced by about 50% compared to a scenario where this restriction does not apply (Figure 7.12). This effect constitutes the primary effect of the policy measures and triggers several subsequent effects. As a secondary effect, those buildings which cannot install the wood log boilers anymore must resort to other energy carriers. The results show that, according to the model approach and data, these buildings substitute the wood log mainly with wood chips and wood pellets. To a minor degree also natural gas, electric heat pumps and small scale district heating are used as alternatives. As a consequence, a higher share of the available wood chips and wood pellets (see cost-potential curves shown in Figure 6.10) is utilized in IG-L regions, and lower quantities at prices as low as in the alternative scenario are available to buildings in non-IG-L regions. This triggers a reduced usage of these energy carriers in non-IG-L regions, which are then substituted mainly by natural gas and wood log.

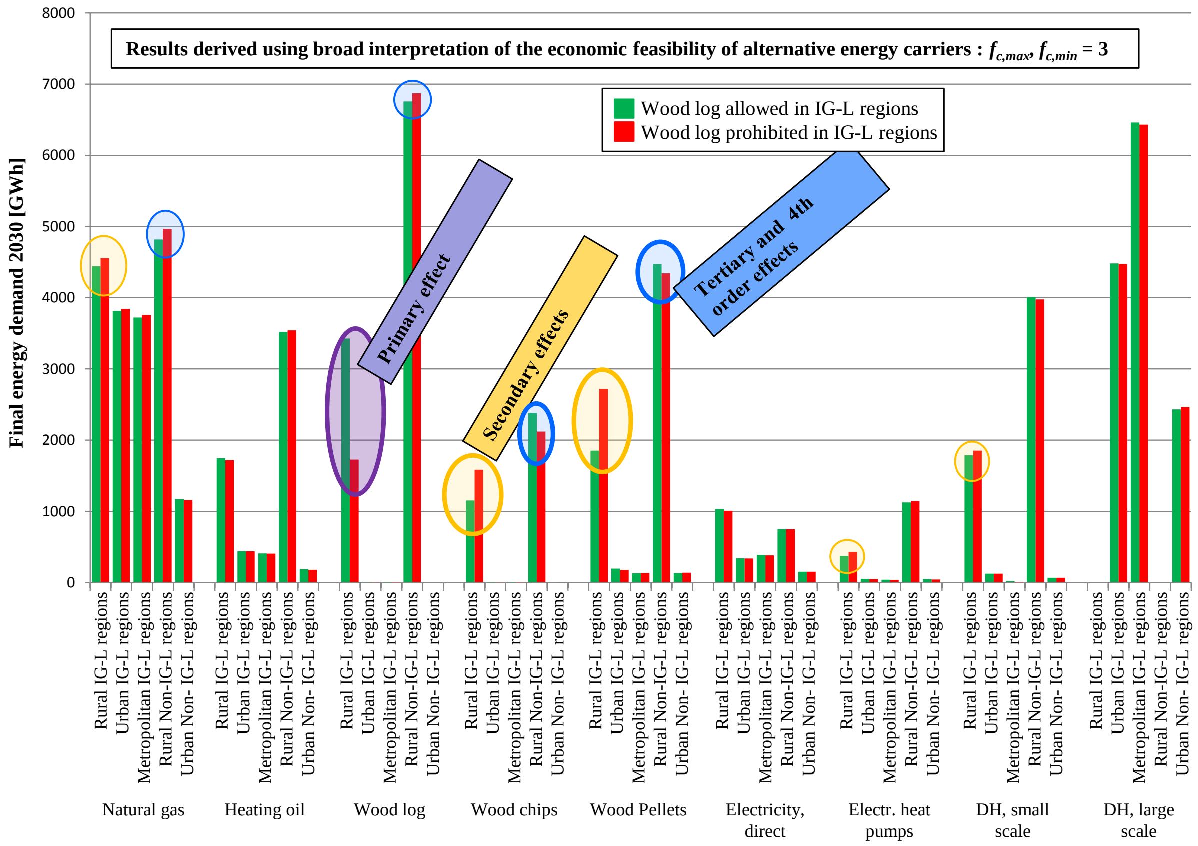

Figure 7.12 – Analysis of the effect of prohibiting wood log in IG-L regions applying a comprehensive interpretation of economic feasibility. (The data in this graph include the final energy demand of buildings from the industrial sector, see Appendix A.1).

(4) Introduction of a CO_2 tax of 70 €/t CO_2 by 2021.

By 2021, a CO_2 tax of 70 €/t CO_2 (incl. 20% VAT)[91] will be imposed on fossil energy carriers, district heat and electric energy. The tax is incorporated in the retail consumer energy prices and has to be paid by all consumers of delivered energy (at least) for space conditioning and domestic hot water supply. The following CO_2 factors for fossil and secondary energy carriers are applied.

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[91] 58.3 €/t CO_2 + 20% VAT.

Table 7.4 – Specific CO_2-emission factors.

	CO_2 emission factors [kg/MWh]
Electricity	350
Natural gas	200
Heating oil	272
Coal	364
District heating	100

Due to the CO_2 tax, the retail energy price are increased by about 12%-17% for electricity and district heating, 20%-24% for natural gas and heating oil products and 65% for coal.

7.4 Comparing the scenarios WEM, WAM and WAM+

7.4.1 Renovation rate and boiler replacement rate

The additional policy effort in the WAM and WAM+ scenarios to reduce the energy needs of and delivered energy to buildings has an impact on the number of buildings which are retrofitted in some way. The increased financial support budget in the WAM scenario leads to an increase of the thermal renovation rate between 2010 and 2020 from 1.0%p.a. to 1.1%p.a. In the period 2021-2030 the renovation rate drops by 0.8%. Although the renovation rate does not substantially increase compared to the WEM-scenario, the WAM scenario yields higher energy savings since refurbishments with a higher thermal quality are applied in the WAM scenario (see assumptions shown in section 7.2). The total rate of envelope related measures remains unchanged compared to the WEM-scenario.

Until 2020, the WAM+ scenario is identical with the WAM-scenario, thus resulting in the same retrofitting rates. For the period 2021 to 2030 significant changes can be observed. First, a drop in the total rate of building envelope related measures is observed. While in the WEM and WAM scenario about 2.5% of buildings set any envelope related measures, this indicator drops to 2.1% in the WAM+ scenario. This is triggered by increased average costs of refurbishment measures, since the low quality thermal renovations and the maintenance options, which constitute the most economic options for many buildings, are prohibited for most buildings by the (exogenously) defined scenario assumptions. While facing increasing average costs, the share of buildings which refurbish their buildings declines (defined by equations (4.24) - (4.27)). At the same time, the thermal renovation rate increases from 0.8% to 1.8%, leading to a steep drop (from 1.7% to 0.3%) of buildings choosing the maintenance option.

Table 7.5 – Renovation rates and heating systems installation rates (including heating systems in new buildings).

	2010-2020			2021-2030		
	WEM	**WAM**	**WAM+**	**WEM**	**WAM**	**WAM+**
Thermal renovation rate	1.0%	1.1%	1.1%	0.8%	0.8%	1.8%
Total measure rate, incl. maintenance	2.4%	2.4%	2.4%	2.5%	2.5%	2.1%
Boiler exchange rate, residential buildings	1.7%	1.7%	1.7%	2.4%	2.5%	2.6%

7.4.2 Energy needs for heating

The effects on the energy needs for heating (considering user-behavior) are shown in the next figure. The black area represents the energy need of buildings which do not perform any envelope related measures within the simulation period until 2030. In the WEM and WAM scenario a gross floor area of about 205 to 210 million m² (representing about 25 TWh) is not refurbished by 2030, while in the WAM+ scenario an additional 30 million m² (+2 TWh) is not refurbished. Since the black area represents the near term potential for building refurbishment after the simulation period, the WAM+ scenario does not deplete the refurbishment potential to the same degree as the WEM and WAM scenario.

The gray area depicts the energy needs of buildings which choose the maintenance (renovation) option in the scenarios until 2030. The area indicates an unfulfilled energy saving potential in the scenario, since these buildings are not likely to set building envelope related energy saving measures in the near term future after the scenario's timeframe of 2030. In the WEM and WAM scenario a gross floor area of about 210 to 215 million m² (~24 TWh) opts for the maintenance options. Due to the introduced policy instruments after 2020 in the WAM+ scenario, the energy needs of buildings choosing the maintenance option is cut down to ~13 TWh. The energy needs of buildings after applying thermal renovation is shown by the blue area, the energy savings are indicated by the green area. In the WEM scenario, 141 million m² are thermally renovated, decreasing the energy needs by about 10.3 TWh. In the WAM scenario, the energy savings increase by 22% (12.6 TWh), although the refurbished gross floor area increases by less than 3%. Thermal renovation in the WEM scenario decreases the energy needs of refurbished building, considering the rebound effect (see section 4.4.4), on average by 48%. In the WAM scenario this indicator increases to 55%. In the WAM+ scenario the thermally refurbished gross floor area increases to about 215 million m² (almost +50%). The energy needs of refurbished buildings decreases in this scenario by 60%.

The energy needs of newly constructed buildings amount to about 5.2 TWh in the WEM and WAM scenario. In the WAM+ scenario they are by about 5% lower. As can be seen in Figure 7.13, although it is generally important to construct new buildings in an energetically efficient way, the possible additional energy reduction of additionally (compared to the WEM/WAM scenario) enforced policy instruments targeting new buildings is limited, compared to the potentials resulting from the existing buildings stock.

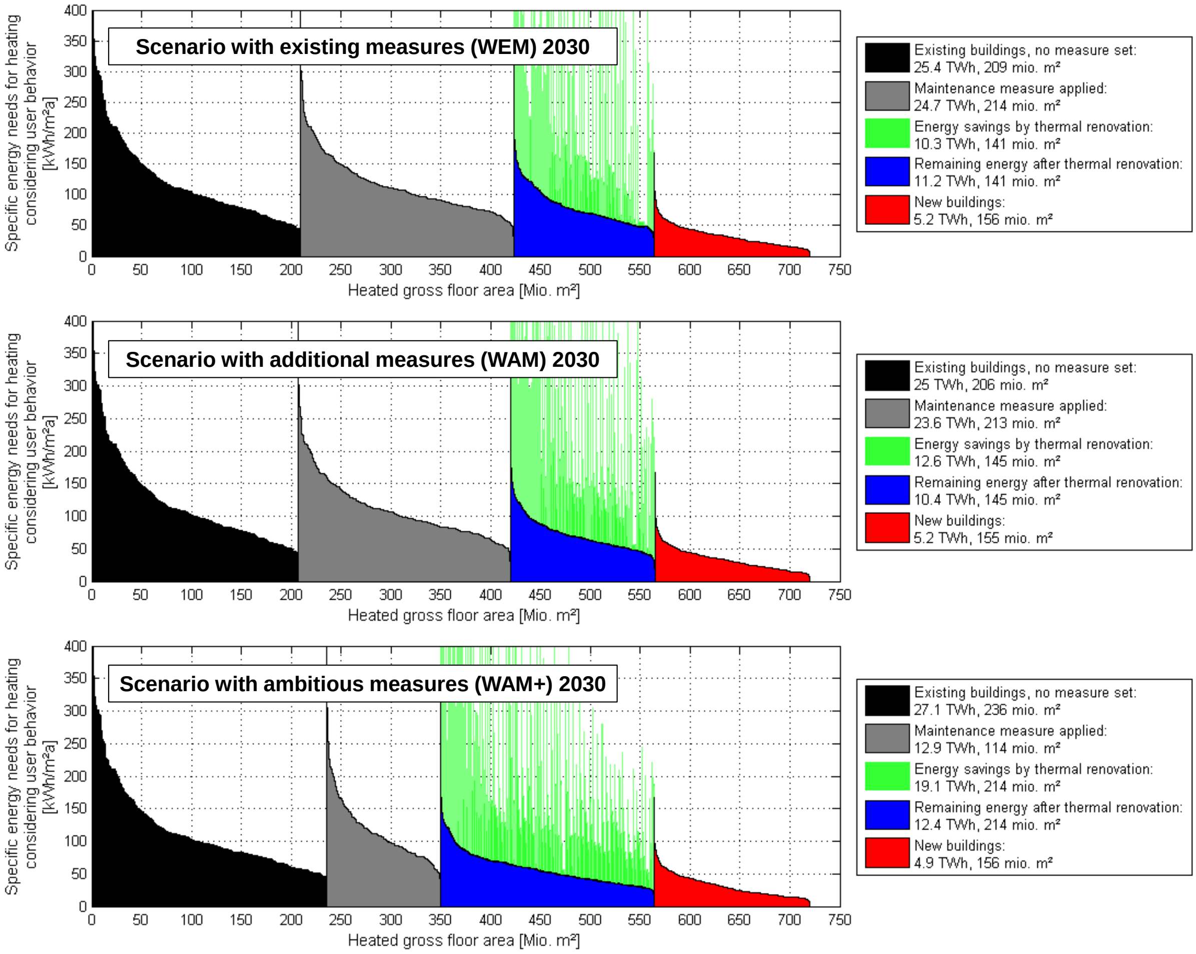

Figure 7.13 – Energy needs for heating per type of measure.

The renovation activities do not only have a direct impact on the energy needs for heating, but also influence the supply line temperature of the heat distribution system. This parameter defines the efficiency of the heat generation system (boiler) and is especially critical for the performance of heat pumps and thus their cost-efficiency. The share of energy needs for heating per supply line temperature categories depicts Figure 7.14. For the existing building stock in 2010 it is considered that about 50% of the energy needs occur in buildings with no building central space heating distribution system or heat distribution system with a supply line temperature of 56°C or more. This share declines until 2030 to about 40%, while the share of energy needs supplied by systems with a supply line temperature of less than 41°C rises to about 30%.

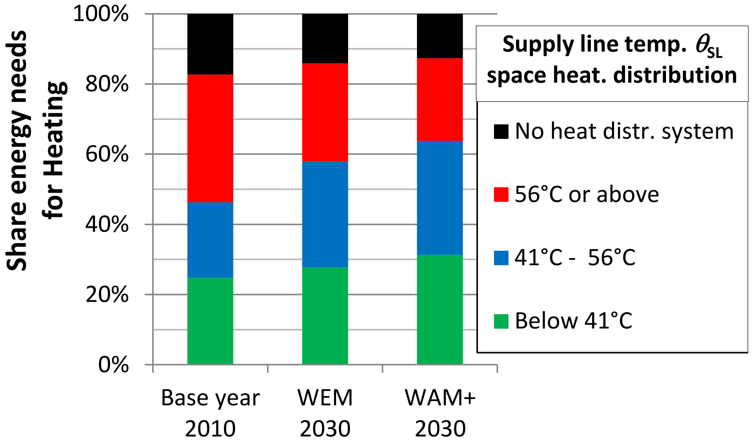

Figure 7.14 – Energy needs for heating per supply line temperature categories of the space heating distribution system.

7.4.3 Final energy demand for heating and domestic hot water supply

A comparison of the final energy demand in the three scenarios, WEM, WAM and WAM+, is done in Table 7.6. Starting with the status-quo in 2010, the development until 2020 (WEM only, since the differences between the scenarios are almost negligible) and 2030 per federal states is shown. Compared to the situation in 2010, in the three scenarios the Austrian final energy demand is reduced by 15% to 25% until 2030.

Table 7.6 – Reduction of final energy demand compared to status-quo of 2010.

	2020	**2030**		
	WEM	**WEM**	**WAM**	**WAM+**
Burgenland	-5.6%	-14.3%	-15.8%	-23.9%
Carinthia	-8.9%	-18.8%	-21.2%	-28.8%
Lower Austria	-5.9%	-14.6%	-16.7%	-24.7%
Upper Austria	-6.8%	-16.1%	-18.1%	-25.9%
Salzburg	-8.1%	-17.8%	-19.9%	-28.1%
Styria	-7.9%	-17.6%	-19.7%	-27.5%
Tyrol	-8.4%	-18.3%	-21.1%	-29.1%
Vorarlberg	-7.6%	-17.2%	-20.0%	-27.6%
Vienna	-2.1%	-8.3%	-10.0%	-18.8%
Austria	**-6.3%**	**-15.2%**	**-17.3%**	**-25.3%**

Looking at the final energy demand reduction per federal state, it can be seen that reduction in Vienna is significantly lower than that in the other federal states. The reasons lie in the building stock and the energy carriers used. First, due to its urban structure, the building stock in Vienna mainly consists of larger apartment buildings. They are already associated with lower energy needs and thus lower energy saving potentials than buildings with a larger surface-to-volume ratio. Secondly, the share of energy used in historic buildings, which are more difficult and costly to refurbish, is above average. Thirdly, district heating is widely applied Vienna, while heating oil only plays a minor role (Figure 7.15). This means that energy carriers associated with low renovation rates, due to their lower-than-average energy-consumption-depended annual costs (biogenic energy carriers, heat pumps and district heating) are applied in Vienna[92] above the Austrian average (2010: 44% versus 40%), and heating systems associated with high refurbishment rates (heating oil and direct electric heating) are deployed below average (2010: 15% versus 31%).

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[92] Of these three types, only district heating is widely applied in Vienna.

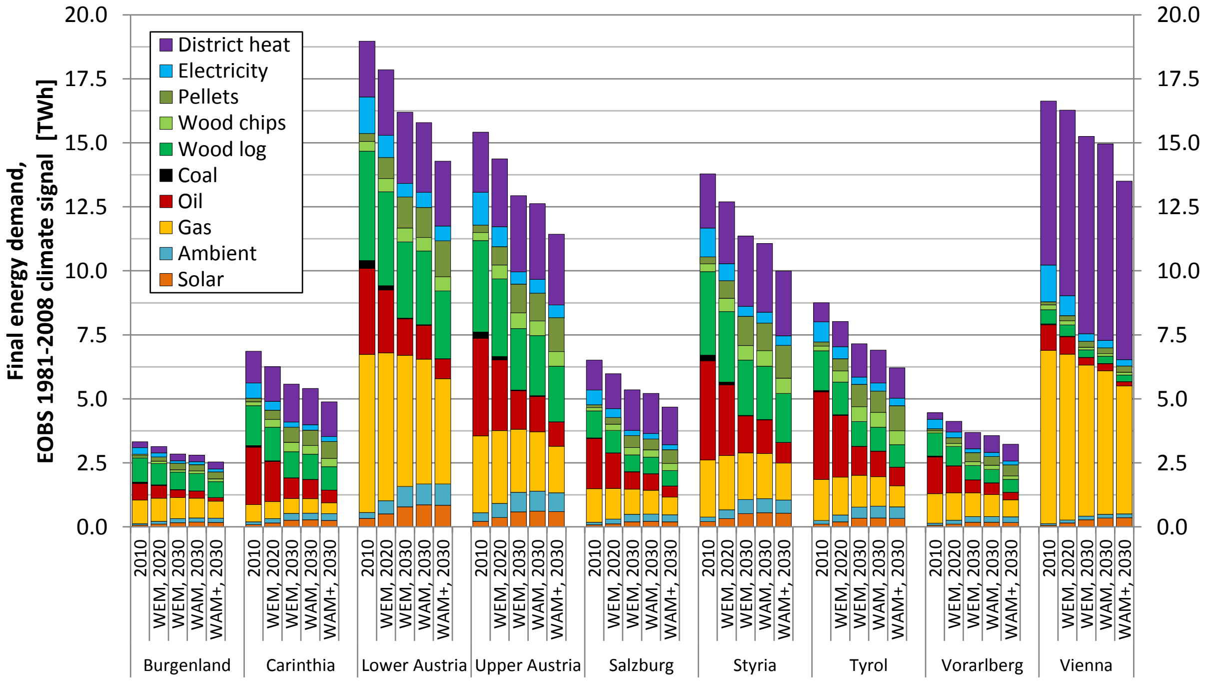

Figure 7.15 – Final energy demand for heating and domestic hot water supply per energy carrier and federal state.

In fact, the share of heating oil and electricity of the final energy demand in 2010 correlates in the three scenarios with the reduction of the final energy demand reduction until 2030 (Figure 7.16).

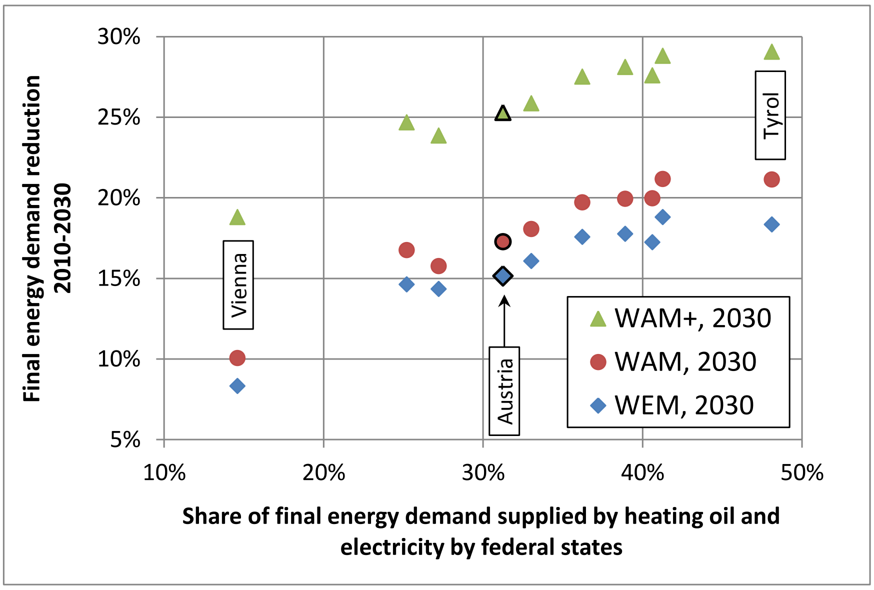

Figure 7.16 – Final energy demand reduction against the share of heating oil products and electricity in 2010.

7.4.4 Annual expenditures

This section assesses the total annual costs associated with the energy consumption for space heating and domestic hot water, building construction and refurbishment activities as derived in the three scenarios. Six cost groups are defined for the subsequent analysis; directly given public investment subsidies are reported separately:

- Annual energy-consumption-depending running costs;
- Annual energy-consumption-independent operation costs;
- Estimated investments in building construction activities (only cost categories 2, 3C.02, 3C.03 and 4A-4C according to ÖNORM 1801-1 are considered, which represent about 50% of total construction costs)
- Estimated investment in building refurbishment activities (cost categories 4A-4C)
- Estimated investment in heat supply systems (cost category 3C.01)
- CO_2-tax

For the period of 2010 to 2015, the average annual expenditures are estimated to be around $€_{2010}$ 18 billion (Figure 7.17). The construction of new buildings (incl. subsidies) is responsible for the largest share (€ ~8.2 billion p.a., ~46%) of these expenses, followed by consumption-dependent annual energy costs ($€_{p.a.}$ 6.2 billion, ~35%). The investments into building refurbishments (including maintenance and public subsidies) and heat supply systems for this period amount to about € 2.8 billion p.a. (16%). This composition changes over time in and between the drawn scenarios. In all scenarios, the annual expenditures decrease until 2030 compared to the 2010 values. This, however, is largely driven by reduced construction activities related to new buildings. Compared to the period 2010-2015, the expenditures for new constructions for the period 2026-2030 decrease by about € 2.3 billion p.a., and are thus responsible for about 65-70% of the annual expenditure reduction in the WEM and WAM scenario. If the new-buildings-construction activities are not counted, the annual expenditures decrease in the WEM scenario from $€_{2010}$ 9.8 billion for the period of 2010-2015 to about $€_{2010}$ 8.6 billion for the period of 2026-2030. This number results from a net decrease in investment activities (€ -150 million p.a.) and a decrease in annual energy costs of about € 1.05 billion. Compared to the WEM-scenario, the additional policy instruments in the WAM-scenario decrease the annual energy expenditures by additional $€_{2010}$ 170 million for the period of 2026 to 2030. This, however, comes with increasing investment activities of €$_{p.a.}$ 430 million. This means that if future benefits from energy cost savings are not counted, the WEM-scenario is more cost-efficient than the WAM scenario. Nonetheless, annual expenditures (excluding construction cost of new buildings) in the WAM scenario are still lower in the period 2026-2030 (less than €$_{2010}$ 9 billion) than they are in 2010-2015. The WAM+ scenario forces massively increased renovation activities for the period after 2020. This can be seen in the annual expenditures. Compared to the WAM scenario, average annual investments increase from ~€$_{2010}$ 3.3 billion (excl. new constructions) to €$_{2010}$ 5.4 billion for the period of 2021 to 2030. The average annual energy costs for the period 2026-2030, however, only decrease by €$_{2010}$ 500 million, compared to the WAM scenario.

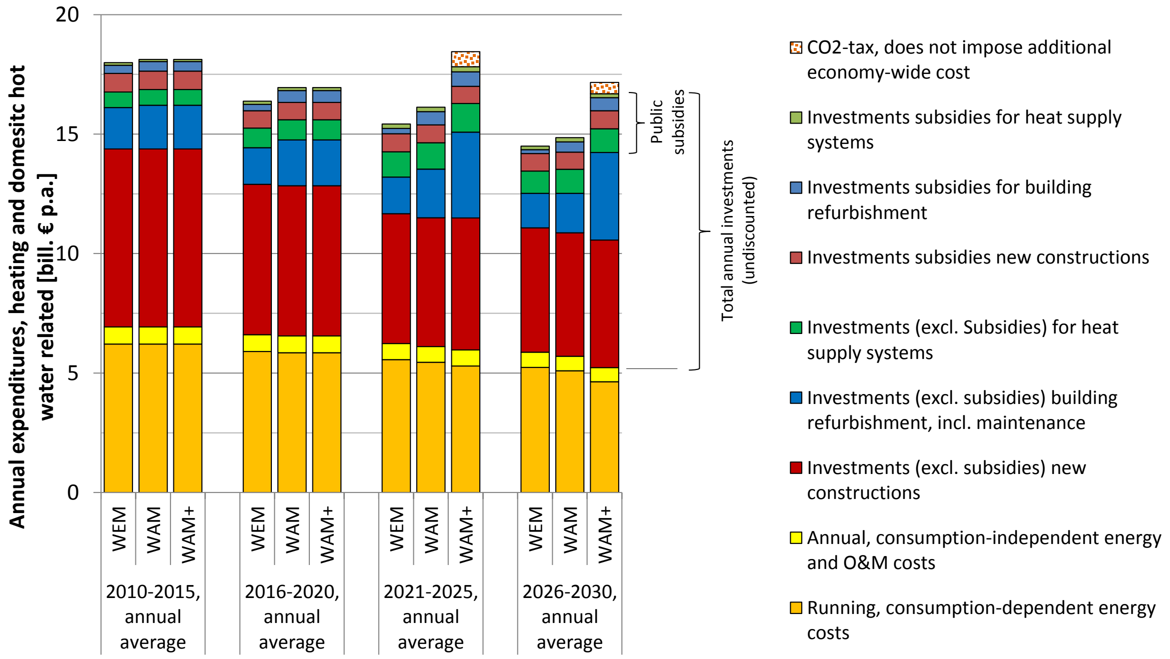

Figure 7.17 – Annual expenditures related to building construction and refurbishment, space heating and domestic hot water preparation.

Although the WAM+ scenario is probably not cost-effective in the long run, the additional costs depicted in Figure 7.17 highly overestimate the overall costs the WAM+ scenario adds. First, the annual energy costs represent the average for a five year period. Thus, the energy savings triggered by the annual investment costs are not fully accounted for in the five year period, but lead to already lower annual energy costs by 2030. Secondly, the WAM+ scenario incorporates an accelerated investment-cycle scenario for a given period. This then implies that future investment activities in the WAM+ are lower than in the WAM-scenario, since a larger share of the building stock undertakes a high quality thermal renovation already (see Figure 7.3).

7.5 Decomposition of the impact of different drivers on the final energy demand in buildings

In order to understand the drivers and their impact for the development of the final energy demand, a decomposition analysis is done. The following drivers are distinguished in this analysis:

- **Increasing heated floor area and increasing income of household:** In the applied model, the increasing household income decreases the budget share spent for consumption-dependent heating and domestic hot water related energy expenditures und leads ceteris paribus to increasing indoor temperatures. The gross floor area is not endogenously influenced by this variable.
- **Energy prices:** The energy prices have an impact on the decision process of (1) whether to refurbish a building or not, and if so, (2) how, and (3) the choice for newly installed heating systems. In addition, the prices determine the budget share spent for energy and thus have an impact on the chosen indoor temperature.
- **Demolition of existing buildings and their replacement by newly constructed buildings:** A specific share of existing buildings is replaced by newly constructed buildings every year. The demolition rate is determined according to the approach described in chapter 4.5.2.
- **Legislative measures regulating the energy performance of newly constructed buildings:** According to the OIB (2012a), the energy performance of new constructions needs to increase steadily until it reaches a Nearly Zero Energy Performance level in 2021 and thus meets the requirements defined in the Directive 2010/31/EU.
- **Refurbishment measures that reduce the energy needs of existing buildings:** By improving the thermal quality of the building envelope of existing buildings, their energy needs can be reduced. In the applied model, measures can, but must not necessarily have an impact on the energy need of the buildings. The subsequently so-called maintenance measures are measures which are set because façades and windows have reached the end of their lifetime and need to be replaced or at least demand some comprehensive repair

work. They, however, do not reduce the energy needs. The share of energy relevant refurbishment options that are chosen depends on the regulatory policy instruments, the economics of those measures and the alternative maintenance.

- **The replacement of existing heat supply systems (boilers):** Based on the cumulated failure rate of boilers, a certain share needs to be replaced on an annual basis. The choice of newly installed heating systems depends on the existing systems, regulatory policy instruments, the availability of energy carriers in different regions and on the economics of the different available alternatives. Usually the replaced heat boilers have lower efficiencies than the new ones which consequently lead to a decreasing final energy demand.
- **Financial policy instruments that support energy-efficient new buildings:** Newly constructed buildings receive some support if they comply with a better energy indicator as demanded by the regulatory instrument.
- **Financial policy instruments that support the refurbishment of existing buildings:** Existing buildings receive some support if they improve their energy performance.
- **Financial policy instruments that support alternative heating systems:** Investment subsidies are granted for the installation of heating systems deploying renewable energy sources or for the connection to district heating.
- **Climate change** and the associated increasing outdoor temperatures have an impact on the energy needs of buildings. The analysis of this effect is shown in section 7.6.

The actual impacts of these drivers on the final energy demand of the policy scenarios described above are analyzed in a set of 23 scenarios. Beginning with the building stock in 2010 and its final energy demand for heating and domestic hot water, different drivers are activated sequentially. The results for the gross floor area according to type of measure and the final energy demand for the building stock are shown in the following figure. The base year of this decomposition is the year 2010 with a final energy demand of 96.6 TWh and a conditioned gross floor area of 584 million m². The results are depicted in Figure 7.18 (Effects on heated gross floor area), Figure 7.19 (Final energy demand in 2020) and Figure 7.20 (Final energy demand in 2030).

- **Scenario 1: Increasing household income**
  The existing building stock (the number of buildings, their envelopes as well as their heat supply systems) remains the same as in 2010; no construction activities take place.

Compared to the 2010 level, households increase their income by 13% in 2020 and by 26% until 2030. The energy prices remain at the 2010 level, and the EOBS 1981-2006 climate data, which represent the average climate for the period of 1981 to 2006 are applied.

Impact: The effect of increasing household incomes, as implemented in the model, increases the final energy demand by 1.5% in 2020 and by 2.8% in 2030. Due to the higher consumption-depending energy costs of heating systems utilizing fossil energy carriers or electricity, the effect for these energy carriers is slightly higher (2.9%) than the effect for buildings using renewable energy carriers and district heating (2.6%). Considering that the income dependency is applied for residential buildings only, which are responsible for about 70% of the final energy demand, the implicitly modeled short-term[93] income elasticity for the existing residential building stock is about 15%.

- **Scenario 2: Additional conditioned floor area**

  Compared to scenario 1, the number of buildings and thus the conditioned floor area increases according to the assumptions outlined in 6.2. The energy performance indicator corresponds to the performance of buildings constructed in the period 2000-2010.

  Impact: Between 2010 and 2030 the gross floor area increases by about 100 million m² or 17%. About 85% of the newly constructed floor area have energy needs comparable to the energy needs common for buildings constructed between 2000 and 2007. As a result, the final energy demand increases by 10% until 2030 compared to the scenario 1 (6.4% in 2020). 65% of the additional final energy demand is supplied by renewable energy carriers. The remaining 35% are supplied by fossil energy carriers and electricity, of which natural gas holds a share of more than 50%.

- **Scenario 3: Increasing energy prices**

  Compared to scenario 2, energy prices increase according to the assumptions shown in section 6.3. The energy related expenditures of households subsequently also increase, which leads to decreasing average indoor temperatures and lower user-behavior-corrected energy needs for heating.

  Impact: The modeled short-term effect of increasing energy prices reduces the final energy consumption by 2.1% (2,300 GWh) in 2030. In the applied energy price scenarios, fossil energy carriers face a higher price increase than renewable energy carriers and

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[93] The relative change of income triggers in the model only short-term effects.

district heating. Therefore, the effect is stronger for fossil energy than in scenario 2, namely -2.7% compared to -1.3% for renewable energy carriers.

- **Scenario 4: Increasing energy performance of new constructions**

  Compared to scenario 3, the increasing energy performance of new buildings depicted in Figure 6.11, is implemented in scenario 4.

  Impact: The effect of the tightened building code (without financial subsidies) reduces the final energy consumption by 4.8% (5,100 GWh) in 2030 (-3,000 GWh in 2020) compared to the 2000-2007 building standard. Compared to scenario 3, only 25% of the mitigated final energy consumption comes from fossil energy carriers and electricity.

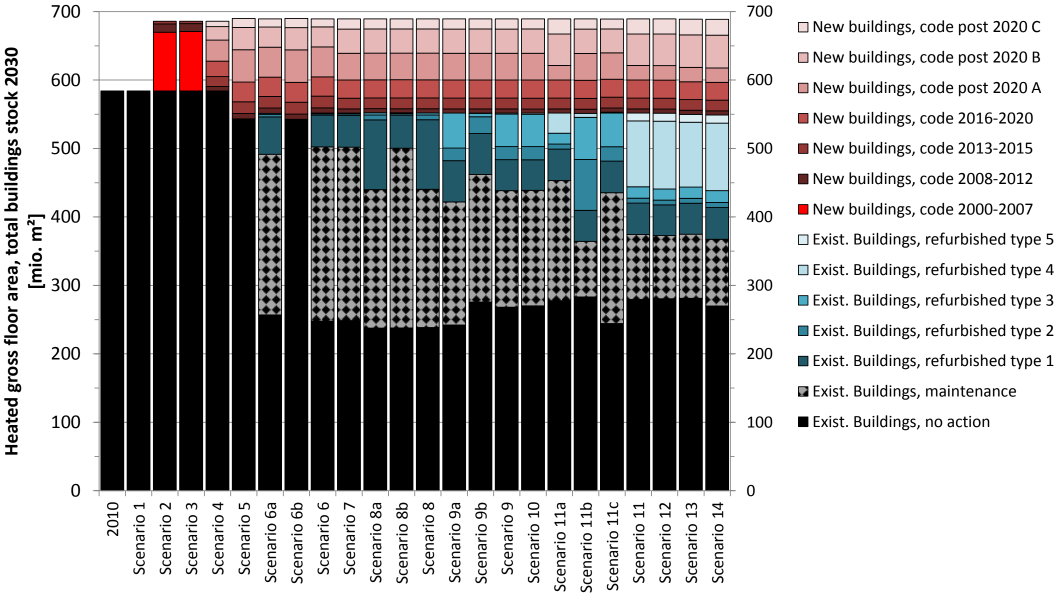

Figure 7.18 – Conditioned gross floor area in 2030 by measurement type.

- **Scenario 5: Building demolition and subsequent replacement with new constructions**

  Compared to scenario 4, existing buildings are demolished according to the survival rate based on the assumption for the service lifetime of buildings and the demolition process described in section 4.5.2. The energy performance indicators of new constructions remain on the 2000-2007 level.

  Impact: According the implemented service lifetime approach, about 40.6 million m² (6.95%) of existing conditioned gross floor area is demolished until 2030 and subsequently replaced with new constructions. Considering the energy performance indicators as defined by OIB (2007) for new buildings, reduces the final energy consumption by 6,700 GWh (6.5%). In this scenario, 27.1 million m² of existing residential buildings are replaced by 31.2 million m² of newly constructed residential buildings, as an effect of increasing specific apartment sizes. The additional 4.2 million m² mark a heated floor-area-related rebound effect of 15%. In contrast to income and price and other user-behavior effects, this rebound effect is defined exogenously via the definition of the dwelling floor area of new buildings.

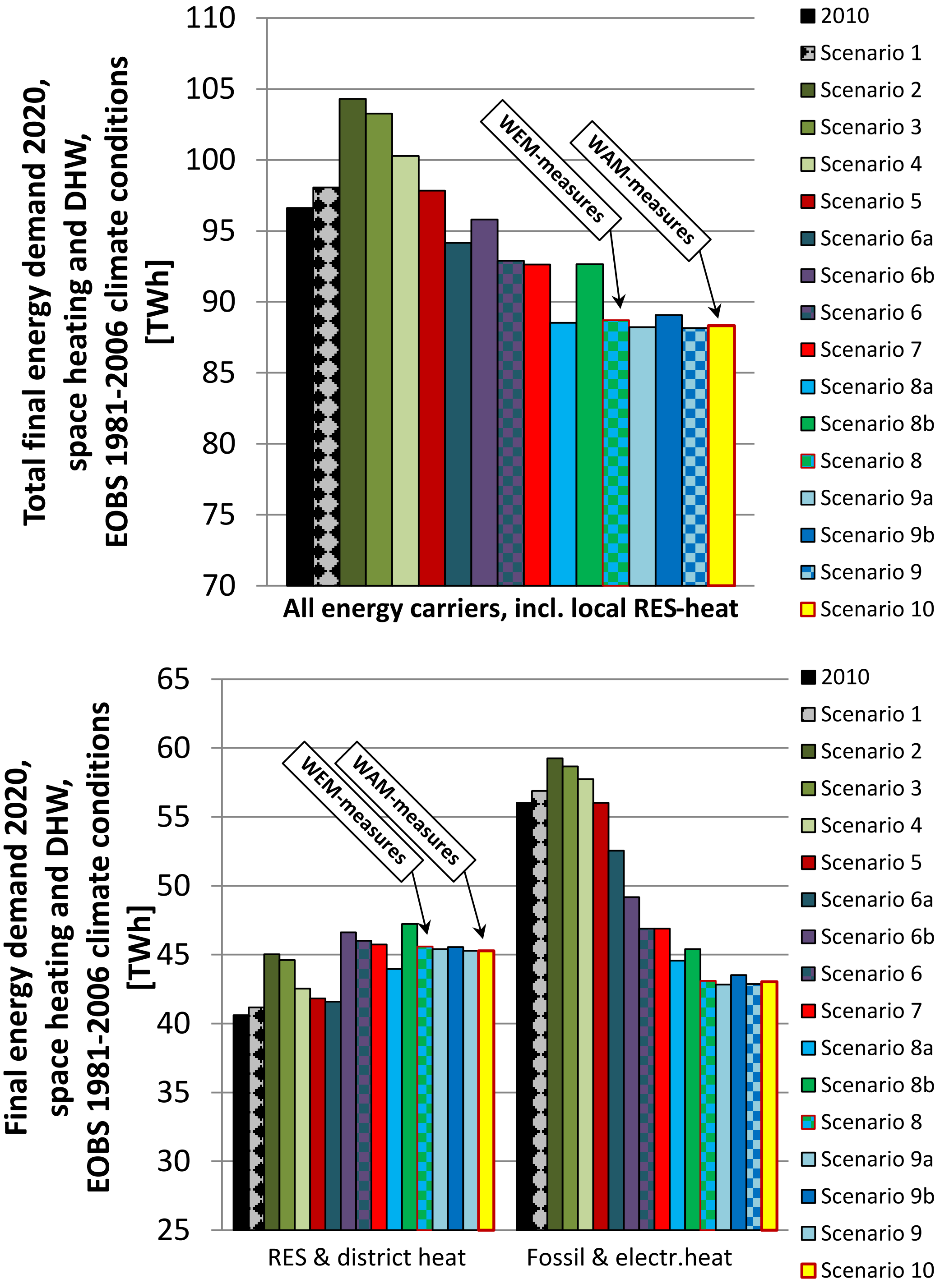

Figure 7.19 – Total final energy demand (upper figure) and the split between renewable energy carriers and district heating (lower figure, bars on the left side) and heat from electricity and fossil energy carriers (lower figure, bars on the right side) in 2020.

- **Scenario 6a: Refurbishment of existing building**
  Compared to scenario 5, building envelope measures are included according to their service lifetime assumptions. No financial support is given for these measures.
  Impact: In this scenario, 53% (294 million m²) of the existing building stock perform measures on the building envelope between 2010 and 2030. The corresponding annual rate of measures is calculated as 2.67%p.a., which is above the observed rate of 2.0% for the period 1991-2000 (see section 3.4). The demolition rate (2010-2030: 5.6%) is 20% lower than in scenario 5; an effect of the additional investments in the existing building stock (see equation (4.28)). 80% of the applied measures, weighted by the heated gross floor area, are maintenance only. Only 20% of the performed refurbishments have an impact on the energy performance indicators, of which the least ambitious refurbishment type 1 is chosen in most cases. The thermal renovation rate is calculated as 0.5%p.a. The final energy demand decreases until 2030 by 5,800 GWh (3,700 GWh until 2020). Furthermore, according to the model results, almost all thermal active renovations are done in buildings using heating systems with high annual consumption-depending energy costs, namely direct resistant electricity, heating oil and natural gas. Thus, the energy savings mainly reduce the delivered fossil and electric energy (5,500 GWh), whereas district heating and renewable energy carriers are only reduced by less than 300 GWh.
- **Scenario 6b: Renewing the heat supply system in existing building**
  Compared to scenario 5, heat supply systems are replaced according to their service lifetime assumptions. No financial support is given for these measures.
  Impact: Scenario 6b has no impact on the gross floor (Figure 6.7), yet significantly reduces the final energy demand. Until 2030, the increasing efficiencies of the heat supply systems reduce the final energy demand by 4,400 GWh compared to scenario 5. In addition to the efficiency effect, a shift from fossil energy carriers to renewable energy carriers and district heating is observed. In this scenario, the renewable energy carriers input increases by 8,600 GWh (+22%) until 2030, the delivered fossil and electric energy consumption for heating and domestic hot water supply drops by 25% (-13,400 GWh).
- **Scenario 6: Considering replacement of existing components**
  Compared to scenario 5, scenario 6a and 6b are implemented. The energy savings in scenario 6 compared to scenario 5 are lower than the sum of the effects of scenario 6a and 6b, because the measures are subadditiv. By replacing existing boilers with new, more cost and energy efficient heating systems, the annual energy costs decrease. Subsequently,

the cost effectiveness of refurbishment measures decreases (and vice-versa).

<u>Impact:</u> Compared to scenario 5, the final energy consumption decreases by 9,200 GWh in 2030 (-9.6%). These savings are about 10% lower than the sum of results for the measures individually implemented and evaluated (scenario 6a and scenario 6b). The final energy demand of renewable energy carriers and district heat increases by 21% (8,900 GWh), the delivered fossil and electric energy drops by 1/3 (-13,400 GWh), again compared to scenario 5. The annual measurement rate including maintenance is 2.75%

- **Scenario 7: Investment subsidies for new constructions with higher energy performance than demanded by the building code**

  Compared to scenario 6, the investment subsidies given for newly constructed buildings which outperform the demanded minimum energy standards are implemented and evaluated.

  <u>Impact:</u> Due to investment subsidies given to extra energy-efficient newly constructed buildings, the share of buildings applying the energy performance indicator type *"2008-2012"* is reduced by 21%, and the share of buildings applying an energy performance indicator not exceeding type *"2016-2020"* is reduced by about 9%. The reduced share of low performing envelope types is accompanied with an increasing share of high performance buildings. The share of buildings with envelopes exceeding the *"New buildings, code post 2020 A"* type increases by 23% and that of *"New buildings, code post 2020 C"* by even 26%. Compared to scenario 6 the final energy demand is reduced by less than 400 GWh in 2030.

- **Scenario 8a: Investment subsidies for building refurbishment activities**

  Compared to scenario 7, investment subsidies for thermal refurbishment activities are considered.

  <u>Impact:</u> Triggered by the given subsidies, the thermal renovation rate doubles from 0.5%p.a (scenario 5) to 1%p.a., and the overall rate of measures related to the envelope of buildings (including maintenance) increases from 2.75%p.a. to 2.85%p.a. The final energy demand decreases by 5,300 GWh in 2030, in comparison to scenario 7. The energy input from renewable energy carriers and district heat is reduced by 5%, the delivered fossil and electric energy by 8%.

- **Scenario 8b: Investment subsidies for alternative heat supply systems**

  Compared to scenario 7, the investment subsidies for alternative heating systems as depicted in Table 7.1 are given.

Impact: Subsidizing the installation of heating systems that utilize renewable energy carriers has no impact on the gross floor area, and only a minor effect on the total final energy consumption. However, renewable energy carriers increase by 2,600 GWh (+5.2%) and fossil energy carriers are reduced by 2500 GWh (-6.9%). The increase of the total final energy consumption by 100 GWh results from typically lower efficiencies of biomass fueled heating systems compared to natural gas boilers, as well as some rebound effects related to the lower annual consumption-dependent energy costs of non-fossil energy carriers.

- **Scenario 8: Investment subsidies**

  Compared to scenario 7, scenario 8a and 8b are implemented. Again, the effects of 8a and 8b are subaddditive, since the supported heat supply system are technologies which have, generally speaking, higher investment, but lower running costs. However, these systems become less competitive in low energy demand buildings.

  Impact: The given investment subsidies reduce the final energy demand for heating and domestic hot water by about 5.9% (-5,100 GWh) in 2030, compared to scenario 7. The utilization of renewable energy carriers remains on the same level, the delivered fossil and electric energy for heating and domestic hot water consumption decreases by 14.4% (-5200 GWh).

Scenario 8 corresponds to the policy **scenario with existing measures (WEM)**[94]. The following four scenarios evaluate the measures which are part of the **scenario with additional measures (WAM)**.

- **Scenario 9a: Increased refurbishment budget**

  Compared to scenario 8, scenario 9a considers additional investments subsidies for building refurbishments. The annual budget available for thermal renovation activities and the specific subsidies rates are shown in Table 7.2.

  Impact: The additional subsidies trigger a reduction of the final energy demand by 2,100 GWh in 2030 (-2.6%). These energy savings are almost equally distributed between the two energy carrier clusters, RES and district heating on the one hand (-2.5%), and fossil and electric energy on the other (-2.9%).

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[94] Except for climate data: This decomposition applies EOBS 1981-2006 climate data, while the analyses in the previous sections (7.1-7.4) are based on 2005 climate condition data.

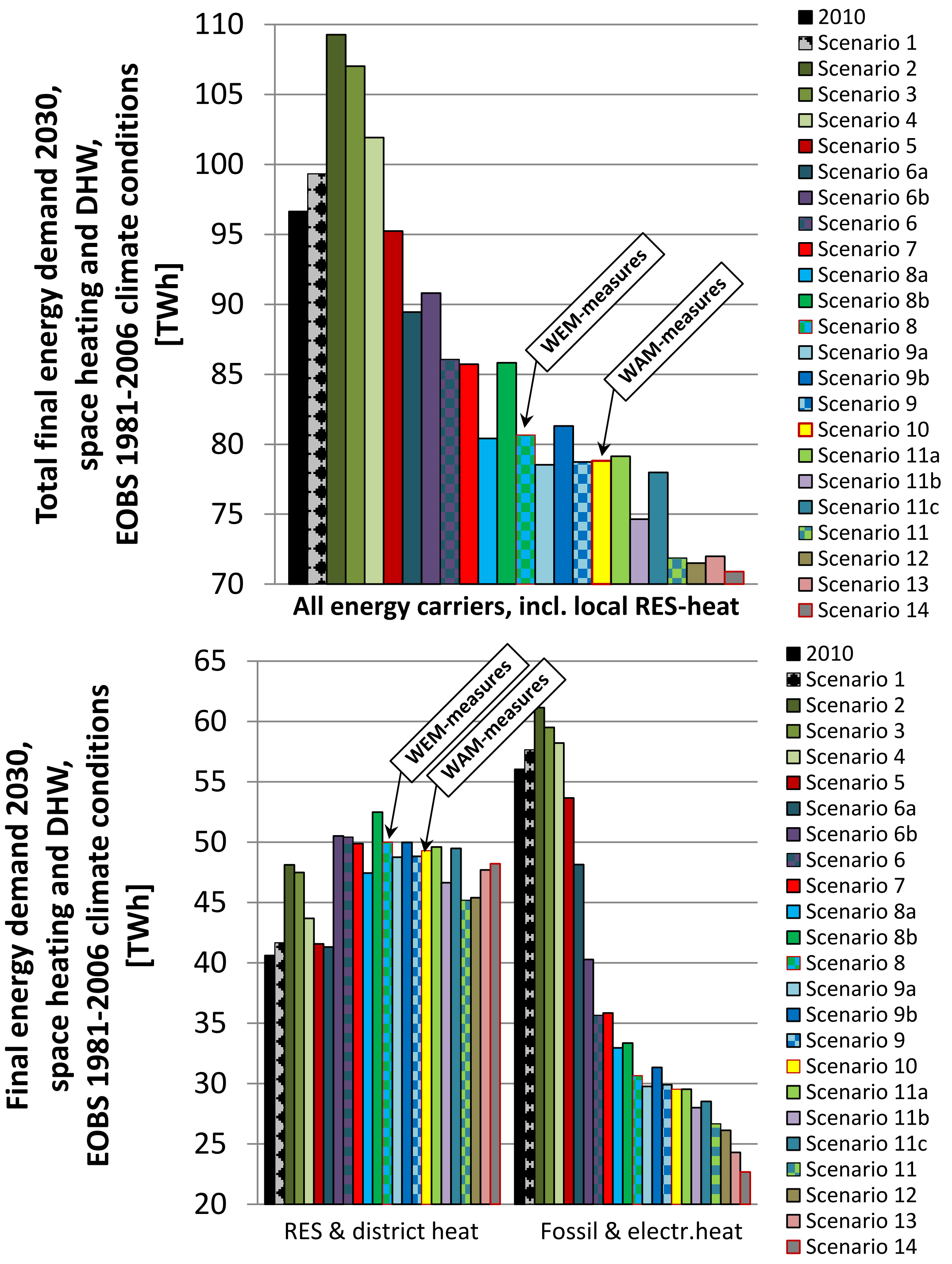

Figure 7.20 – Total final energy demand (upper figure) and the split between renewable energy carriers and district heating (lower figure, bars on the left side) and heat from electricity and fossil energy carriers (lower figure, bars on the right side) in 2030.

- **Scenario 9b: Higher refurbishment standards after 2021**

  Compared to scenario 8, scenario 9b demands increased energy performance indicators for buildings are refurbished after 2020. Thus, when buildings are refurbished by 2021, the refurbishment types 2-4 can be chosen (Figure 6.12).

Impact: The model results suggest that the final energy demand increases in 2030, compared to scenario 8, if higher renovation standards, without accompanied measures, are demanded. The energy savings of scenario 9b are about 4% lower than those of scenario 8. This is caused by a 20% reduction in the thermal renovation rate. It is not evident whether or not this scenario performs better than scenario 8 in the long run. On the one hand, the number of existing buildings where no measures are done is about 16% higher in scenario 9b compared to scenario 8, which leaves additional refurbishment potentials for future periods. On the other hand, the thermal-refurbishment-to-maintenance rate drops from 55% (scenario 8) to 48% (scenario 9b), which means that non-thermal measures get a higher share.

- **Scenario 9: Increased renovation activities**
  Compared to scenario 8, this scenario incorporates scenario 9a and 9b.
  Impact: The final energy demand in 2030 of scenario 9 is about 1,900 GWh lower than in scenario 8. The total energy savings are at the same level than those of scenario 8a. But, as can be seen from Figure 7.18, scenario 9 has a higher number of existing buildings, where no measures are performed until 2030 (+12%) and a higher thermal-refurbishment-to-maintenance rate (67% versus 55%). This implies that the future energy savings potentials are higher in scenario 9.
- **Scenario 10: Enhanced support for renewable energy carriers**
  Compared to scenario 9, regulatory measures which demand a minimum share of energy delivered by RES as well as higher efficiencies for newly installed fossil heating systems.
  Impact: These policies increase the share of renewable energy carriers by about 1% (less than +500 GWh), and decrease the delivered fossil and electric energy by 1.3% (less than 400 GWh). The total final energy demand slightly increases.

Scenario 10 corresponds to the policy measures in the **scenario with additional measures (WAM)**. The following scenarios analyze the measures which are part of the **scenario with ambitious policies (WAM+).**

- **Scenario 11a: Further improved refurbishment standards**
  In comparison to scenario 10, the energy performance indicators of refurbished buildings are increased. After 2020, these buildings have to meet the refurbishment type 4 or 5 standards (see Figure 6.12). However, the maintenance type (renovation without impact on the energy needs) is still a valid option.

Impact: The effect of this measure is similar to the one of scenario 9b. The final energy consumption increases slightly and the thermal-refurbishment-to-maintenance rate drops from 66% (scenario 10) to 56%. The share of existing buildings which do not perform envelope related measures increases by 3%. Although the energy performance indicator for renovated buildings rises compared to scenario 10, in the long run the scenario probably performs not as well as scenario 10.

- **Scenario 11b: Disabling the energetically ineffective renovation type *"maintenance"***
  Compared to scenario 10, the maintenance renovation type cannot be chosen any more after 2020. In this scenario, buildings can postpone measures according to the approach discussed in 4.5.1. Yet, once envelope related measures are set, buildings have to meet at least the energy performance indicator of refurbishment type 1 (Figure 6.12).
  Impact: In this scenario, the final energy consumption drops by 5.3% (-4,200 GWh) compared to scenario 10. The gross floor area of existing buildings where no envelope-related measures are performed increases by 5% until 2030, again in comparison to scenario 10. The thermal-refurbishment-to-maintenance rate rise to a level of 2.3.
- **Scenario 11c: Obligation to set measures for buildings with low energy performance indicators**
  Compared to scenario 10, the refurbishment obligation, as discussed in section 7.3.2, using a parameter $f_{\text{ren\_inc}}$=1.0, is implemented. The maintenance renovation type can still be chosen.
  Impact: This policy boosts the rate of envelope-related measurements by 13% for the period 2021 to 2030. This increase, however, is basically driven by an increasing maintenance rate, whereas the thermal renovation rate remains almost at the same level as in scenario 10, resulting in a thermal-refurbishment-to-maintenance rate of 0.61. This means that modest energy savings of 800 GWh are realized at the costs of a significantly lower future refurbishment potential.
- **Scenario 11: Enhanced refurbishment activities**
  Compared to scenario 10, the policies of the scenarios 11a, 11b and 11c are implemented in scenario 11. When combined, the effects show a superadditive character, which means that the effect of the combination exceeds the additive effect of the separately implemented measures.
  Impact: The combined effect of increased refurbishment standard (scenario 11a), the regulatory requirement not to apply non-thermal maintenance measures as long as the

building doesn't fulfill certain energy performance indicators (scenario 11b), and the obligation to perform measures in buildings with very poor energy performance indicators within a certain time span (scenario 11c), lead to energy savings of 7,000 GWh in 2030 (compared to scenario 10), as well as a high potential for future refurbishments.

- **Scenario 12: Increased boiler replacement**

  Compared to scenario 11, the increased boiler replacement policy in IG-L regions are implemented.

  Impact: The increased boiler replacement program reduces the final energy demand by less than 400 GWh. The potential here is limited, because in a very large share of buildings the boilers need to be replaced anyway within the period 2010 and 2030. Also, no technological improvements for systems using fossil energy carriers and only modest efficiency improvements for biomass based boiler are assumed to take place after 2010.

- **Scenario 13: Forced utilization of renewable energy carriers**

  Compared to scenario 12, policies that enforce the usage of renewable energy carriers, if economically and technically feasible (using f_{hs_inc}=1.0), as well as measures which disallow the installation of natural gas if an building central heating system exists and the building is not located in an IG-L region are considered.

  Impact: Forcing the utilization of renewable energy carriers increases the total final energy demand by about 500 GWh in 2030. This goes along with a reduced delivered fossil and electric energy of 1,800 GWh (-7%) and an increase usage of renewable and district heat of 2,300 GWh (+5%).

- **Scenario 14: CO_2 tax of 70 €/t CO_2 by 2021**

  Compared to scenario 13, a CO_2 tax of 70 €/t CO_2 after 2020 is implemented.

  Impact: The effects of the CO_2-tax can be distinguished between the short-term price effect (see scenario 3) and the long-term effect, which triggers decisions to invest in low-carbon technologies. Altogether, the final energy demand is reduced by 1,100 GWh in 2030, the fossil and electric energy carriers decline by 1,600 GWh (6.7%), while renewable energy carriers and district heat rise by 500 GWh in 2030.

7.6 Impact of climate change on the long-term energy needs of the Austrian building stock

The following section examines the impact of climate change on the energy needs for heating and cooling. In the first part, the impact of changing climate conditions is shown based on four building types. In this part, the buildings are defined statically, only the climate conditions are changing. A similar analysis is presented by Berger et al. (2014) for four different office buildings, but their analysis is limited to one climate scenario (derived by the REMO-UBA model based on a global IPCC A1B scenario world) and to the region of Vienna. The section 7.6.2 draws scenarios for the energy needs for heating and cooling of the Austrian built environment under constant climate conditions until 2080. In section 7.6.3, the impact of climate change on Austrian space conditioning (heating and cooling) in a dynamic building stock environment is analyzed. Finally, a sensitivity analysis for the cooling needs with respect to shading and the cooling set-point temperature is done.

7.6.1 Impact of climate change on the energy needs of reference buildings

In the following, the impact of climate change on different building types is analyzed. For comparison, a set of four residential reference buildings is chosen: detached single family houses and apartment buildings, as well as u-values and construction types typical for old buildings (construction period 1900-1918) and recently erected buildings (construction period 2000-2008). It is assumed that night ventilation is possible. The main characteristics of the building types are given in Table 7.7.

Table 7.7 – Properties of reference buildings.

	Detached single family houses (SFH)		**Apartment buildings (AB)**	
Construction period	1900-1918	1990-2005	1900-1918	1990-2005
Gross floor area [m^2]	130		1540	
Surface-to-volume ratio [m^{-1}]	0.84		0.40	
Construction type	heavy	light	heavy	light
Share windows (glass only) on vertical surface	14% (of which: 30% south, 14% north)			
Solar shading	inside	outside	inside	outside
Heat transfer coefficient, transmis. losses [W/K]	357	153	1971	844
Heat transfer coefficient, ventilation losses [W/K]	36	13	436	155

The energy needs are calculated for three different climate zones in Austria: first, the coldest climate cluster used in this work, which is based on data for the region “Semmering” with an average annual outdoor air temperature of 2.8 °C. Second, the population weighted average climate for Austria with an average outdoor air temperature of 8.5 °C and, third, the hottest climate cluster in the dataset, “Kleinzicken”, with 10.5 °C (based on EOBS 1981-2006). The SSCD 2051-2080 data sets are used to estimate the impact of the climate change in comparison to the latest observed time period (EOBS 1981-2006).

The results for the energy needs for heating and cooling of the buildings specified above are depicted in Figure 7.21 and Figure 7.22. Under the population weighed average Austrian EOBS 1981-2006 climate conditions (black bars), the specific energy needs for heating of the four buildings varies in a range of 25 to 220 kWh/m² (based on an operative set-point temperature of 20 °C). Due to the favorable surface-to-volume ratio of apartment buildings compared to detached single family houses, the energy needs for heating of the defined single family houses (SFH) are higher by the factor of about 2.0-2.5 than the energy needs of apartment buildings (AB). With respect to the construction period and thus the typical U-values of components and associated heat losses, the recent construction period is more efficient by the factor of about 3.5-4. In the cold climate cluster (“Semmering”) energy needs for heating are about 70% above that of buildings in the average climate zone. In the warmest climate cluster (“Kleinzicken”) energy needs decrease by about 15% compared to the average. The changing climate signal (based on SSCD 2051-2080) leads to a reduction of about 20% (in a range of 15-25%), compared to the EOBS 1981-2006 signal.

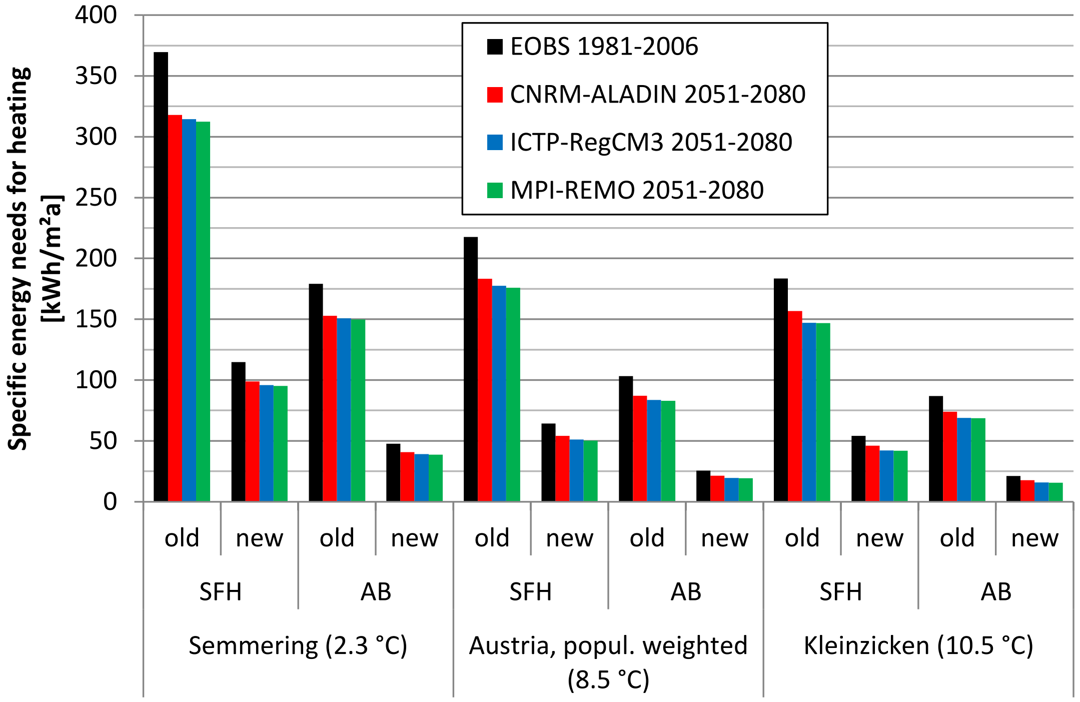

Figure 7.21 – Specific energy needs for heating of residential reference buildings in three different climate zones.

In the case of cooling an additional impact factor on the energy needs, the set temperature, is analyzed. While ÖNORM B 8110-5 suggests a set-point temperature of 26°C, the expect average set-point temperature of buildings equipped with an air conditioning system is expected to be rather in the range of 22 – 24 °C. Again, under observed climate conditions, the energy needs for cooling are lower in apartment buildings. On average however, the newer reference buildings have higher energy needs for cooling compared to older reference buildings. One reason lies in the inverted energy flux. When applying typical Austrian climate conditions, the average daily outdoor air temperature is usually below the set-point temperature for cooling. Thus, assuming unchanged ventilation behavior, the energy needs for cooling decrease with increasing heat transfer coefficients.

For the population weighted Austrian EOBS 1981-2006 climate, the energy needs are within a range of 4-22 kWh/m², if a set-point temperature of 26 °C is applied. Using a set-point temperature of 22 °C instead of 26 °C, on average the energy needs double (increase within a range of 0.5 – 2.7). In the coldest climate cluster, energy needs are 60 – 80% lower, in the hottest cluster they are about 50-100% higher compared to the average climate cluster. The change climate signal based on the CNRM-ALADIN increases the energy needs for cooling on average by 90%, the two other RCM by about 60%. This means, that the climate signal of the CNRM-ALADIN model for the period 2051-2080, for a set-point temperature of 26 °C, leads to an energy need that corresponds with a set-point temperature of 22 °C under EOBS 1981-2006 conditions. Under ICTP-RegCM3 and MPI-REMO conditions, the energy needs for a set-point temperature of 26 °C is comparable with the energy needs for cooling using a 24 °C threshold under EOBS 1981-2006 conditions.

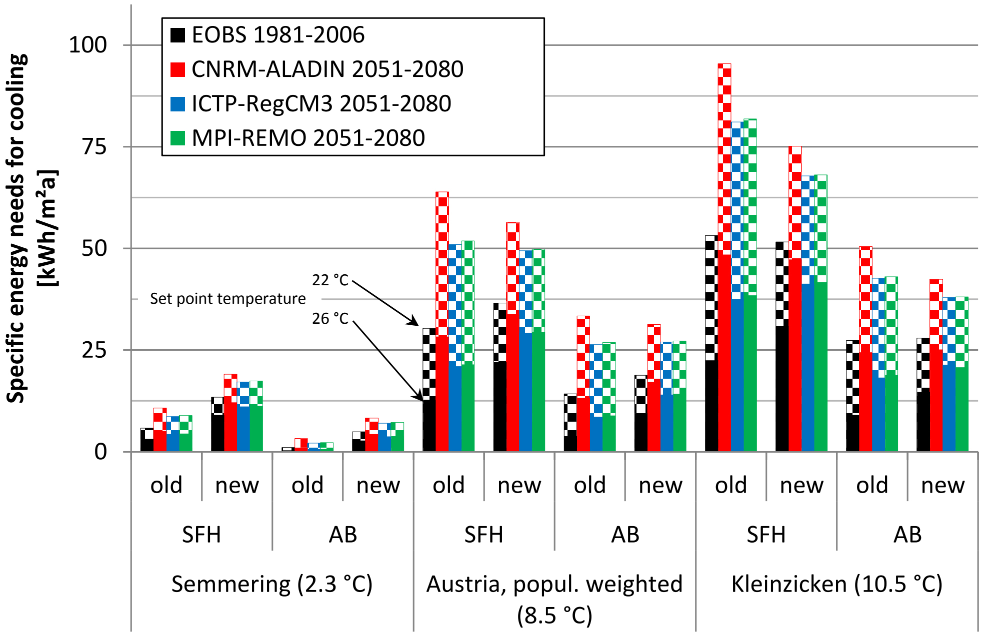

Figure 7.22 – Specific energy needs for the cooling of residential reference buildings in three different climate zones.

Although these buildings do have a significant energy need for cooling (shown in Figure 7.22) most of the residential buildings in Austria are not equipped with air conditioning (AC) systems. This means that in contrast to heat supply systems, the market penetration rate of AC systems is well below 100%. In order to calculate the electricity demand for space cooling, it is necessary to estimate the future AC market penetration. Based on the idea that AC systems attract a large attention on days where the average daily indoor temperature during heat wave periods exceeds a certain threshold temperature, an indicator which covers this aspect is defined. By using the hourly temperature profiles (SSCD), the number of days where a specific indoor threshold temperature (without active cooling) is exceeded are counted[95]. Four threshold temperatures are defined: 26 °C, 28 °C, 30 °C, and 32 °C.

Using these threshold temperatures, a novel degree day indicator, similar to the commonly used cooling degree day indicator (CDD), is defined. Contrary to the CDD, the average indoor temperature is used instead of the outdoor temperature, and 26 °C as lower threshold temperature.

$$CiDD_{26/26} = \sum_{d=1}^{365} \max\left(0, \vartheta_{d,i} > 26\right) \tag{7.12}$$

where

$CiDD_{26/26}$ ... Cooling indoor-Degree Days

$\vartheta_{d,i}$ ... Average daily indoor temperature without active cooling

The analysis shows that, for the majority of the Austrian cases, this indicator is more sensible to the changing climate signal than the specific cooling demand. In case of the old SFH reference building under EOBS 1981-2006 climate conditions, the average operative indoor temperature exceeds 26 °C on 25 days per year, and 28 °C on 5 days. If the CNRM-ALADIN 2051-2080 climate signal is applied to this building, the energy needs for cooling increases by the factor 2.2 (Figure 7.23). In this case the number of heat wave days where 26°C is exceeded increases by the factor of 2.6, while the cooling indoor degree day *CiDD* indicator, which also takes into account the extent to which the threshold temperature is exceeded, quadruples from 35 °Cd to 145 °Cd. In the new apartment reference buildings, the indoor temperature exceeds the thresholds not as often as this is the case for the older SFH; mainly due to the better solar shading assumption. But again, the number of days on which the indoor temperature exceeds the threshold as well as the *CiDD* indicator rise steeply in the scenarios considering climate change.

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[95] The indoor temperatures were calculated by project partners (Institute of Building Construction and Technology at the Vienna University of Technology) in the PRESENCE project and not by the author of this thesis. The methodology is described in Müller et al. (2014a).

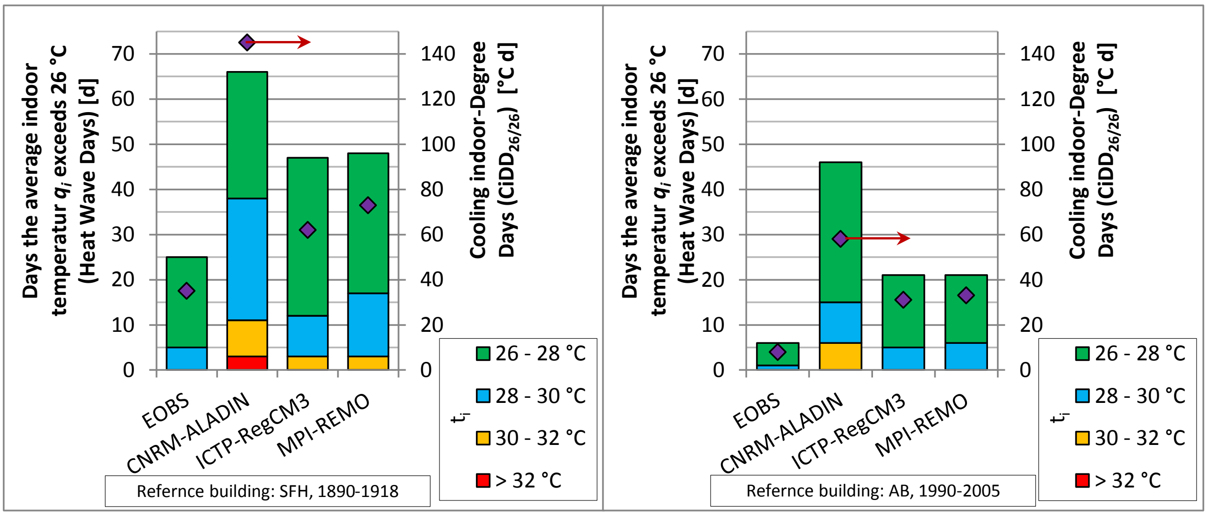

Figure 7.23 – Development of heat wave days and Cooling indoor-Degree Day *CiDD* indicator of the detached single family house reference building, construction period 1900-1918 (left) and the Apartment reference buildings, construction period 1990-2005 (right) under recent (EOBS 1981-2006) and changing climate signal conditions Semi-Synthetic-Climate-Data for the period 2051-2080 for the average Austrian climate zone.

7.6.2 Scenario results for the Austrian building stock under constant climate conditions until 2080

In order to assess the long-term energy needs for heating and cooling, two scenario sets are defined: the Grey scenario and the Blue scenario. These two scenarios define trajectories for the energy needs of the Austrian building sector under different framework conditions until 2080. The Grey scenario defines a low efficiency development, while the Blue scenario represents a development with additional, yet still not ambitious, efforts to reduce the energy demand. This assessment focuses on the impact of climate change and not on policy instruments; therefore the measures which lead to such trajectories are not further described.

It is important to note that the change climate signal (temperature) is the only input variable that is covered for the whole period. All other input variables (such as the total number of buildings, energy prices, household incomes, thermal qualities of newly constructed and refurbished buildings, investment costs, efficiencies of heat supply systems, availability of energy carriers, etc.) are kept constant on their 2055-level until 2080. Although the total number of buildings does not increase in the shown scenarios after 2055, existing buildings are still demolished to some extend and then replaced by newly constructed buildings in period between 2055 and 2080. Thus, the heated gross floor area still increases, since the dwellings in newly constructed (residential) buildings are larger than in the removed buildings.

Development of the heated gross floor area per construction period

The development of the gross floor area per construction period is shown in the following figure. While the total heated gross floor area increases, the floor area of buildings existing today declines. Starting with a heated gross floor area of 568 million m² in 2008, about 40% to 50% of this floor area will be demolished within the coming 7 decades in the scenarios. The demolition rate in the Blue scenario is lower than in the Grey scenario. This is caused by the additional refurbishment efforts, which binds additional investment capital to the existing buildings and thus increase the buildings service lifetimes in the model. Depending on the policy scenario group, newly constructed buildings (construction year after 2008) hold a share of 55% to 60% of the total floor area in 2080.

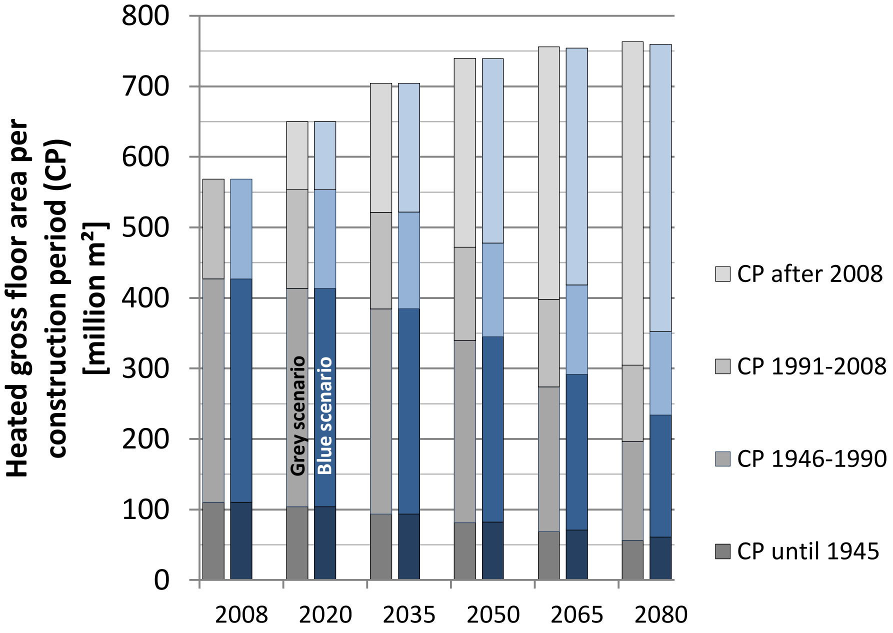

Figure 7.24 – Development of the gross floor area per construction period in the two scenario sets: Grey and Blue scenario.

Development of the energy needs for heating, DHW and cooling under constant climate conditions

If constant climate conditions (EOBS 1981-2006) are assumed, the energy needs for heating and DHW decrease in the Grey scenario by ~20% within the next 4 decades and by ~40% until 2080. In the applied approach, the domestic hot water consumption depends on the conditioned floor area and the utilization of the associated building zone. Therefore, the energy needs for DHW rise in the scenarios. The energy needs for heating decrease by 45% until 2080 in the less ambitious Grey scenario and by 75% in the Blue scenario.

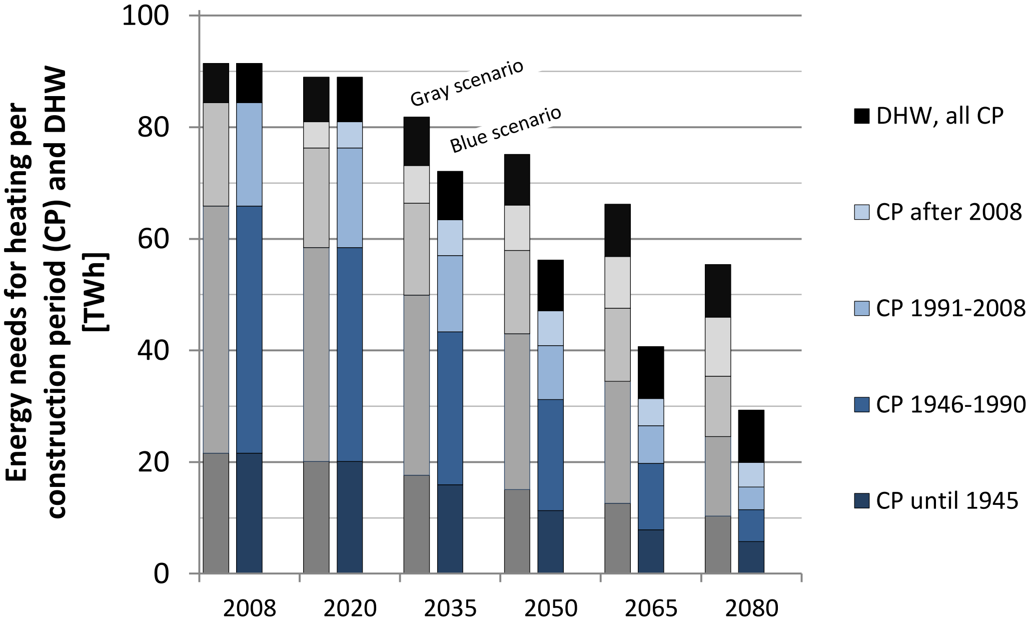

Figure 7.25 – Energy needs for space heating and DHW supply under constant climate conditions.

In the case of cooling an inverted trend can be observed. While, with respect to the energy needs for heating the performance of the existing building stock is worse than that of newly constructed buildings, the specific energy needs for cooling are tend to be lower in older buildings (Table 7.8). This is caused by higher heat losses, the typically lower share of transparent surfaces on the building envelope and the higher internal heat storage capacity due to a more massive construction. If these buildings are conventionally refurbished – without explicitly considering cooling – the heat flux dissipating the unwanted heat during cooling periods is reduced and the energy needs for cooling are increased.

Table 7.8 – Specific average energy needs for cooling per construction period under constant climate signal (EOBS 1981-2006).

	Scenario							
	Grey	**Blue**	**Grey**	**Blue**	**Grey**	**Blue**	**Grey**	**Blue**
	Construction period							
	until 1945		1946-1990		1991-2008		after 2008	
	Specific energy needs for cooling [kWh/m²a]							
2008	12.1	12.1	17.8	17.8	19.9	19.9	-	-
2020	12.2	12.0	18.2	17.3	19.8	19.7	19.7	19.7
2035	12.3	10.8	18.6	15.3	19.7	18.9	20.0	19.9
2050	12.8	9.9	18.7	14.8	19.5	19.0	20.1	20.0
2065	13.2	10.7	18.5	15.0	19.2	19.4	19.9	20.0
2080	13.7	11.5	18.2	14.6	18.9	19.5	19.6	19.8

Based on the implemented building stock data, the current energy needs for space cooling of the Austrian building stock amount to roughly 10 TWh (Figure 7.26). In the Grey scenario, the energy needs increase under constant climate conditions by about 40% until 2050, in comparison to the current level. The Blue scenario, which assumes a somewhat higher passive solar shading of newly constructed and refurbished buildings, is able to curb the increase by 1/3 until 2050, even though better insulation for new and refurbished buildings are applied. In the following period this difference is reduced again, since improved shading measures (the same as applied in the Blue scenario) are also implemented in the Grey scenario after 2050.

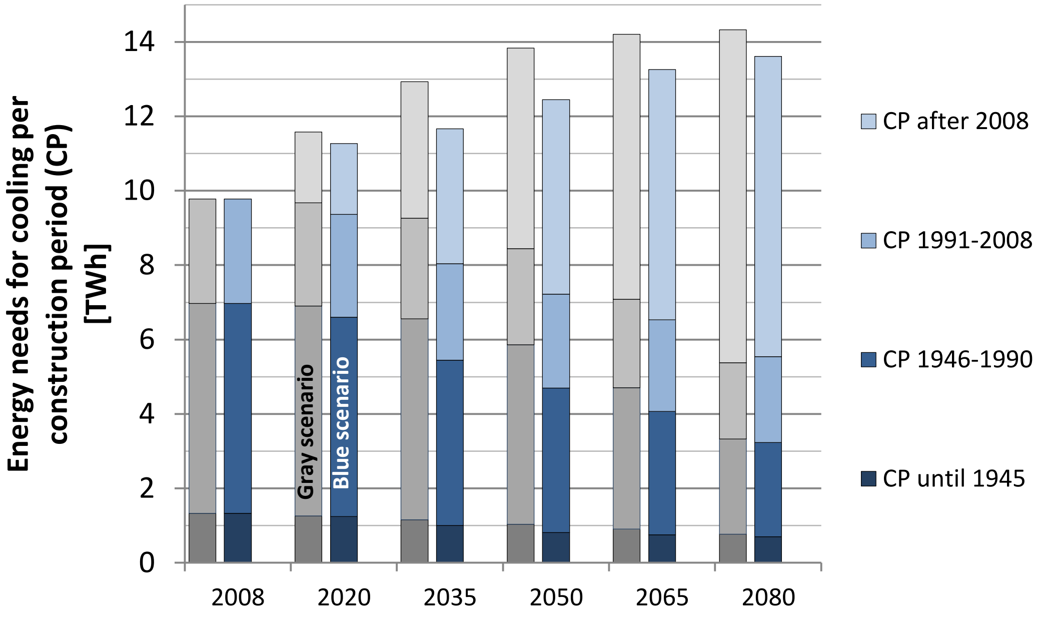

Figure 7.26 – Energy needs for cooling under constant climate conditions.

7.6.3 Impact of the climate change on the energy needs for heating and cooling

The results shown above are now compared to scenarios which use an annually changing climate signal (section 6.5). Depending on the applied scenario results of the RCMs[96] described above, the energy needs for heating decrease by between 20% and 25% until 2080 compared to the EOBS 1981-2006 data. Cooling, as can be seen in Figure 7.27 is more sensitive to the climate signal. In the scenarios, the cooling needs increase between 60% to 100% in 2080, again compared to the scenarios using a constant climate signal. Although the policy scenario settings have an impact on the absolute energy needs and demand numbers, they do not significantly change the relation between constant and changing climate. Climate change is not only expected for future periods, but has already been observed in the past (see the comparison of EOBS data for the period 1951-1980 with the period 1981-2006 in Haylock et al., 2008; and the heating degree days for the period 1990-2012 in Müller et al., 2013). Based on the results of the applied results from the RCMs for the period 2011 - 2040 and the EOBS 1981-2006 data, the impact of the changing climate that has already occurred is estimated for the decade between 1995 and 2005. The results indicate that the energy needs for heating decreased by about 2.5%, while the cooling needs increased by 6%.

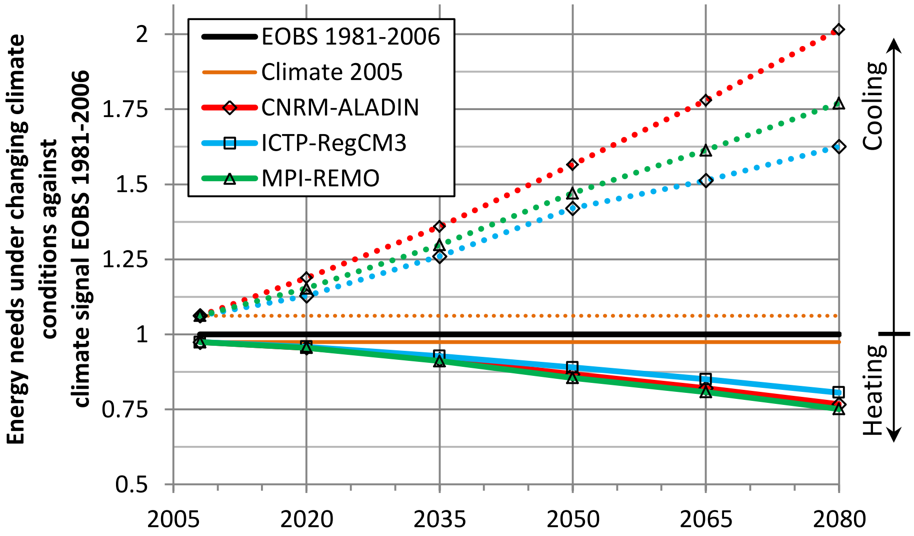

Figure 7.27 – Impact of the change climate signal on the energy needs for heating and cooling of the Austrian built environment.

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[96] Regional climate models.

7.6.4 Sensitivities

Literature discussed in section 4.4.4 indicates that the thermodynamic processes in buildings and the user-behavior related to space heating are well understood, documented and captured in statistical data. Based on this sound basis, it can be concluded that the impact on the energy needs for heating of the changing climate until 2080, under conditions as described by the analyzed regional climate scenarios, is within a range of 20% to 25% compared to the current climate conditions. The main uncertainty for the future final energy demand for heating arises from the unknown future energy price and energy policy framework conditions. The final energy demand of the Blue Scenario is about 40% lower than that of the Grey Scenario in 2080. Müller et al. (2012) and Müller and Kranzl (2013b) indicate that more ambitious policy settings leading to a substantially lower final energy demand, are not just feasible, but might also be necessary in order be in line with a global 2°C climate change scenario (Müller et al., 2012).

In contrast to heating, little is known about the current cooling behavior and its possible evolution in Austria. With respect to the actual energy needs for cooling, there are two main uncertainties. Firstly, the actual average indoor set temperatures for cooling of buildings with existing AC systems are not statistically captured. Secondly, no statistically data on the current stock penetration levels of different passive solar shading systems are known to the author. The ÖNORM B 8110-5 defines 26°C as indoor cooling set temperature. Common experience suggests, however, that this temperature level exceeds the indoor temperatures in actively cooled buildings zones. Therefore, for the calculations an indoor cooling set temperature of 24°C for all buildings is used, except for office, retail and wholesale buildings where 22°C is used. This assumption has a large impact on the energy need for cooling. If a cooling set temperature of 26°C is used the energy needs of the current building stock are in the range of 6.2 TWh. If a set temperature of 24°C is used the associated energy needs increase to 10.2 TWh. The assumption that the cooling temperature in some building types[97] is as low as 22°C does not have a large impact on the overall results. The associated energy needs increase by about 0.5 TWh.

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[97] Namely office, retail and wholesale buildings.

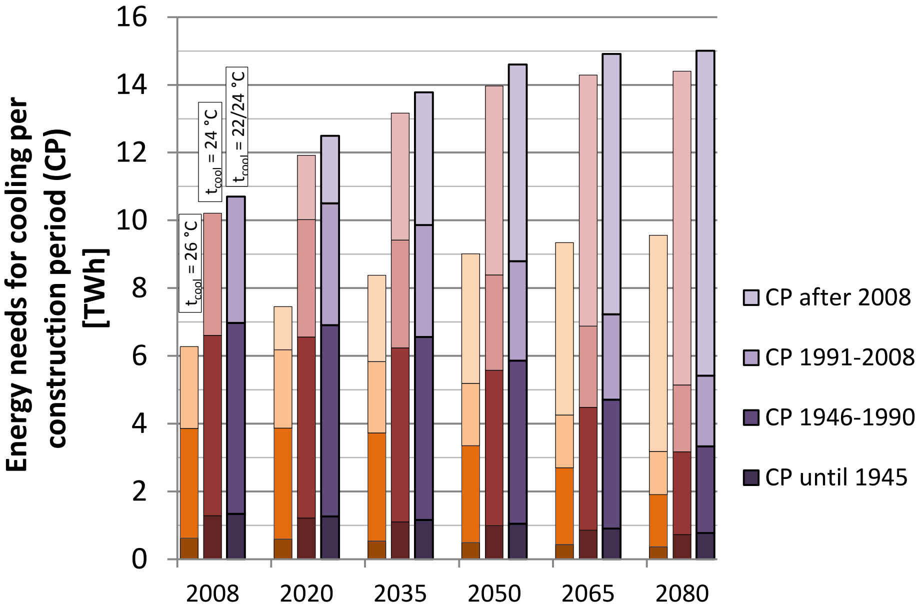

Figure 7.28 – Impact of the cooling set temperature on the energy needs for cooling under constant EOBS 1981-2006 climate conditions for the Grey scenario.

Another uncertainty related to the energy needs for cooling arises from the unknown distribution of passive solar shading measures. The assumptions on the present status are that on an aggregated level, the applied measures are comparable with internal shading, if applied on the total building stock. The implemented shading measures reduce the cooling demand by about 1.9 TWh (-14%) compared to the situation where no solar shading is applied. However, if external shading would be applied to the total building stock, the cooling needs could be reduced by about 3.5 to 5.8 TWh (-30% to -50%). In the policy scenarios drawn it is assumed that passive solar shading will be applied to a somewhat higher extent. By 2080, the Grey scenario exploit 55% of the additional energy saving potentials external shading offers (green bars) in comparison to internal shading (red bars), while the Blue scenario exploits about 70% of that additional potential. Still, there is much room for further improvements. By applying radiation controlled solar shading devices on the total building stock, the energy needs for cooling in the Blue scenario could be reduced by another 35%.

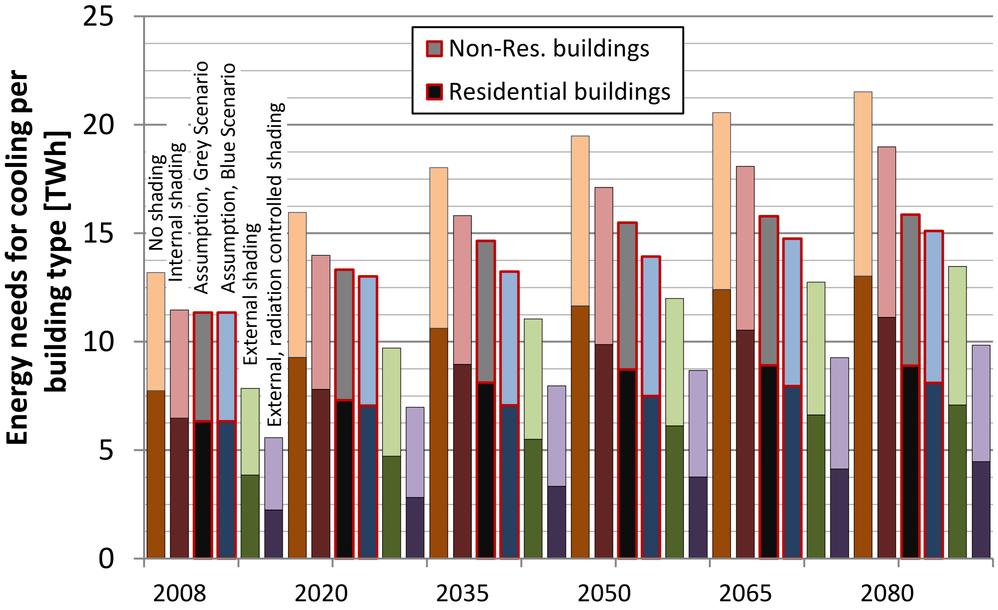

Figure 7.29 – Impact of passive solar shading measures on the energy needs for cooling under constant EOBS 1981-2006 climate conditions.

8 Conclusions and outlook

In this thesis a model developed for assessing the possible energy demand trajectories for heating, cooling and domestic hot water, and the applied heating technologies and energy carriers has been described. The model is applied to the Austrian building stock and different energy demand trajectories are evaluated, as well as the energy related effects of various energy policy measures are assessed and discussed.

The conclusions drawn from this work are clustered into two sections. The first part summarizes the findings with respect to methodological aspects such as the modeling approach and the disaggregation of the building stock input data. The scenario-specific findings for the future development of the energy demand for heating, cooling, and domestic hot water preparation of the Austrian built environment and its interaction with renovation activities and policy implications are presented in the second part.

Finally, it concludes with an outlook, challenges and open questions for further work in this field of research.

8.1 Methodology

This thesis describes a novel integrated approach of building stock modeling by combining existing methodologies within a single integrated modeling framework. Furthermore, the modeling framework is implemented in a computationally efficient way, capable of processing large amount of data. This allows the implementation of building stock data on a new level of disaggregation for larger building stocks, while at the same time ensuring that decision processes and decision results are fully traceable throughout the simulation.

Methodologically, the developed model is an engineering-based bottom-up model that incorporates statistical bottom-up elements. The three core elements of the model are the energy calculation engine based on a monthly quasi-steady-state building physics approach, the building and building components replacement calculation module applying the concept of distribution-based service lifetimes of components and finally the investment decision module, which anticipates decisions based on the concept of logit models combined with a technology diffusion model. The combination of these concepts increases the robustness and reliability of results; the main conclusions are summarized below.

Calculating the energy demand of buildings

- The energy calculation engine of the developed Invert/EE-Lab model is based on the Austrian implementation of the European calculation standard EN-ISO 13790:2008 using the quasi-steady-state monthly energy balance approach. A comparison of the implemented energy needs module with two other calculation methods is shown in this thesis: a spreadsheet model implementation of the EN-ISO 13790:2008 simple hourly dynamic method as well as the detailed dynamic simulation approach using the EnergyPlus model. The comparison is done for the energy needs of different building types in different European climate zones, ranging from Helsinki to Seville. The results underline that the implemented model is capable of deriving the energy needs for space heating and cooling in a wide range of climate conditions with sufficient precision.
- The comparison of the results derived by the EnergyPlus model with the quasi-steady-state monthly energy balance approach (which is applied by the Invert/EE-Lab) shows that when using the second calculation approach, the operative temperature θ_{op} and not the indoor air temperate θ_{air} needs to be used to define the indoor set-temperature. Otherwise, the energy needs for cooling would be overestimated by the monthly approach. This means that the commonly measured indoor air temperatures cannot directly be used to calculate the losses.
- If the building can be described in detail, the detailed dynamic simulation approach applied by simulation tools such as EnergyPlus or TRNSYS might be superior to the monthly approach and can provide more insights. However, such a degree of detail (the exact shape of the building, detailed specifications of (unheated) cellar and attic conditions, multiple temperature and utilization zones within the building, the share of radiant and convective heat gains by the heat radiation system) is usually available only for individual buildings and not for the building stock of a larger area. From the comparison shown in this thesis it can be concluded that, for a larger building stock, the uncertainties resulting from the deviation between the quasi-steady-state monthly energy

balance approach and the dynamic hourly building simulation are outweighed by the uncertainties related to the input data.

- Given these findings, from a computational-efficiency aspect, the implemented monthly approach is highly superior to the dynamic, highly detailed, multiple thermal zones, and partly sub-hourly approach for a larger set of buildings. While the developed Invert/EE-Lab model calculates the energy needs, final energy demand and energy use of a building set of 400 buildings (4 building categories x 10 thermal quality settings x 10 climate zones) within a fraction of a second, the calculation with the EnergyPlus[98] model takes almost 20 CPU-hours on the same hardware.
- For non-residential buildings it is necessary to consider the monthly occupancy of the buildings, otherwise the energy needs (for cooling) are severely miscalculated for some types of buildings where utilization during the summer months is significantly lower (e.g. buildings of the education sector).

Modeling renovation activities and component replacement rates

- The replacement rates of building components are, on a national level, dynamic parameters, which mainly depend on the age and lifetime of the components in question. Thus, future replacement or renovation rates highly depend on the distribution of building stock cohorts. Historically observed replacement rates are needed to calibrate such a process, yet extrapolating from them beyond the near or eventual medium term future is of limited validity. If the mid- or long-term development is focused on, modeling approaches which define such replacement processes endogenously based on service lifetime data for the component should be used.
- For the scenario analyses as performed in this thesis, the observed service lifetime of technical components cannot be described by a single parameter but needs to be defined by distributions. The Weibull distribution is commonly used for this purpose. In this work, it is shown in section 6.1 that this type of distribution is able to reproduce historical observations sufficiently well.
- If the service lifetime of technical components is defined only based on historically observed data, the model has no degree of freedom with respect to future replacement

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[98] The computational demand increases (sublinearly) with the complexity of the building description. The single thermal-zone rather simply defined single-family houses (see Zangheri et al., 2014) are significantly faster (~40 seconds per building).

rates. This stands in contrast to the reasonable assumption that investment-decision-makers also react to the cost level of measures. On a short-term horizon measures will be pre- or postponed; on a long term horizon investors will adopt their perceptions related to the (visible and technical) effects of aging of components, which will affect the typical service lifetime of components. This thesis presents an approach which allows— to some degree—to respond to the cost level of refurbishment measures and policy instruments, if they have a strong impact on the weighted average costs of available (refurbishment) options.

Modeling investment decision

- Addressing the research question on possible trajectories for the energy demand of the building stock goes along with a larger number of individual decisions. When confronted with such decision situations, individual investors will opt for different options. At least three reasons can be given for such a behavior. The first two are related to uncertainties. On the one hand, when assessing a larger building stock, the actual parameters (building geometry, renovation costs and qualities, detailed utilization of building, etc.) influencing each decision cannot be observed. Thus, the model does not provide the correct least-cost solution for each object. On the other hand, decision-makers are also confronted with limited information about available technologies, their performance and associated least-cost offers and will therefore not always choose the option with the highest utility[99]. Finally, given such a large base of decision-makers, the probably most important reason is defined by individual preferences, which differ at least to some degree from the preferences of other decision-makers.
- An optimization algorithm which chooses only the option with the highest utility (e.g. cost optimal solution) clearly cannot describe the underlying decision processes and the observed choices well. Literature suggests using a logit or probit model or one of their derivatives.
- For the research question analyzed, a nested logit model (NLM), which is not bounded by the *independence from irrelevant alternatives* precondition, is used. The NLM approach allows clustering the set of available technology options into subsets, based on the idea that the decision-maker facing these options will decide in multiple stages. They are likely to decide upfront whether to apply maintenance or a thermal renovation based on

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[99] E.g. lowest costs.

(weighted) average costs for maintenance and thermal renovations. If the decision to perform a thermal renovation is taken, the attractiveness (which is then translated into shares or probabilities) for the different available thermal renovation options is evaluated. The same pattern can be expected to hold for heating systems. It is likely that decision-makers will focus either on the main energy carrier or on whether or not to install solar thermal collectors in a first step, again based on the (weighted) average penalty/utility (e.g. costs). The decision between different types of boiler technologies (e.g. standard gas boiler versus condensing boiler) or different sizes of solar thermal collector areas are expected to be taken subsequently on different decision levels.

- In the assessed area, decision-makers face a relatively large number of individual technologies (different types of thermal renovation options, different types of heating systems, different sizes of solar thermal collectors, or PV) and their combination at different points in time. Therefore, a model algorithm describing this process needs to calculate in each simulation step the market shares (or probabilities) of a large number (in the order of 10^2-10^3) of technology combinations for an even larger number of different buildings (for the applied Austrian building stock database in the order of 10^5 in 2008). Furthermore, the decision of whether or not to perform some sort of building envelope-related measure and to replace the existing heating system does not necessarily need to be taken at the same point of time (simulation step). Therefore the number of different building settings (in this work referred as “building segments”) and the number of buildings for which decisions need to be assessed, increases over time[100]. When developing the model, one target was to keep all decisions traceable throughout a simulation run[101]. This specification conflicts with a re-clustering of buildings and requires storing all different building settings and their probabilities individually. If this is not restricted to some extent, this would lead to a more or less exponentially increasing number of individual building segments (building settings) throughout the simulation and would push computational demand quickly beyond limits.
- To address this problem, a stochastic algorithm is presented in this work. The implemented algorithm, while introducing only a very low variance (due to the stochastic implementation) of the model results, keeps the computational demand at a low level and

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[100] For the Austrian scenarios calculated until 2080, a calculation precision parameter is chosen to keep the number of different buildings settings in 2080 in the order of $2x10^7$.

[101] And are also available for post-processing of non-standard results.

meets the precondition of traceability. And most importantly, it ensures that the results do not significantly shift with the calculation precision parameter (share of deterministic and stochastic elements) or the simulation step width.

- Combining the logit model with a diffusion model is a further innovative aspect of the developed model. This combination allows to consider technology deployment and related market barriers endogenously and prevents an unreasonably fast market uptake of new technologies.

Restricting the applicability of energy carriers

- At least three different types of restrictions can constrain the applicability of energy carriers and models should consider them separately. The first limitations are tradable restrictions, such as the total availability of biomass. In such case, resources not used by one object are available the other objects. This type of restriction can be modeled by using cost-resource-potential-curves. The two other restrictions refer to non-tradable restrictions. In such case, a potential not used by one object is not available to others. This is typically the case for grid-bounded energy carriers such as natural gas and district heating or the applicability of solar thermal technologies. If the availability of energy carriers do not correlate (covariance is close to zero), then such a restriction can be modeled by restricting the ultimate market share of the technologies. If the availabilities are not statistically independently distributed (e.g. availability of usage of wood log and district heating), different types of restrictions, such as dividing the building stock into different regions (in this work referred as “energy carrier regions”) need to be implemented, in order to derive unbiased results.

8.2 Scenario results and policy implications: the need for action versus the danger of lock-in effects

Mitigating the climate change requires the reduction of global GHG-emissions. Reducing emissions in the building sector is, to some extent, cost-efficient (see e.g. Beurskens and Hekkenberg, 2011; Ragwitz et al., 2012). From a thermodynamic point of view, huge energy saving and GHG emission reduction potentials could be tapped if existing ambitious state-of-the-art low-energy-technologies and standards were applied to an all-encompassing extent. However, implementing these technologies often faces some serious barriers; either technological, economic, socio-economic, market failures or a combination of these barriers. This means that in reality the development of a low-energy consuming built environment will always lag behind the theoretically technical possibilities.

Energy policies measures need to be implemented, if the energy consumption and associated GHG emissions of the built environment are supposed to decrease according to energy and climate policy related targets. This thesis evaluates a set of policy instruments and measures, either implemented (by 2012) in Austria or discussed, by applying the developed model framework. The following conclusions are drawn based on the outcome of the analyses performed.

Until the beginning of the last decade the final energy demand and delivered energy for space heating and domestic hot water preparation kept rising. Since then, triggered by technological progress and implemented policies, the realized energy saving potentials have outweighed the effects of increasing heated floor area and rising comfort levels, leading to a decreasing observed energy consumption of this end-use sector.

The final energy demand until 2030

The first policy scenario, the WEM[102]-scenario analyses the policy packages implemented by 2012 in Austria. In this scenario, the final energy demand decreases by about 15% between 2010 and 2030. In addition to the realized energy savings, the share of on-site and delivered renewable energy carriers increases from 25 to 35% in 2030. Thus, the delivered energy decreases by -22%, and the CO_2-emissions decrease by about 55% within the same timeframe. The WAM-scenario includes additional policy packages not implemented by 2012, yet that are planned to be implemented in the near future. Additional measures are the national implementation of policy packages demanded by the two European Framework Directives: the recast of the energy performance of buildings (Directive 2010/31/EU) and the renewable energy directive (Directive 2009/28/EC). They include a minimum share of renewable energy carriers in new and comprehensively refurbished buildings, high-efficiency heating system technologies, and better energy performance standards by 2021 for newly constructed buildings, as well as additional financial support schemes for building renovations. Under the assumptions outlined in section 7.2, the delivered energy decreases by an additional 2 percentage points (final energy demand: -

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[102] With Existing Measures.

17.5% compared to 2010), while the share of renewable energy carriers (including on-site production) and district heating increases from 42% in 2010 to about 63% in 2030 (62% in the WEM-scenario).

The WAM+ scenario represents a scenario with an additional set of policy measures by 2021 to increase efficiency measures and the share of renewable energy carriers. Compared to the currently implemented policy measures, the settings implemented in the WAM+ scenario are already quite ambitious. This scenario includes, in addition to other instruments, a renovation obligation for buildings which do not fulfill certain energy performance indicators by 2021, if cost-efficient refurbishment options are available. Furthermore it implies measures which ensure that the current building codes are fulfilled to a higher degree. The additionally tapped energy efficiency potentials compared to the WAM scenario amount to about 8 TWh, which is almost twice the final energy demand reduction between 2020 and 2030 than in the WAM scenario. In the WAM+ scenario, the final energy demand decreases between 2010 and 2030 by 25%, and the delivered energy decreases by 40% and CO_2-emissions decrease by about 65%. Given the short period of time (10 years) that these measures are in place, it can be concluded that the policy measures implemented in the WAM+ scenario effectively increase the energy efficiency in the building sector.

The danger of lock-in effects

Although these policy settings considerably reduce the delivered energy, even the WAM+ scenario barely achieves the energy savings and GHG-emissions reductions that would be required to meet the long-term climate mitigation targets. Scenarios developed by Müller et al. (2012) indicate that the GHG-emission of the Austrian building stock needs to be reduced by about 65-70% until 2030 compared to 2010 and at least by 90% until 2050 in order to be consistent with scenarios in which the increase of the global mean temperature is stabilized at 2°C – 3°C above preindustrial level. Furthermore, the final energy demand should be reduced by 30-40% (delivered energy: 40%-50%) until 2030 and by more than 60% (delivered energy: 70%) until 2050 compared to the 2010 level. Streicher et al. (2010) reports similar levels of energy reductions by 2050. In order to meet the target of their study, to supply Austria in 2050 fully by renewable energy carriers, the delivered energy for heating, cooling and domestic hot water needs to be reduced by even more than 85%, having on-site renewable energy carriers providing 65%-85% of the final energy demand for heating and domestic hot water preparation. Such an ambitious target can only be by achieved ambitious policy settings.

This leads to the conclusion that due to the high inertia of the building stock and the long lead times, the need for action is higher than ever. Refurbishing the currently existing building stock is the (sectorial) key to achieve a development that is consistent with climate mitigation targets. It needs to be kept in mind that due to the long service lifetime of building components, shallow renovation activities lead to lock-in effects. Once renovation measures are set, the achieved status is conserved for decades. Thus, with respect to long term energy and emission reduction performances, it can be said that the renovation depth and quality[103] needs to be in focus while the quantity (the annual renovation rate) plays a less important role. This means that policies need to target low energy needs of buildings after refurbishments, by ensuring simultaneously that only a very low share of buildings performs thermally non-effective maintenance measures on the building envelope and thus bypass the quality standards required for thermal renovation activities.

The crucial question remains: How to overcome the barriers in real life policy making? All policy analyses carried out with the model Invert/EE-Lab lead to the conclusion that in the building sector a bundle of policy instruments are required to address the multiple and diverse barriers and obstacles of different investors. Such a bundle needs to contain tight regulatory measures on an ambitious level, sufficient financial support and financial instruments to absorb availability-of-capital barriers and to shift the economic focus towards the total costs of heating and domestic hot water preparation at socially optimal interest rates. All this needs to be accompanied by informational measures.

The impact of climate change

Climate change reduces the energy needs for space heating. However, compared to the reduction potential of efficiency improvements triggered by different policy settings, the impact of climate change on the heating needs is small. In the assessed A1B-scenarios (~3°C global temperature increase scenarios) the effects of climate change reduce the energy needs for heating of the building stock compared by about 10% until 2050, compared to current climate conditions. The effects on the energy needs for cooling are significantly larger. Compared to the current climate conditions, the cooling needs increase in these scenarios by

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[103] With respect to energy savings achieved by thermal renovation activities compared to the initial state.

about 40%-60% until 2050. This figure does not even take into account the positive feedback loop which is expected for the final energy demand of air conditioning. In contrast to heating systems, space cooling systems still have a low penetration rate in many building types, especially in residential buildings. With increasing energy needs for cooling, also the penetration level of air conditioning systems will increase. If policy measures do not adequately address the cooling needs of newly constructed and refurbished buildings, the final energy demand for cooling will increase by more than 50% compared to the reference climate conditions. However, when comparing the absolute effect of climate change on the energy demand for space heating and for cooling, it has to be taken into account, that currently the energy demand for space cooling in Austria is less than 1% of the energy demand for space heating and hot water.

8.3 Outlook

The developed model considers many effects endogenously and allows the assessment of a broad range of drivers of and barriers to the development of the future energy demand and the diffusion of energy carriers. This, however, comes at the cost of a high input data demand. In this respect, the limited availability of data on renovation activities and market trends in Austria lead to challenges in calibrating the renovation activities. Currently, no publicly (neither free nor commercial) accessible database exists, which monitors the actual refurbishment activities and renovation market. Subsequently, estimations on the average refurbishment rate of the last 5-10 years by experts in this field vary in a range of plus/minus 50%. At this point the question of how to deal with regions with very poor data availability, as it is the case for many countries, remains unanswered.

With respect to the building physics model a tighter integration with the electricity market and district heating sector could bring some additional insights. Especially the integration of power-to-heat options, considered on a sub-monthly level, and the integration of PV systems into the energy model, as well as an endogenous integration of the expansion (process) of district heating grids, possibly by adding information on the spatial distribution of buildings, would be beneficial.

Furthermore, the decision behaviors of investors could be investigated in greater detail and implemented into the model. Currently, it is implied that the total annual costs, a preference for the existing energy carrier and consumer-preferences, calibrated on a top-level, are the main decision criteria. Other criteria are considered to be unobserved and define the variance of the decision parameter. The author could not derive conclusive data (based on the results of a conducted survey, on which the author collaborated) that would allow to calibrate other decision criteria for different investor types. Yet, literature on this area of research suggests that different investor types have individual preferences and that factors other than economic ones also play a relevant role. Analyzing the decision criteria further and transforming data from this research field in such a way that the information can be used in the model would certainly strengthen the conclusion based on the model results.

Additional data-driven research could be conducted with respect to the service lifetime of buildings and building components and the interrelationship between building demolition and construction and the property value; such data are rare, especially for regions with a decreasing population.

Finally, it is highly recommended to improve the monitoring of the impact of policy measures on a bottom-up level. Measures targeting the energy performance of buildings are confronted with the very inert built environment; components once installed are in place for a long period of time. Therefore it takes years to observe effects on a macro level. However, given the urgent need to take action, such a long time-lag prevents flexible target-oriented policy measures, which are simultaneously cost-efficient, socially balanced and effective.

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A. Appendix

A.1 Building stock data

Table A.1 – Number of buildings and total conditioned gross floor area (GFA) per building category.

	Buildings [tds. Build.]		**Conditioned GFA** [km²]		**GFA/build.** [m²]	$n_{min,BCA}$ **($f_{min\ share}$=4)**
	2008	**2030**	**2008**	**2030**	**2008**	
Residential sector						
Single family houses, detached	1314	1527	208	245	158	8.55
Single family houses, semi detached	239	277	61	73	257	3.73
Multifamily Houses	120	141	64	76	532	1.82
Apartment Block	59	70	95	115	1595	0.66
Tertiary sector						
Wholesale & retail trade, mall-style	11	14	7	9	648	1.26
Wholesale & retail trade, small	12	16	11	14	875	0.94
Hotel & restaurants, large	2	2	9	12	5461	0.15
Hotel & restaurants, small	25	33	36	48	1441	0.62
Private offices, large	7	9	17	22	2537	0.33
Private offices, small	42	55	14	18	324	2.57
Private offices, in res.	8	11	14	19	1693	0.49
Sport and Leisure, mall-style	1	2	1	2	778	1.03
Other warehouses-style build., large	7	9	7	9	981	0.83
Other warehouses-style build., small	15	18	3	4	206	3.90
Health, large buildings	0	0	6	6	28424	0.03
Education and culture	13	14	15	16	1182	0.71
Public offices, small	0	0	1	1	2537	0.31
Public offices, large	2	2	1	1	324	2.47
Production sector **Energy demand not accounted in Scenarios**						
Warehouses-style build., large	19	21	19	21	981	0.86
Warehouses-style build., small	41	45	8	9	206	3.97

Table A.2 – Defined building classes.

Name	**Construction period**	**BCA**	**DW/build.**	**Persons /DW**	**Length building [m]**	**Width building [m]**	**GFA [m^2]**	**Detach.facade surface area [m^2]**	**GV [m^3]**	**lc [m]**	**LEK**
farm_house old1890-1918_CR2_REN1917	1890-1918	1	1	3.2	11.9	8.4	201.1	200.0	643.5	1.4	143.8
farm_house old1890-1918_CR2_REN1995	1890-1918	1	1	3.2	11.9	8.4	201.1	200.0	643.5	1.4	99.5
farm_house old_ADDBARR1890-1918_CR2_REN1917	1890-1918	1	1	3.2	11.9	8.4	201.1	200.0	643.5	1.4	149.1
farm_house old_ADDBARR1890-1918_CR2_REN1995	1890-1918	1	1	3.2	11.9	8.4	201.1	200.0	643.5	1.4	80.9
SFH_A 1890-1918_CR2_REN1917	1890-1918	1	1	2.7	9.9	6.5	128.9	162.0	412.5	1.2	172.7
SFH_A 1890-1918_CR2_REN1995	1890-1918	1	1	2.7	9.9	6.5	128.9	162.0	412.5	1.2	118.1
SFH_A _ADDBARR1890-1918_CR2_REN1917	1890-1918	1	1	2.7	9.9	6.5	128.9	162.0	412.5	1.2	178.0
SFH_A _ADDBARR1890-1918_CR2_REN1995	1890-1918	1	1	2.7	9.9	6.5	128.9	162.0	412.5	1.2	90.4
SFH_B 1919-1944_CR2_REN1919	1919-1944	1	1	2.7	10.2	6.7	135.7	166.1	434.1	1.2	175.7
SFH_B 1919-1944_CR2_REN1945	1919-1944	1	1	2.7	10.2	6.7	135.7	166.1	434.1	1.2	167.0
SFH_B 1919-1944_CR2_REN1995	1919-1944	1	1	2.7	10.2	6.7	135.7	166.1	434.1	1.2	86.7
SFH_B _ADDBARR1919-1944_CR2_REN1919	1919-1944	1	1	2.7	10.2	6.7	135.7	166.1	434.1	1.2	181.0
SFH_B _ADDBARR1919-1944_CR2_REN1945	1919-1944	1	1	2.7	10.2	6.7	135.7	166.1	434.1	1.2	181.0
SFH_B _ADDBARR1919-1944_CR2_REN1995	1919-1944	1	1	2.7	10.2	6.7	135.7	166.1	434.1	1.2	88.9
SFH_C 1945-1960_CR2_REN1949	1945-1960	1	1	2.7	10.5	6.9	144.3	157.9	425.5	1.2	155.0
SFH_C 1945-1960_CR2_REN1995	1945-1960	1	1	2.7	10.5	6.9	144.3	157.9	425.5	1.2	86.3
SFH_D 1961-1970_CR2_REN1961	1961-1970	1	1	2.7	10.9	7.1	154.1	163.3	454.6	1.2	145.2
SFH_D 1961-1970_CR2_REN1971	1961-1970	1	1	2.7	10.9	7.1	154.1	163.3	454.6	1.2	94.5
SFH_D 1961-1970_CR2_REN1995	1961-1970	1	1	2.7	10.9	7.1	154.1	163.3	454.6	1.2	82.9
SFH_F 1971-1980_CR2_REN1971	1971-1980	1	1	2.7	11.2	7.3	163.3	170.9	489.8	1.3	116.8
SFH_F 1971-1980_CR2_REN1981	1971-1980	1	1	2.7	11.2	7.3	163.3	170.9	489.8	1.3	116.8
SFH_F 1971-1980_CR2_REN1995	1971-1980	1	1	2.7	11.2	7.3	163.3	170.9	489.8	1.3	80.8
SFH_G 1981-1990_CR2_REN1981	1981-1990	1	1	2.7	11.3	7.4	165.9	172.3	497.8	1.3	82.3
SFH_G 1981-1990_CR2_REN1991	1981-1990	1	1	2.7	11.3	7.4	165.9	172.3	497.8	1.3	82.3
SFH_H 1991-2000_CR2_REN1991	1991-2000	1	1	2.7	11.4	7.4	169.6	174.1	508.7	1.3	68.3
SFH_I 2001-2008_CR2_REN2001	2001-2008	1	1	2.7	11.4	7.4	169.6	174.1	508.7	1.3	59.8
DH_A 1890-1918_CR2_REN1917	1890-1918	2	2	2.7	16.0	8.0	255.3	229.0	816.9	1.5	135.3
DH_A 1890-1918_CR2_REN1995	1890-1918	2	2	2.7	16.0	8.0	255.3	229.0	816.9	1.5	94.2
DH_A _ADDBARR1890-1918_CR2_REN1917	1890-1918	2	2	2.7	16.0	8.0	255.3	229.0	816.9	1.5	140.7
DH_A _ADDBARR1890-1918_CR2_REN1995	1890-1918	2	2	2.7	16.0	8.0	255.3	229.0	816.9	1.5	79.3
DH_B 1919-1944_CR2_REN1919	1919-1944	2	2	2.7	15.2	7.6	231.8	218.3	741.7	1.4	145.5
DH_B 1919-1944_CR2_REN1945	1919-1944	2	2	2.7	15.2	7.6	231.8	218.3	741.7	1.4	138.5
DH_B 1919-1944_CR2_REN1995	1919-1944	2	2	2.7	15.2	7.6	231.8	218.3	741.7	1.4	73.0
DH_B _ADDBARR1919-1944_CR2_REN1919	1919-1944	2	2	2.7	15.2	7.6	231.8	218.3	741.7	1.4	150.9
DH_B _ADDBARR1919-1944_CR2_REN1945	1919-1944	2	2	2.7	15.2	7.6	231.8	218.3	741.7	1.4	150.9
DH_B _ADDBARR1919-1944_CR2_REN1995	1919-1944	2	2	2.7	15.2	7.6	231.8	218.3	741.7	1.4	80.5
DH_C 1945-1960_CR2_REN1949	1945-1960	2	2	2.7	15.2	7.6	231.0	200.9	681.5	1.4	133.1
DH_C 1945-1960_CR2_REN1995	1945-1960	2	2	2.7	15.2	7.6	231.0	200.9	681.5	1.4	74.7
DH_D 1961-1970_CR2_REN1961	1961-1970	2	2	2.7	15.8	7.9	249.4	208.7	735.6	1.4	124.1
DH_D 1961-1970_CR2_REN1971	1961-1970	2	2	2.7	15.8	7.9	249.4	208.7	735.6	1.4	83.3
DH_D 1961-1970_CR2_REN1995	1961-1970	2	2	2.7	15.8	7.9	249.4	208.7	735.6	1.4	71.6
DH_F 1971-1980_CR2_REN1971	1971-1980	2	2	2.7	16.5	8.2	271.5	221.5	814.6	1.4	98.7
DH_F 1971-1980_CR2_REN1981	1971-1980	2	2	2.7	16.5	8.2	271.5	221.5	814.6	1.4	98.7
DH_F 1971-1980_CR2_REN1995	1971-1980	2	2	2.7	16.5	8.2	271.5	221.5	814.6	1.4	69.2
DH_G 1981-1990_CR2_REN1981	1981-1990	2	2	2.7	16.8	8.4	280.6	225.1	841.8	1.4	69.5
DH_G 1981-1990_CR2_REN1991	1981-1990	2	2	2.7	16.8	8.4	280.6	225.1	841.8	1.4	69.5
DH_H 1991-2000_CR2_REN1991	1991-2000	2	2	2.7	16.9	8.5	287.2	227.8	861.5	1.5	58.0
DH_I 2001-2008_CR2_REN2001	2001-2008	2	2	2.7	16.9	8.5	287.2	227.8	861.5	1.5	50.4
AHs_A 1890-1918_CR2_REN1917	1890-1918	3	5.56	2.0	19.8	9.9	587.4	413.5	2056.1	2.0	101.8
AHs_A 1890-1918_CR2_REN1995	1890-1918	3	5.56	2.0	19.8	9.9	587.4	413.5	2056.1	2.0	70.5
AHs_A _ADDBARR1890-1918_CR2_REN1917	1890-1918	3	5.56	2.0	19.8	9.9	587.4	413.5	2056.1	2.0	105.3
AHs_A _ADDBARR1890-1918_CR2_REN1995	1890-1918	3	5.56	2.0	19.8	9.9	587.4	413.5	2056.1	2.0	67.2
AHs_B 1919-1944_CR2_REN1919	1919-1944	3	5.56	2.0	17.6	8.8	463.3	346.2	1529.0	1.8	117.6
AHs_B 1919-1944_CR2_REN1945	1919-1944	3	5.56	2.0	17.6	8.8	463.3	346.2	1529.0	1.8	111.2
AHs_B 1919-1944_CR2_REN1995	1919-1944	3	5.56	2.0	17.6	8.8	463.3	346.2	1529.0	1.8	59.1
AHs_B _ADDBARR1919-1944_CR2_REN1919	1919-1944	3	5.56	2.0	17.6	8.8	463.3	346.2	1529.0	1.8	121.4
AHs_B _ADDBARR1919-1944_CR2_REN1945	1919-1944	3	5.56	2.0	17.6	8.8	463.3	346.2	1529.0	1.8	121.4
AHs_B _ADDBARR1919-1944_CR2_REN1995	1919-1944	3	5.56	2.0	17.6	8.8	463.3	346.2	1529.0	1.8	71.3
AHs_C 1945-1960_CR2_REN1949	1945-1960	3	5.56	2.0	17.4	8.7	455.1	306.7	1342.4	1.8	108.2
AHs_C 1945-1960_CR2_REN1995	1945-1960	3	5.56	2.0	17.4	8.7	455.1	306.7	1342.4	1.8	61.0
AHs_D 1961-1970_CR2_REN1961	1961-1970	3	5.56	2.0	18.6	9.3	521.0	328.2	1537.0	1.8	98.6
AHs_D 1961-1970_CR2_REN1971	1961-1970	3	5.56	2.0	18.6	9.3	521.0	328.2	1537.0	1.8	65.2
AHs_D 1961-1970_CR2_REN1995	1961-1970	3	5.56	2.0	18.6	9.3	521.0	328.2	1537.0	1.8	56.9
AHs_F 1971-1980_CR2_REN1971	1971-1980	3	5.56	2.0	19.5	9.8	571.5	349.6	1714.5	1.9	78.4
AHs_F 1971-1980_CR2_REN1981	1971-1980	3	5.56	2.0	19.5	9.8	571.5	349.6	1714.5	1.9	78.4
AHs_F 1971-1980_CR2_REN1995	1971-1980	3	5.56	2.0	19.5	9.8	571.5	349.6	1714.5	1.9	54.7
AHs_G 1981-1990_CR2_REN1981	1981-1990	3	5.56	2.0	19.6	9.8	576.6	351.1	1729.8	1.9	55.8

Name	**Construction period**	**BCA**	**DW/build.**	**Persons /DW**	**Length building**	**Width building**	**GFA**	**Detach.facade surface area**	**GVA**	**lc**	**LEK**
AHs_G 1981-1990_CR2_REN1991	1981-1990	3	5.56	2.0	19.6	9.8	576.6	351.1	1729.8	1.9	55.8
AHs_H 1991-2000_CR2_REN1991	1991-2000	3	5.56	2.0	19.0	9.5	542.4	340.6	1627.3	1.9	48.0
AHs_I 2001-2008_CR2_REN2001	2001-2008	3	5.56	2.0	19.1	9.5	545.7	341.6	1637.1	1.9	42.0
AHl_A 1890-1918_CR2_REN1917	1890-1918	4	18.54	1.9	33.3	12.5	1663.6	836.9	5822.7	2.8	74.3
AHl_A 1890-1918_CR2_REN1995	1890-1918	4	18.54	1.9	33.3	12.5	1663.6	836.9	5822.7	2.8	52.9
AHl_A _ADDBARR1890-1918_CR2_REN1917	1890-1918	4	18.54	1.9	33.3	12.5	1663.6	836.9	5822.7	2.8	76.9
AHl_A _ADDBARR1890-1918_CR2_REN1995	1890-1918	4	18.54	1.9	33.3	12.5	1663.6	836.9	5822.7	2.8	55.8
AHl_B 1919-1944_CR2_REN1919	1919-1944	4	18.54	1.9	29.8	11.2	1330.9	705.8	4392.0	2.5	85.2
AHl_B 1919-1944_CR2_REN1945	1919-1944	4	18.54	1.9	29.8	11.2	1330.9	705.8	4392.0	2.5	80.6
AHl_B 1919-1944_CR2_REN1995	1919-1944	4	18.54	1.9	29.8	11.2	1330.9	705.8	4392.0	2.5	54.6
AHl_B _ADDBARR1919-1944_CR2_REN1919	1919-1944	4	18.54	1.9	29.8	11.2	1330.9	705.8	4392.0	2.5	88.1
AHl_B _ADDBARR1919-1944_CR2_REN1945	1919-1944	4	18.54	1.9	29.8	11.2	1330.9	705.8	4392.0	2.5	88.1
AHl_B _ADDBARR1919-1944_CR2_REN1995	1919-1944	4	18.54	1.9	29.8	11.2	1330.9	705.8	4392.0	2.5	58.5
AHl_C 1945-1960_CR2_REN1949	1945-1960	4	18.54	1.9	30.3	11.4	1376.5	641.6	4060.8	2.4	77.0
AHl_C 1945-1960_CR2_REN1995	1945-1960	4	18.54	1.9	30.3	11.4	1376.5	641.6	4060.8	2.4	54.0
AHl_D 1961-1970_CR2_REN1961	1961-1970	4	18.54	1.9	32.0	12.0	1539.5	678.6	4541.6	2.5	70.8
AHl_D 1961-1970_CR2_REN1971	1961-1970	4	18.54	1.9	32.0	12.0	1539.5	678.6	4541.6	2.5	50.0
AHl_D 1961-1970_CR2_REN1995	1961-1970	4	18.54	1.9	32.0	12.0	1539.5	678.6	4541.6	2.5	46.9
AHl_F 1971-1980_CR2_REN1971	1971-1980	4	18.54	1.9	33.9	12.7	1721.2	729.7	5163.7	2.6	55.9
AHl_F 1971-1980_CR2_REN1981	1971-1980	4	18.54	1.9	33.9	12.7	1721.2	729.7	5163.7	2.6	55.9
AHl_F 1971-1980_CR2_REN1995	1971-1980	4	18.54	1.9	33.9	12.7	1721.2	729.7	5163.7	2.6	44.8
AHl_G 1981-1990_CR2_REN1981	1981-1990	4	18.54	1.9	34.3	12.9	1765.9	739.1	5297.8	2.6	39.6
AHl_G 1981-1990_CR2_REN1991	1981-1990	4	18.54	1.9	34.3	12.9	1765.9	739.1	5297.8	2.6	39.6
AHl_H 1991-2000_CR2_REN1991	1991-2000	4	18.54	1.9	33.3	12.5	1661.9	717.0	4985.7	2.6	34.1
AHl_I 2001-2008_CR2_REN2001	2001-2008	4	18.54	1.9	33.3	12.5	1661.9	717.0	4985.7	2.6	29.8
Sale_mall1960-2008_CR2_REN1960	1960-2008	5			36	18	648	350	2527	1.5	147
Hotel_large_A1940-1960_CR2_REN1960	1940-1960	6			57	19	5461	2344	20205	4.0	46
Hotel_large_B1961-1990_CR2_REN1970	1961-1990	6			57	19	5461	2090	18020	3.8	46
Hotel_large_C1991-2008_CR2_REN1991	1991-2008	6			57	19	5461	2090	18020	3.8	22
Hosiptal_A1940-1970_CR2_REN1960	1940-1970	7			304	23	28424	8036	105170	4.4	45
Hosiptal_B1971-2008_CR2_REN1971	1971-2008	7			304	23	28424	8036	105170	4.4	37
Off_large_A1940-1960_CR2_REN1960	1940-1960	8			58	9	2537	2038	9387	2.7	76
Off_large_B1961-1990_CR2_REN1970	1961-1990	8			58	9	2537	1817	8372	2.6	76
Off_large_C1991-2008_CR2_REN1991	1991-2008	8			58	9	2537	1642	8372	2.6	40
Education_A1940-1970_CR2_REN1960	1940-1970	9			44	9	1182	972	4373	2.2	100
Education_B1971-2008_CR2_REN1980	1971-2008	9			44	9	1182	972	4373	2.2	83
Sport-_u._Freizeiteinrichtungen1960-2008_CR2_REN1960	1960-2008	10			36	14	778	615	3810	2.1	110
Handel_small_A1940-1960_CR2_REN1960	1940-1960	11			27	16	875	448	3237	2.1	77
Handel_small_B1961-1990_CR2_REN1970	1961-1990	11			27	16	875	400	2887	2.0	78
Handel_small_C1991-2008_CR2_REN1991	1991-2008	11			27	16	875	400	2887	2.0	38
Hotel_small_A1940-1960_CR2_REN1960	1940-1960	12			42	14	1441	755	5331	2.4	70
Hotel_small_B1961-1990_CR2_REN1970	1961-1990	12			42	14	1441	673	4754	2.3	71
Hotel_small_C1991-2008_CR2_REN1991	1991-2008	12			42	14	1441	673	4754	2.3	35
Off_small_A1940-1960_CR2_REN1960	1940-1960	13			30	7	324	309	1200	1.4	123
Off_small_B1961-1990_CR2_REN1970	1961-1990	13			30	7	324	276	1070	1.3	124
Off_small_C1991-2008_CR2_REN1991	1991-2008	13			30	7	324	276	1070	1.3	61
Offs_in_MFH_A1940-1960_CR2_REN1960	1940-1960	14			31	13	1577	937	5836	2.8	69
Offs_in_MFH_B1961-1980_CR2_REN1970	1961-1980	14			31	13	1612	843	5320	2.7	68
Offs_in_MFH_C1981-1990_CR2_REN1981	1981-1990	14			33	14	1827	899	6029	2.8	38
Offs_in_MFH_D1991-2008_CR2_REN1991	1991-2008	14			33	14	1858	907	6132	2.8	31
Wharehosue_IND_groß1960-2008_CR2_REN1960	1960-2008	15			36	14	981	886	5296	2.6	95
Wharehosue_IND_klein1960-2008_CR2_REN1960	1960-2008	16			18	8	206	280	908	1.5	169
Off_pub_large_A1940-1960_CR2_REN1960	1940-1960	17			58	9	2537	2038	9387	2.7	76
Off_pub_large_B1961-1990_CR2_REN1970	1961-1990	17			58	9	2537	1817	8372	2.6	76
Off_pub_large_C1991-2008_CR2_REN1991	1991-2008	17			58	9	2537	1642	8372	2.6	40
Off_pub_small_A1940-1960_CR2_REN1960	1940-1960	18			30	7	324	309	1200	1.4	123
Off_pub_small_B1961-1990_CR2_REN1970	1961-1990	18			30	7	324	276	1070	1.3	124

Name	Construction period	BCA	DW/build.	Persons /DW	Length building	Width building	GFA	Detach.facade surface area	GVA	lc	LEK
Off_pub_small_C1991-2008_CR2_REN1991	1991-2008	18			30	7	324	276	1070	1.3	61
Wharehosue_large_GHD1960-2008_CR2_REN1960	1960-2008	19			36	14	981	886	5296	2.6	95
Wharehosue_small_GHD1960-2008_CR2_REN1960	1960-2008	20			18	8	206	280	908	1.5	169
Hotel_large_A_Addbarr1920-1945 CR2_REN1960	1920-1945	6			57	19	5461	2344	20205	4.0	52
Hosiptal_A_Addbarr1920-1945_CR2_REN1960	1920-1945	7			304	23	28424	8036	105170	4.4	42
Off_large_A_Addbarr1920-1945 CR2_REN1960	1920-1945	8			58	9	2537	2038	9387	2.7	85
Education_A Addbarr1920-1945_CR2_REN1960	1920-1945	9			44	9	1182	972	4373	2.2	96
Handel_small_A_Addbarr1920-1945_CR2_REN1960	1920-1945	11			27	16	875	448	3237	2.1	86
Hotel_small_A_Addbarr1920-1945_CR2_REN1960	1920-1945	12			42	14	1441	755	5331	2.4	79
Off_small_A_Addbarr1920-1945 CR2_REN1960	1920-1945	13			30	7	324	309	1200	1.4	138
Offs_in_MFH_A_Addbarr1920-1945_CR2_REN1960	1920-1945	14			31	13	1577	937	5836	2.8	77
Off_pub_large_A_Addbarr1920-1945_CR2_REN1960	1920-1945	17			58	9	2537	2038	9387	2.7	85
Off_pub_small_A_Addbarr1920-1945_CR2_REN1960	1920-1945	18			30	7	324	309	1200	1.4	138

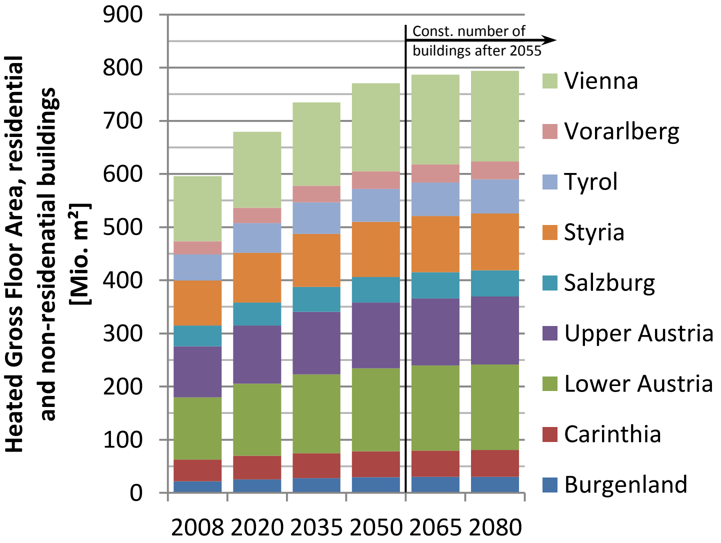

Figure A.1 – Heated gross floor area per federal state until 2080.

A.2 Assumptions on heating systems and energy carriers

A.2.1 Assumptions on energy carriers

Table A.3 – Estimated availability of heating systems and energy carriers per defined regions.

	Heat demand density	**Burgen-land**	**Carinthia**	**Lower Austria**	**Upper Austria**	**Salzburg**	**Styria**	**Tyrol**	**Vorarl-berg**	**Vienna**
		Upper market penetration level								
Oil, coal, electricity	all	100%								
Heat pumps, heat source: air	all	80%								
Heat pumps, heat source: ground	high 1)	20%								
	medium 2)	50%								
	low 3)	80%								
Solar thermal collectors	high	60%								
	medium	65%								
	low	75%								
Wood log, wood chips	high	20%								
	medium	55%								
	low	70%								
Wood pellets	high	70%								
	medium	8%								
	low	90%								
Non-commercial wood log, wood chips, available at 70% of regular energy price	high	0								
	medium	5%								
	low	20%								
District heating, urban type	high	36%	85%	80%	85%	80%	85%	77%	57%	81%
	medium	10%	25%	12%	25%	10%	25%	10%	10%	50%
	low	0%	0%	0%	0%	0%	0%	0%	0%	0%
District heat, rural type	high	0%	0%	0%	0%	0%	0%	0%	0%	0%
	medium	10%	25%	12%	25%	5%	25%	5%	5%	0%
	low	4%	5%	2%	5%	3%	5%	3%	3%	0%
Natural gas	high	100%	86%	94%	94%	75%	86%	83%	85%	94%
	medium	82%	48%	79%	82%	0%	60%	0%	0%	88%
	low	42%	15%	34%	24%	0%	18%	23%	0%	0%

1) > 16 GWh/km²
2) 8 - 16 GWh/km²
3) < 8 GWh/km²

A.2.2 Assumptions on heating systems

Table A.4 – Investment costs of heating systems.

	Heat load of building [kW]									
	5	10	15	20	35	50	100	200	500	1000
	Investment costs absolute values (specific values per kW in brackets)									
Single stove systems										
Heating oil	8300€ (1664)	8300€ (832)	9000€ (602)	9700€ (486)	--	--	--	--	--	--
Natural gas	7000€ (1396)	7000€ (698)	7700€ (514)	8500€ (423)	--	--	--	--	--	--
Coal	13500€ (2695)	13500€ (1347)	13500€ (898)	14000€ (698)	--	--	--	--	--	--
Wood log	13500€ (2695)	13500€ (1347)	13500€ (898)	14000€ (698)	--	--	--	--	--	--
Pellets	3600€ (720)	5800€ (576)	7600€ (504)	9400€ (468)	--	--	--	--	--	--
Electrical converter	200€ (30)	300€ (30)	500€ (30)	600€ (30)	1100€ (30)	1500€ (30)	3000€ (30)	6000€ (30)	15000€ (30)	30000€ (30)
Electrical night storage	700€ (144)	1400€ (140)	2000€ (136)	2600€ (132)	4300€ (123)	6000€ (120)	11600€ (116)	22800€ (114)	56400€ (113)	112400€ (112)
Apartment central heating										
Natural gas	7000€ (1396)	7000€ (698)	7700€ (514)	8500€ (423)	10400€ (296)	11700€ (234)	14600€ (146)	19800€ (99)	35100€ (70)	61100€ (61)
Building central heating										
Heating oil	6200€ (1230)	6200€ (615)	6700€ (449)	7300€ (366)	9100€ (259)	10800€ (216)	14300€ (143)	20200€ (101)	37700€ (75)	67200€ (67)
Heating oil, condensing boiler	6900€ (1387)	6900€ (693)	7500€ (501)	8100€ (405)	9900€ (282)	11700€ (234)	15100€ (151)	20900€ (105)	38000€ (76)	67000€ (67)
Natural gas	4500€ (1396)	4500€ (698)	5100€ (514)	5700€ (423)	7300€ (296)	8400€ (234)	10900€ (146)	15500€ (99)	29000€ (70)	51800€ (61)
Natural gas condensing boiler	5800€ (907)	5800€ (453)	6400€ (341)	7000€ (285)	8600€ (207)	9700€ (167)	12200€ (109)	16500€ (77)	29300€ (58)	50900€ (52)
Coal	11200€ (1163)	11200€ (582)	11200€ (429)	11600€ (352)	14100€ (247)	16500€ (195)	17800€ (122)	17800€ (83)	40000€ (80)	75000€ (75)
Wood log	11200€ (2246)	11200€ (1123)	11200€ (749)	11600€ (582)	14100€ (404)	--	--	--	--	--
Wood chips	19700€ (2246)	19700€ (1123)	19700€ (749)	19700€ (582)	20200€ (404)	--	--	--	--	--
Wood pellets	12200€ (3940)	12200€ (1970)	14100€ (1313)	16000€ (985)	19000€ (578)	21400€ (436)	28400€ (420)	42400€ (414)	83700€ (411)	153400€ (409)
Heat pump, heat source: air	7800€ (2440)	12100€ (1220)	12200€ (940)	14600€ (800)	17300€ (543)	20000€ (428)	29000€ (284)	47100€ (212)	100900€ (167)	191200€ (153)
Heat pump, heat source: ground shallow	12900€ (1554)	15500€ (1205)	17900€ (814)	19900€ (728)	25000€ (494)	30000€ (400)	46800€ (290)	80400€ (236)	180700€ (202)	348400€ (191)
Heat pump, heat source: ground deep	16200€ (2571)	20300€ (1549)	24800€ (1196)	29400€ (996)	39600€ (713)	48700€ (600)	79200€ (468)	140100€ (402)	322100€ (361)	626400€ (348)
District heating, urban type	6600€ (2571)	6600€ (1549)	6600€ (1196)	8400€ (996)	13000€ (713)	16000€ (600)	23000€ (468)	35500€ (402)	72500€ (361)	134800€ (348)
District heat, rural type	8100€ (3239)	8100€ (2028)	8100€ (1656)	10300€ (1471)	16000€ (1131)	19700€ (975)	28300€ (792)	43700€ (701)	89200€ (644)	165900€ (626)

Table A.5 – Implemented efficiencies (2010) of space heating systems.

	Efficiency heating $\eta_{H,sys,25}$	**Temperature coefficient** κ	**Efficiency DHW** $\eta_{DWH,sys,25}$	**Can be combined with sol.thermal collectors**
Single stove systems				
Heating oil	60%	0	51%	No
Natural gas	60%	0	51%	
Coal	55%	0	47%	
Wood log	55%	0	47%	
Pellets	57%	0	48%	
Electrical converter	100%	0	85%	
Electrical night storage	95%	0	81%	
Apartment central heating				
Natural gas	88%	0	84%	No
Building central heating				
Heating oil	85%	0.005	77%	Yes
Heating oil, condensing boiler	93%	0.015	84%	
Natural gas	88%	0.005	84%	
Natural gas condensing boiler	94%	0.015	89%	
Coal	65%	0.005	59%	
Wood log	63%	0.005	57%	
Wood chips	69%	0.005	62%	
Wood pellets	77%	0.005	69%	
Heat pump, heat source: air	310%	0.38	233%	
Heat pump, heat source: ground shallow and deep	420%	0.28	315%	
District heating, urban type	95%	0.005	86%	No
District heat, rural type	95%	0.005	86%	

Table A.6 – Solar thermal systems (2010).

	Size [m²]					
	5	**10**	**25**	**35**	**50**	**>50**
Investment costs [€]	3711	6886	15593	21051	28936	$880*(m^2)^{0.892}$
Energy yield*) [kWh/yr]	430					

*) See section 4.4.3

A.3 Assumptions on the lifetime of buildings and building components

Table A.7 – Service lifetime of buildings.

Building type	Characteristic lifetime λ [years]	Shape parameter k [-]
Buildings, constructed until 1945- with additional renovation barriers	220	6
Buildings, constructed until 1918	145	6
Buildings, constructed between 1919-1945	135	6
Non-residential buildings, ware-house and mall style	60	6
Other buildings	100	6

Table A.8 – Service lifetime of building façade elements and windows.

	Façade		**Windows**	
Building type	Characteristic lifetime λ **[year]**	Shape parameter k **[-]**	Characteristic lifetime λ **[year]**	Shape parameter k **[-]**
Buildings, constructed between 1919-1945	57.11	4.07	41.84	6.99
Buildings, constructed until 1918 and Buildings, constructed until 1945- with additional renovation barriers	57.11	4.07	56.13	4.04
Non-residential buildings, ware-house and mall style	55	6	55	6
New residential buildings	37.99	4.31	39.07	4.7
Residential buildings constructed between 1945 - 1960	39.07	4.7	39.07	4.7
Residential buildings constructed between 1961 - 2010	37.99	4.31	39.07	4.7

Table A.9 – Service lifetime of heating systems.

	Characteristic lifetime λ [year]	Shape parameter k [-]
Building and apartment central natural gas heating systems	28	3.19
Wood pellets and heat pumps	32	3.19
District heating	60	3.19
Other heating systems	35	3.19

A.4 Upper market share of technologies and energy carriers

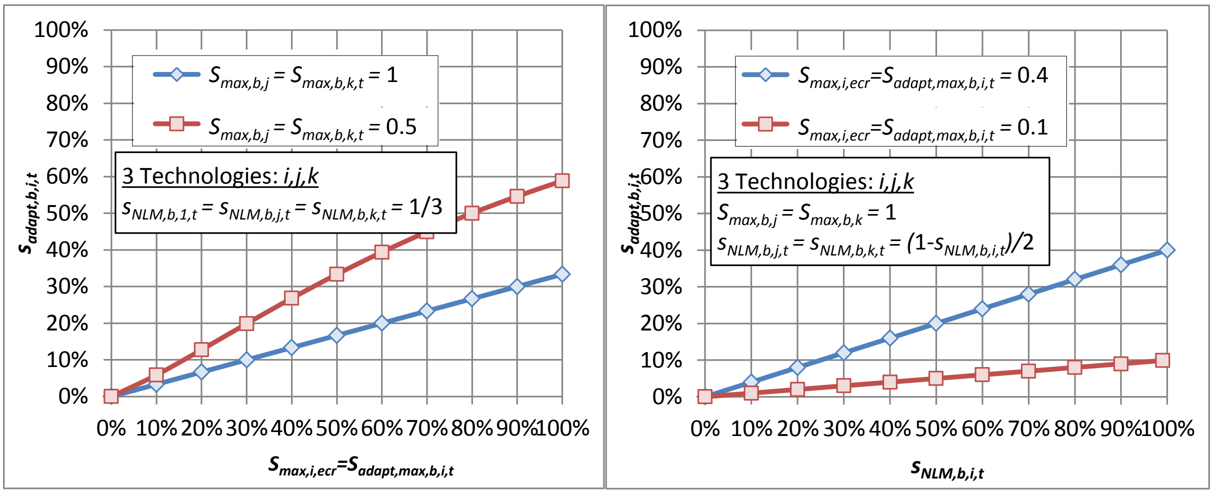

Figure A.1. Market share $s_{adapt,b,i,t}$ of technology *i* against alternatives *j* and *k* for different levels of upper market shares $S_{max,b,i}$ (left figure) and shares $S_{NLM,b,i,t}$ according to the nested logit model (right figure) in *t*.

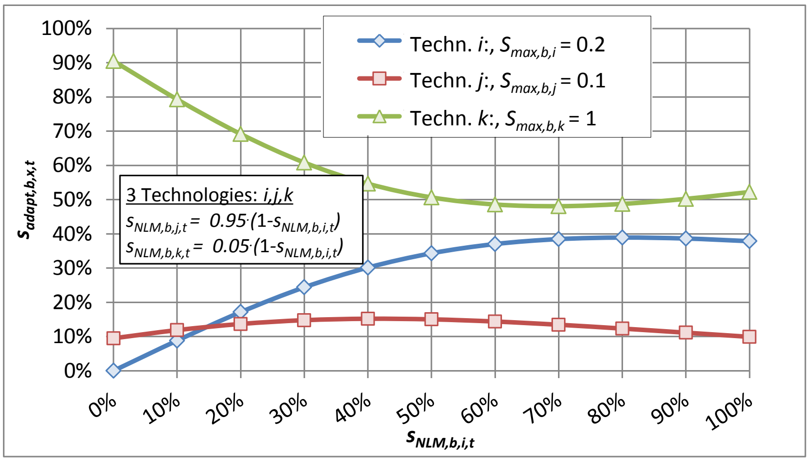

Figure A.2. Market shares $s_{adapt,b,x,t}$ of technology i,*j*,*k* against alternatives *j* and *k* for different shares $S_{NLM,b,i,t}$ for according to the nested logit model.

A.5 Biogenic energy prices in the WEM scenario

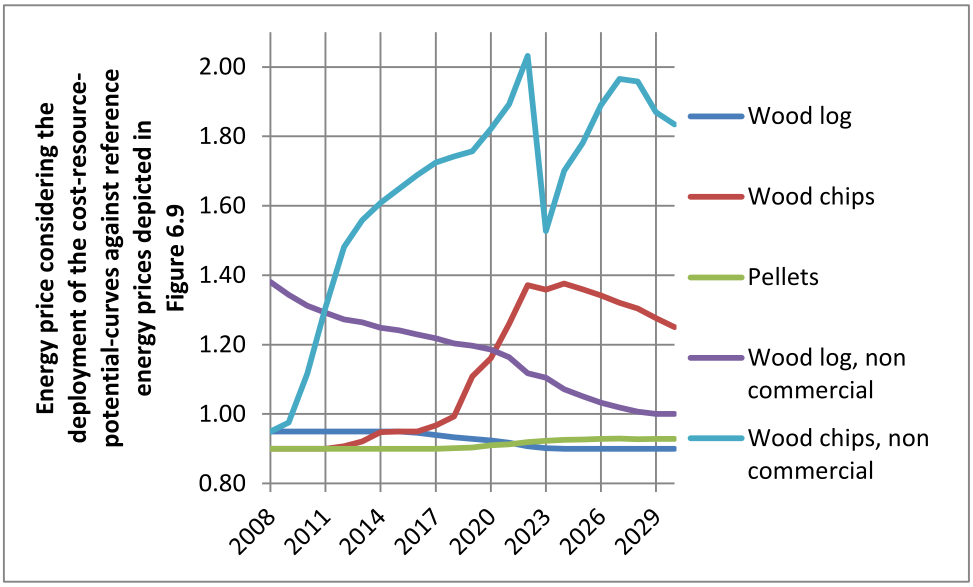

Figure A.4. Biogenic energy price development in the WEM scenario.