Climate change impacts on electricity and residential energy demand

A cumulative dissertation
submitted in fulfilment of the requirements
for the degree of Doctor of Natural Sciences
'doctor rerum naturalium' (Dr. rer. nat.)
in Geoecology

Faculty of Mathematics and Natural Sciences
at the
University of Potsdam, Germany

by
Mady Olonscheck

May 2016

Referees:

Prof. Dr. Jürgen P. Kropp: University of Potsdam, Institute of Earth and Environmental Sciences; Potsdam Institute for Climate Impact Research, Research Domain “Climate Impacts and Vulnerabilities”

Prof. Dr. Christoph Schneider: Humboldt University of Berlin, Institute for Geography, Department “Climate Geography”

Prof. Dr. Matthias Kalkuhl: University of Potsdam, Faculty of Economic and Social Sciences; Mercator Research Institute on Global Commons and Climate Change, Working Group “Economic Growth and Human Development”

Published online at the
Institutional Repository of the University of Potsdam:
URN urn:nbn:de:kobv:517-opus4-98378
http://nbn-resolving.de/urn:nbn:de:kobv:517-opus4-98378

"The saddest aspect of life right now is that science gathers knowledge faster than society gathers wisdom."

Isaac Asimov

Summary

The energy sector is both affected by climate change and a key sector for climate protection measures. Energy security is the backbone of our modern society and guarantees the functioning of most critical infrastructure. Thus, decision makers and energy suppliers of different countries should be familiar with the factors that increase or decrease the susceptibility of their electricity sector to climate change. Susceptibility means socioeconomic and structural characteristics of the electricity sector that affect the demand for and supply of electricity under climate change.

Moreover, the relevant stakeholders are supposed to know whether the given national energy and climate targets are feasible and what needs to be done in order to meet these targets. In this regard, a focus should be on the residential building sector as it is one of the largest energy consumers and therefore emitters of anthropogenic CO_2 worldwide.

This dissertation addresses the first aspect, namely the susceptibility of the electricity sector, by developing a ranked index which allows for quantitative comparison of the electricity sector susceptibility of 21 European countries based on 14 influencing factors. Such a ranking has not been completed to date. We applied a sensitivity analysis to test the relative effect of each influencing factor on the susceptibility index ranking. We also discuss reasons for the ranking position and thus the susceptibility of selected countries.

The second objective, namely the impact of climate change on the energy demand of buildings, is tackled by means of a new model with which the heating and cooling energy demand of residential buildings can be estimated. We exemplarily applied the model to Germany and the Netherlands. It considers projections of future changes in population, climate and the insulation standards of buildings, whereas most of the existing studies only take into account fewer than three different factors that influence the future energy demand of buildings. Furthermore, we developed a comprehensive retrofitting algorithm with which the total residential building stock can be modeled for the first time for each year in the past and future.

The study confirms that there is no correlation between the geographical location of a country and its position in the electricity sector susceptibility ranking. Moreover, we found no pronounced pattern of susceptibility influencing factors between countries that ranked higher or lower in the index. We illustrate that Luxembourg, Greece, Slovakia and Italy are the countries with the highest electricity sector susceptibility. The electricity sectors of Norway, the Czech Republic, Portugal and Denmark were found to be least susceptible to climate change. Knowledge about the most important factors for the poor and good ranking positions of these countries is crucial for finding adequate adaptation measures to reduce the susceptibility of the electricity sector. Therefore, these factors are described within this study.

We show that the heating energy demand of residential buildings will strongly decrease in both Germany and the Netherlands in the future. The analysis for the Netherlands focused on the regional level and a finer temporal resolution which revealed strong variations in the future heating energy demand changes by province and by month. In the German study, we additionally investigated the future cooling energy demand and could demonstrate that it will only slightly increase up to the middle of this century. Thus, increases in the cooling energy demand are not expected to offset reductions in heating energy demand. The main factor for substantial heating energy demand reductions is the retrofitting of buildings. We are the first to show that the given German and Dutch energy and climate targets in the building sector can only be met if the annual retrofitting rates are substantially increased. The current rate of only about 1 % of the total building stock per year is insufficient for reaching a nearly zero-energy demand of all residential buildings by the middle of this century. To reach this target, it would need to be at least tripled.

To sum up, this thesis emphasizes that country-specific characteristics are decisive for the electricity sector susceptibility of European countries. It also shows for different scenarios how much energy is needed in the future to heat and cool residential buildings. With this information, existing climate mitigation and adaptation measures can be justified or new actions encouraged.

Zusammenfassung

Der Energiesektor ist sowohl vom Klimawandel betroffen als auch ein Schlüsselsektor für Maßnahmen zum Klimaschutz. Energiesicherheit ist das Rückgrat unserer modernen Gesellschaft und gewährleistet das Funktionieren der meisten kritischen Infrastrukturen. Daher sollten Entscheidungsträger und Energieversorger verschiedener Länder mit den Faktoren vertraut sein, welche die Anfälligkeit ihres Elektrizitätssektors gegenüber dem Klimawandel beeinflussen. Anfälligkeit meint die sozio-ökonomischen und strukturellen Eigenschaften des Elektrizitätssektors, die die Nachfrage nach und das Angebot an Strom unter sich änderndem Klima erhöhen oder verringern.

Darüber hinaus sollten die relevanten Akteure wissen, ob die gesetzten nationalen Energie- und Klimaziele umsetzbar sind und was getan werden muss, um diese Ziele zu erreichen. In diesem Zusammenhang sollte ein Schwerpunkt auf dem Wohngebäudesektor liegen, da dieser einer der größten Energieverbraucher und damit anthropogen bedingter CO_2-Emittenten weltweit ist.

Diese Dissertation befasst sich mit dem ersten Aspekt, der Anfälligkeit des Elektrizitätssektors, durch die Entwicklung eines Rankings, welches einen quantitativen Vergleich der Anfälligkeit des Elektrizitätssektors von 21 europäischen Ländern anhand von 14 Einflussfaktoren ermöglicht. Solch ein Ranking wurde bisher noch nicht erstellt. Wir führten eine Sensitivitätsanalyse durch, um den relativen Einfluss eines jeden Einflussfaktors auf das Ranking gemäß der Anfälligkeit zu testen. Wir diskutieren zudem Gründe für die Ranking-Position und damit die Anfälligkeit ausgewählter Länder.

Das zweite Thema, der Einfluss des Klimawandels auf den Gebäudeenergiebedarf, wird mittels eines neuen Modells bearbeitet, mit welchem der Heiz- und Kühlenergiebedarf von Wohngebäuden abgeschätzt werden kann. Wir wandten das Modell exemplarisch für Deutschland und die Niederlande an. Es berücksichtigt Prognosen für zukünftige Veränderungen der Bevölkerung, des Klimas und des Dämmstandards von Gebäuden, während die meisten der bestehenden Studien nur weniger als drei verschiedene Faktoren berücksichtigen, die den zukünftigen Energiebedarf von Gebäuden beeinflussen. Darüber hinaus haben wir einen umfassenden Sanierungsalgorithmus entworfen, mit welchem der gesamte Wohngebäudebestand erstmals für jedes Jahr in der Vergangenheit und Zukunft modelliert werden kann.

Die Studie bestätigt, dass es keinen Zusammenhang zwischen der geographischen Lage eines Landes und seiner Position im Ranking gemäß der Anfälligkeit seines Elektrizitätssektors gibt. Wir fanden auch kein deutliches Muster der Einflussfaktoren für die Anfälligkeit zwischen Ländern, die beim Ranking schlechter oder besser abschnitten. Wir verdeutlichen, dass Luxemburg, Griechenland, die Slowakei und Italien die Länder mit der höchsten Anfälligkeit ihres Elektrizitätssektors sind.

Die Elektrizitätssektoren von Norwegen, Tschechien, Portugal und Dänemark zeigten sich als am wenigsten anfällig gegenüber dem Klimawandel. Kenntnisse hinsichtlich der wichtigsten Faktoren für die schlechte bzw. gute Rankingposition dieser Länder sind von entscheidender Bedeutung, um geeignete Anpassungsmaßnahmen zu finden, welche die Anfälligkeit des Elektrizitätssektors reduzieren. Daher werden solche Faktoren in dieser Studie beschrieben.

Wir zeigen, dass der Heizenergiebedarf von Wohngebäuden sowohl in Deutschland als auch in den Niederlanden in der Zukunft stark abnehmen wird. Die Analyse für die Niederlande konzentrierte sich auf die regionale Ebene und hatte eine feinere zeitliche Auflösung, wodurch starke zukünftige Veränderungen beim Heizenergiebedarf pro Provinz und Monat deutlich wurden. In der deutschen Studie untersuchten wir zusätzlich den zukünftigen Kühlenergiebedarf und konnten darlegen, dass dieser bis zur Mitte dieses Jahrhunderts nur leicht zunehmen wird. So werden Steigerungen beim Kühlenergiebedarf voraussichtlich nicht die Reduktionen des Heizenergiebedarfs wettmachen. Der wichtigste Faktor für beträchtliche Heizenergiebedarfssenkungen ist die Sanierung von Gebäuden. Wir sind die ersten, die zeigen, dass die festgelegten deutschen und niederländischen Energie- und Klimaziele im Gebäudesektor nur dann erfüllt werden können, wenn die jährliche Sanierungsrate deutlich erhöht wird. Die derzeitige Rate von nur etwa 1 % des Gesamtgebäudebestandes pro Jahr reicht nicht aus, dass bis zur Mitte dieses Jahrhunderts alle Wohngebäude einen nahezu energieneutralen Standard erreichen. Dafür müsste sie mindestens verdreifacht werden.

Diese Arbeit betont, dass länderspezifische Merkmale eine entscheidende Rolle spielen für die Anfälligkeit des Elektrizitätssektors europäischer Länder. Sie zeigt zudem für verschiedene Szenarien, wie viel Energie in der Zukunft benötigt wird, um Wohngebäude zu heizen und zu kühlen. Mit diesen Informationen lassen sich bestehende Klimaschutz- und Anpassungsmaßnahmen rechtfertigen oder neue Maßnahmen anregen.

Samenvatting

De energiesector wordt beïnvloed door klimaatverandering maar is tegelijkertijd ook een belangrijke sector waar maatregelen getroffen kunnen worden ter bescherming van het klimaat. Energiezekerheid is de ruggengraat van onze moderne samenleving en garandeert de werking van de essentiële infrastructuur. Juist daarom moeten besluitvormers en energieleveranciers van verschillende landen vertrouwd zijn met de factoren die de gevoeligheid van hun elektriciteitssector tegenover klimaatverandering veranderen. Met gevoeligheid bedoelen we de sociaal-economische en structurele kenmerken van de elektriciteitssector die de vraag naar en het aanbod van elektriciteit in het kader van de klimaatverandering verhogen of verlagen.

Bovendien is het van belang dat relevante belanghebbenden weten of de gestelde nationale energie- en klimaatdoelstellingen haalbaar zijn en wat er gedaan moet worden om deze doelstellingen te halen. In dit verband moet vooral aandacht worden besteed aan de residentiële bouwsector omdat deze sector wereldwijd één van de grootste energieverbruikers en dus uitstoters van anthropogeen CO_2 is.

Dit proefschrift richt zich op het eerste aspect, de gevoeligheid van de elektriciteitssector, door het ontwikkelen van een index, die een kwantitatieve vergelijking van de gevoeligheid van de elektriciteitssectoren van 21 Europese landen op basis van 14 beïnvloedende factoren mogelijk maakt. Tot op heden is een dergelijke ranking niet uitgevoerd. We pasten een gevoeligheidsanalyse toe om het relatieve effect van elke factor die van invloed is op de gerankschikte gevoeligheidsindex te testen. Daarnaast bespreken we ook de redenen voor de positie in de ranking en daarmee de gevoeligheid van de electriciteitssector in de geselecteerde landen.

Het tweede onderwerp, het effect van klimaatverandering op de energiebehoefte van gebouwen, wordt aangepakt door middel van een nieuw model waarmee de energiebehoefte voor verwarming en koeling van woongebouwen geschat kan worden. Om het model te testen hebben we het toegepast op zowel Duitsland als Nederland. Het model houdt rekening met prognoses over de toekomstige veranderingen in de bevolking, het klimaat en de isolatienormen van gebouwen. De meeste modellen van bestaande studies omvatten minder dan drie verschillende factoren die van invloed zijn op de toekomstige energiebehoefte van gebouwen. Verder is er ook een uitgebreid renovatiealgoritme ontwikkeld waarmee voor het eerst de totale voorraad woongebouwen voor elk jaar in het verleden en in de toekomst kan worden gemodelleerd.

De studie bevestigt dat er geen verband bestaat tussen de locatie van een land en zijn positie in de gevoeligheidsranking van de elektriciteitssector. Bovendien vonden we geen uitgesproken patroon van factoren die van invloed zijn op de gevoeligheid tussen landen die hoger of lager in de index gerangschikt zijn. We laten zien dat de elektriciteitssectoren van Luxemburg, Griekenland, Slowakije en Italië het meest gevoelig zijn.

De elektriciteitssectoren van Noorwegen, Tsjechië, Portugal en Denemarken bleken het minst gevoelig voor klimaatverandering te zijn. Kennis over de belangrijkste factoren voor de slechte en goede posities in de ranking van deze landen is van cruciaal belang om te komen tot adequate aanpassingsmaatregelen met als doel het verminderen van de gevoeligheid van de elektriciteitssectoren. Daarom worden deze factoren in dit onderzoek benoemd en beschreven.

We laten zien dat de vraag naar energie voor verwarming van woongebouwen voor zowel Duitsland als Nederland in de toekomst sterk zal afnemen. Bij de analyse voor Nederland lag de aandacht meer op de regionale schaal en een fijnere temporele resolutie. Deze analyse laat sterke variaties in de veranderingen van de toekomstige energiebehoefte voor verwarming per provincie en per maand zien. In de Duitse studie onderzochten we bovendien de toekomstige behoefte aan koeling en konden aantonen dat het slechts licht zal stijgen tot aan het midden van deze eeuw. Zo zal een toename van de vraag naar koeling naar verwachting niet de reducties in de behoefte naar verwarming compenseren. De belangrijkste factor voor de aanzienlijke vermindering in de energiebehoefte voor verwarming is de renovatie van gebouwen. Wij zijn de eersten om aan te tonen dat de bestaande Duitse en Nederlandse energie- en klimaatdoelstellingen in de bouwsector alleen kunnen worden behaald als het aantal jaarlijkse renovaties aanzienlijk wordt verhoogd. Het huidige tempo van slechts ongeveer 1 % van de totale voorraad per jaar is onvoldoende voor het bereiken van een bijna energieneutraal bestand van woongebouwen in het midden van deze eeuw. Om dit doel te kunnen bereiken, zou het aantal jaarlijkse renovaties tenminste moeten worden verdrievoudigd.

Kortom, dit proefschrift benadrukt dat landenspecifieke kenmerken bepalend zijn voor de gevoeligheid van de elektriciteitssectoren van Europese landen. Het toont ook voor verschillende scenario's hoeveel energie in de toekomst nodig is om woongebouwen te verwarmen en te koelen. Met deze informatie laten zich bestaande en aangepaste maatregelen voor klimaatbescherming rechtvaardigen of nieuwe acties stimuleren.

List of publications

Klein D.R., **Olonscheck M.**, Walther C., Kropp J.P. (2013): Susceptibility of the European electricity sector to climate change. Energy, 59, 183-193.

Olonscheck M., Holsten A., Kropp J.P. (2011): Heating and cooling energy demand and related emissions of the German residential building stock under climate change. Energy Policy, 39/9, 4795-4806.

Olonscheck M., Walther C., Lüdeke, M., Kropp, J. P. (2015): Feasibility of energy reduction targets under climate change: The case of the residential heating energy sector of the Netherlands. Energy, 90, 560-569.

Acknowledgments

First of all, I would like to thank Prof. Dr. Jürgen P. Kropp for the opportunity of writing my PhD at the Potsdam Institute for Climate Impact Research (PIK). I am very thankful to Prof. Dr. Christoph Schneider from Humboldt University of Berlin and Prof. Dr. Matthias Kalkuhl from University of Potsdam and Mercator Research Institute on Global Commons and Climate Change for reviewing this thesis.

Thanks also to my mentor Prof. Dr. Annegret Thieken for taking the chair of the examination committee and to Prof. Dr. Ariane Walz and Prof. Dr. Manfred Stock for being additional members of the commission.

I would like to offer my special thanks to Carsten Walther who repeatly motivated me to continue my PhD and who always had excellent suggestions for improvements. A big thanks also goes out to my close friend Jens who made the last weeks before my defense awesome.

I am particularly grateful for the assistance given by Steffen Kriewald who found solutions for seemingly unsolvable problems at all times as well as to Dr. Luís Costa, Dr. Bernd Gewiese, Dr. Anne Holsten, Dr. Matthias Lüdeke, Olivia Roithmeier and my friend Marcus who always had a sympathetic ear for questions and made suggestions that substantially brought forward this work.

I also wish to acknowledge the help by Dr. Hannah Förster, Ramana Gudipudi, Judith Reise, Dr. Sebastian Schubert and Till Sterzel who provided several useful remarks.

I very much appreciated the check for accuracy and consistency of spelling and grammar which was performed by Stefanie L. Becker and Daniel R. Klein. Also thanks to Luc van Summeren, Henny Westerhof, Henny Wiegmink and my friend Frank for checking small parts of this thesis.

Thanks to Marcel Meistring, the librarian of PIK, for sending me hundreds of research papers during the last years as well as to Lydia Polakowski for assisting in beautifying several of the figures.

I apologize to my grandparents and my great-aunt for having to wait that long for the submission of this work and thank them for their support in various ways.

I would like to express my deepest gratitude to my parents, my brother and my boyfriend Martin for their stunning support, their infinite encouragement and their unconditional love.

Contents

List of Figures

List of Tables

List of Abbreviations

ArcGIS : Aeronautical Reconnaissance Coverage Geographic Information System

AT : Austria

BE : Belgium

CCLM : COSMO Climate Limited-area Model

CDD : Cooling Degree Days

CH : Switzerland

CLC : CORINE Land Cover

COP : Conference of the Parties

CO_2 : Carbon Dioxide

CZ : Czech Republic

DE : Germany

DIN : Deutsche Industrienorm (German Industrial Standard)

DK : Denmark

DWD : Deutscher Wetterdienst (German Weather Service)

ECA&D : European Climate Assessment & Data

ECHAM5/MPI-OM : ECHAM/ Max Planck Institute Ocean Model

EnEV : Energieeinsparverordnung (Energy saving regulation)

E-OBS : European Gridded Observational Data Set

ES : Spain

EU : European Union

EURO-CORDEX : Coordinated Regional Downscaling Experiment (European Domain)

FI : Finland

FR : France

GB : Great Britain

GHG : Greenhouse Gases

GR : Greece

HDD : Heating Degree Days

HU : Hungary

ICHEC-EC-EARTH : Irish Center for High-End Computing EC-EARTH

IE : Ireland

IEKP : Integriertes Energie- und Klimaschutzkonzept (Integrated Energy and Climate Protection Program)

ISO : International Organization for Standardization

IT : Italy

IWU : Institute for Building and Environment

LU : Luxembourg

NEN : Nederlandse Norm (Dutch Industrial Standard)

NL : The Netherlands

NO : Norway

PCA : Principal Component Analysis

PCC : Pearson Correlation Coefficient

PL : Poland

ppm : Parts per million

PT : Portugal

RCA : Rossby Centre Regional Atmospheric Model

RCP : Representative Concentration Pathway

SE : Sweden

SK : Slovakia

STAR : STatistical Analogues Resampling

UNFCCC : United Nations Framework Convention on Climate Change

U.S. : United States

U-Value: Heat transmission value

WSchV : Wärmeschutzverordnung (Heat insulation regulation)

1

General introduction

1.1 Background

It is extremely likely that at least half of the increase in global mean temperature over the past few decades has been caused by human activities (IPCC, 2013). The majority of the anthropogenic greenhouse gas (GHG) emissions that are responsible for this increase in global annual mean temperature stems from the production and consumption of energy (Blanco et al., 2014). Conversely, increasing temperatures also affect both the energy sector in general and the energy demand in particular. This, in turn, has implications on subsequent GHG emissions.

In December 2015, the 21st Conference of the Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC) confirmed the political target to limit global warming to well below 2 °C compared to the preindustrial level of the global mean surface temperature (UNFCCC, 2015a). This goal implies the decarbonisation of the world's economy by the end of the 21st century and a carbon dioxide (CO_2) emission reduction of 40-70 % between 2010 and 2050 (Guardian, 2015). Accounting also for other GHGs in addition to CO_2, it was estimated that there is a total remaining budget of about 2,900 Gt of CO_2 that could be emitted since the period 1861-1880. By that, the 2 °C target would have at least a 66 % chance of being met (IPCC, 2013). However, by 2011 about 1,890 Gt of the allowed budget has already been emitted at a rate of circa 33 Gt of CO_2 yr^{-1} in recent years (IPCC, 2013; PBL, 2014). In 2012, about 17 % of these emissions originated from the building sector (IEA, 2013a) which both contributes to and is affected by climate change. The building sector is seen as a key sector for reducing emissions, but could be also responsible for increasing emissions resulting from a higher demand for space cooling during more frequent and longer lasting hot periods.

The world's reserves of fossil fuels are enough to deplete the remaining GHG emissions budget. Consequently, 80 % of the global coal reserves, 50 % of gas reserves and about a third of oil reserves should stay unexploited (McGlade & Ekins, 2015). However, globally, the consumption of coal, gas and oil is still increasing each year (BP, 2015). Thus, the global CO_2 concentration in the atmosphere has been continuously increasing with an average rate of 2.1 parts per million (ppm) yr^{-1} between 2005 and 2014 compared to 1.1 ppm yr^{-1} between 1965 and 1974 (NOAA, 2015). So far, there are no signs of a significant slowdown of this annual increase.

Considering the time delay until emissions reach their full warming effect due to inertia of the climate system, it is estimated that mankind has caused already more than 1 °C warming over the past couple of centuries (Hansen et al., 2005; Met Office, 2015; Rypdal & Rypdal, 2014). Although manifested as a political target, limiting global warming to 2 °C may not be sufficient to avoid dangerous climate change as current levels of warming are exceeding the adaptive capacity of numerous people and ecosystems worldwide (Frieler et al., 2013; Hansen et al., 2013; Hare et al., 2011; UNFCCC, 2015b). Societies and infrastructures, as well as fields such as the energy sector, already today have to cope with the consequences of the 1 °C global temperature increase and will increasingly have to in the future.

Thus, considering all currently intended national contributions regarding future GHG emission reductions, societies are on the path to a more than 2 °C warmer world (Climate Interactive, 2015; Rocha et al., 2015). How this could affect human society and infrastructures is described in reports by The World Bank (2013) and the IPCC (Oppenheimer et al., 2014). One sector that will be increasingly affected in a rapidly warming world is the electricity sector. This is problematic as energy security is the backbone of modern society (Altvater et al., 2012). Blackouts can have major impacts on the functioning of critical infrastructures such as the health sector, the communication infrastructure, the transport sector, the water supply and disposal, as well as the disaster management (Barben, 2010; Petermann et al., 2010; Rübbelke & Vögele, 2011a). The degree the energy sector is affected by climate change differs between countries. The interesting question is in what way it differs.

1.1.1 Susceptibility of the electricity sector of European countries

The degree to which a country's electricity sector is influenced by future temperature changes depends on many factors. These include the structure of the electricity production, electricity import and export activities as well as heating and cooling requirements for buildings. In this regard, the electricity sector of Europe is especially relevant to investigate because large differences in the structures of the countries' electricity sectors are apparent. However, in contrast to other geographical regions and structural parts of the energy system, the electricity sector of Europe is characterized by a synchronous grid with close interconnections between the electricity sectors of most countries. Therefore, monthly electricity-related data that is comparable among countries is available.

Within this thesis the term susceptibility is defined as the socioeconomic and structural characteristics of the electricity sector that exacerbate or attenuate the demand for and supply of electricity under future changes of climatic variables. Often, the susceptibility of the energy sector is assessed via its characteristics with regard to security of energy supply. Existing studies present rankings of countries according to their energy security performance. Most of these analyses focus on the oil (Gupta, 2008; Roupas et al., 2009) or oil and gas (Cohen et al., 2011; Jewell, 2011; Le Coq & Paltseva, 2009) security of supply, but neglect electricity. Some studies integrate aspects of electricity among others, like the efficiency of electricity generation (Scheepers et al., 2007), per capita electricity use (Sovacool et al., 2011) or the electricity generation mix (Gnansounou, 2008). However, none of the aforementioned studies looks at possible implications of climate change on the susceptibility of a country's electricity sector, such as a higher demand for cooling energy due to rising temperatures. This is especially relevant since in most parts of Europe temperatures are projected to increase in the future (IPCC, 2013; Jacob et al., 2014). This will have implications for the security of electricity supply - either because of an insufficient production or an increasing consumption of electricity.

A number of studies have examined these future impacts of climate change on the energy production (Arnell et al., 2005; Flörke et al., 2011b; Förster & Lilliestam, 2009; Koch & Vögele, 2009; Linnerud et al., 2011; Rübbelke & Vögele, 2011b; van Vliet et al., 2012) and consumption (Eskeland & Mideksa, 2010; Hadley et al., 2006; Isaac & van Vuuren, 2009; Nejat et al., 2015). The electricity production is affected by climate change in different ways. Some studies focus on the electricity production by thermoelectric power plants in general (Arnell et al., 2005; Flörke et al., 2011b; Koch & Vögele, 2009; van Vliet et al., 2012; Wilbanks et al., 2008) or nuclear power plants in particular (Förster & Lilliestam, 2009; Linnerud et al., 2011; Rübbelke & Vögele, 2011b). They determine their vulnerability to climate change induced lower summer discharges, higher river water temperatures or reduced thermal efficiency. However, most of the studies only focus on selected power plants or countries.

Regarding climatic impacts on the energy demand and consumption, the overwhelming majority of existing studies focuses on the building sector. These studies are introduced in more detail in Section 1.2.2. Others calculate the future residential energy demand without looking at building parameters (Amato et al., 2005; Auffhammer & Mansur, 2014; Eskeland & Mideksa, 2010; Franco & Sanstad, 2008; Hadley et al., 2006; Isaac & van Vuuren, 2009). While a number of studies deal with the implications of temperature increases on the energy consumption in the U.S. (Amato et al., 2005; Franco & Sanstad, 2008; Hadley et al., 2006), there are hardly any studies with a similar focus for Europe. What is most important is the fact that there are as of yet no studies that compare countries' electricity sector susceptibility quantitatively.

1.1.2 Impacts on the future energy demand of buildings

One of the largest energy consumers and therefore emitters of CO_2 worldwide is the residential building sector. In 2010, 24 % of the total global energy was used in buildings (IEA, 2013b). The total final thermal energy consumption from the residential sector is projected to increase in large parts of the world up to at least 2050 due to population growth, improving access to energy, and increasing wealth (Lucon et al., 2014). In contrast, parts of Europe might see stagnation or even a decrease in the energy use for space conditioning of households (Eskeland & Mideksa, 2010; Lucon et al., 2014; Pilli-Sihvola et al., 2010). The main reason for this decrease is the improvement of insulation of residential buildings.

Retrofitting buildings is seen as key to a low energy building stock as buildings normally have a long lifetime of 50-100 years (Mequignona et al., 2013; Szalay, 2007). This means that the renewal rate is low and the focus should be on improving existing buildings. Studies show that a comprehensive retrofitting of a building can reduce its energy demand by 50-90 % (Lucon et al., 2014). Besides retrofitting, there are two other important factors that influence the energy demand of a building: demography and climate change. First, demographic changes normally affect the total amount of energy that is needed for heating and cooling of buildings in a given region. Second, climate change may increase or decrease the sum of the heating and cooling energy demand. Rising temperatures reduce the demand for heating but generally also increase the demand for cooling, which counteracts the reductions in heating energy demand (Aguiar et al., 2002; Chaturvedia et al., 2012; Eskeland & Mideksa, 2010; Loveland & Brown, 1990; Pilli-Sihvola et al., 2010). Such a development could lead to increasing CO_2 emissions from the future energy demand of residential buildings.

The impact of climate change and other influencing factors on the future energy demand has been studied in commercial buildings (Belzer et al., 1996; Chow & Levermore, 2010; Scott et al., 1994; Wan et al., 2011a), residential buildings (Collins et al., 2010; Gaterell & McEvoy, 2005) or both (Frank, 2005; Yu et al., 2014; Zhou et al., 2013). Most of these studies either consider retrofitting or population changes in addition to climate change, but only two of these studies consider more than two influencing factors on the future energy demand for space conditioning (Belzer et al., 1996; Yu et al., 2014): Belzer et al. (1996) only test the effect of theoretically assumed higher insulation standards on the energy demand by comparing a standard and an advanced building envelope. Yu et al. (2014) assume a fixed tightening of building energy standards for each year in the future, but do not take into account temporal dynamics in the annual retrofitting rates.

1.2 Motivation of this thesis

The motivation of this thesis is to focus on two energy related aspects that are affected by climate change: the susceptibility of the electricity sector of European countries and the heating and cooling energy demand of residential buildings.

1.2.1 The ranked susceptibility index

None of the existing publications provide a quantitative comparative analysis between countries' electricity sectors by considering a variety of different aspects related to climate change. In order to determine the susceptibility of the electricity sector to climate change, a ranked index is developed within this thesis. It comprises of 14 influencing factors and is operated for 21 European countries. The influencing factors that are the basis for the susceptibility index presented in this thesis include e. g. projected temperature increases, share of fossil and nuclear electricity production, correlation and discrepancy between production and consumption as well as prevalence of air conditioners. Sovacool (2013) raised the fact that existing susceptibility indices are often based on aggregated data that hide the underlying assumptions. The index developed for the presented thesis is transparent as both each individual influencing factor and the kind of weighting for generating the final ranked index is revealed.

In addition, a sensitivity analysis is conducted to evaluate the robustness of the approach and to identify which country is particularly susceptible to which influencing factor. It also shows whether there are countries with a high susceptibility for particular influencing factors and a low susceptibility for others but are ranked similar in terms of susceptibility than countries with more average values across the influencing factors. This is important as the countries with particularly high values for some factors can more easily determine the main reasons for their high susceptibility. Countries with a large share of air conditioners per number of inhabitants might face strong future increases in electricity consumption for cooling. In contrast, countries in colder regions might benefit from future temperature increases due to stronger decreases in the heating energy demand.

1.2.2 Future building energy demand at the country level using a dynamic approach

Two countries that may benefit from a decreased future heating energy demand caused by higher temperatures are Germany and the Netherlands, which ranked 6th and 32nd worldwide in 2013 in terms of CO_2 emissions (European Commission, 2015). A considerable part of these emissions stems from the space conditioning of residential buildings. Heating and cooling of residential buildings causes about 20 % of the total energy consumption in Germany (Umweltbundesamt, 2015) and about 10 % in the Netherlands (CBS, 2014). The extent of future energy demand changes for space conditioning will not only depend on future changes in temperature, but also on factors such as demographic changes and the quantitative and qualitative amount of retrofitting measures. Thus, this thesis aims to analyse the combined impact of the three influencing factors climate change, future population development and retrofitting on the future heating and cooling energy demand of households. It describes the development of scenarios based on reasonable assumptions of future changes in these factors. The data situation allowed us to use Germany and the Netherlands as test-case countries. They differ concerning their future number of inhabitants. While the German population is projected to decline until 2050, the Dutch population is projected to slightly increase in the future (United Nations, 2015). Furthermore, the building stock of both countries is quite different: While free-standing residential buildings have a share of more than 40 % in Germany (Diefenbach & Born, 2007), they make up only about 14 % in the Dutch residential building stock (CBS, 2013).

Moreover, with a few exceptions (Chow & Levermore, 2010; Collins et al., 2010; Isaac & van Vuuren, 2009; Jenkins et al., 2008; Zhou et al., 2013), existing studies on the impact of climate change on the energy demand of the building stock do not calculate GHG emissions that would result from future changes in building energy demand. This thesis provides information on future GHG emission reductions caused by decreases in the residential heating energy demand in Germany. Furthermore, none of the aforementioned studies tests the feasibility of the given national energy or climate targets or presents the annual retrofitting rates that would be necessary to reach these targets. Additionally, they only focus on the annual level, whereas this thesis examines the heating energy demand of the Netherlands and its provinces for the first time on a monthly scale. A seasonal perspective is utterly important as it provides relevant information for energy suppliers on the months in which heating demand is expected to change more substantially.

However, what is most important is the fact that none of the existing studies takes into consideration dynamic changes in the insulation quality of the total residential building stock over time. To fill this gap, this thesis presents a comprehensive retrofitting algorithm with which the total residential building stock can be modeled for each year in the past and future. This is done based on industrial standards as well as historical, current and expected requirements that new or retrofitted residential buildings officially have to meet due to national or EU legislation.

1.3 Research questions

This thesis aims to assess the electricity sector susceptibility to climate change and the impact of climate change on the future residential energy demand by addressing the following overall research questions:

- RQ1: Does the geographical location of a country allow conclusions on its electricity sector susceptibility to climate change and how sensitive is a ranking of countries to the choice of influencing factors?
- RQ2: Which influencing factors explain the susceptibility positions of the most and least susceptible countries?
- RQ3: How will the energy demand for space conditioning of residential buildings change until the middle of the 21st century and will this be enough to achieve the national energy and climate targets?
- RQ4: What are the dominant factors shaping the future energy demand for space conditioning?

The overall research questions RQ1 and RQ2 are addressed by the development and application of a ranked susceptibility index. For the first time, the electricity sector susceptibility of European countries to climate change is determined quantitatively. The results can be used to find adaptation measures that are targeted at decreasing the susceptibility. Moreover, regarding certain aspects the electricity sector structure of countries with a low susceptibility index can serve as a good example for countries that are more susceptible to climate related temperature increases. In order to address the overall research questions RQ3 and RQ4, a dynamic model is developed to estimate for the first time the combined effect of climate change, population development and retrofitting measures on the future energy demand of residential buildings in Germany and the Netherlands. The corresponding findings can support the validation of the feasibility of national energy reduction targets. Moreover, the approach can be transferred to calculate the energy demand for space conditioning and resulting GHG emissions for other regions or time scales.

1.4 Outline of this thesis

The relation between the overall research questions and the chapters is shown in Table 1.1. The overall research questions RQ1 and RQ2 are addressed in Chapter 2. Both Chapter 3 and Chapter 4 answer research questions RQ3 und RQ4. A discussion and conclusion of the findings with respect to the overall research questions can be found in Chapter 5.

Table 1.1: Overview of thesis chapters and corresponding overall research questions. For readability both chapter titles and research questions are short forms of the original versions given in the text.

<table>
<tr><th>Research questions</th><th colspan="2">Thesis structure</th></tr>
<tr><td></td><td colspan="2">Chapter 1: General Introduction</td></tr>
<tr><td>RQ1: Does the location of a country allow conclusions on its electricity sector susceptibility and how sensitive is a ranking to the choice of influencing factors?

RQ2: Which influencing factors explain the ranking positions of the most and least susceptible countries?</td><td colspan="2">Chapter 2: Susceptibility of the European electricity sector to climate change</td></tr>
<tr><td>RQ3: How will the energy demand of buildings change in the future?

RQ4: What are the dominant factors shaping the future energy demand for space conditioning?</td><td>Chapter 3: Heating and cooling energy demand of the German building stock</td><td>Chapter 4: Feasibility of energy reduction targets: The case of the Netherlands</td></tr>
<tr><td></td><td colspan="2">Chapter 5: Discussion & Conclusion</td></tr>
</table>

2

Susceptibility of the European electricity sector to climate change *

Abstract

The electricity system is particularly susceptible to climate change due to the close interconnectedness between electricity production, consumption and climate. This study provides a country based relative analysis of 21 European countries' electricity system susceptibility to climate change. Taking into account 14 quantitative influencing factors, the susceptibility of each country is examined both for the current and projected system with the result being a relative ranked index. Luxembourg and Greece are the most susceptible relatively due in part to their inability to meet their own electricity consumption demand with inland production, and the fact that the majority of their production is from more susceptible sources, primarily combustible fuels. Greece experiences relatively warm mean temperatures, which are expected to increase in the future leading to greater summer electricity consumption, increasing susceptibility. Norway was found to be the least susceptible, relatively, due to its consistent production surplus, which is primarily from hydro (a less susceptible source) and a likely decrease of winter electricity consumption as temperatures rise due to climate change. The findings of this study enable countries to identify the main factors that increase their electricity system susceptibility and proceed with adaptation measures that are the most effective in decreasing susceptibility.

*This chapter has been published as: Klein D.R., Olonscheck M., Walther C., Kropp J.P. (2013): Susceptibility of the European electricity sector to climate change. Energy, 59, 183-193.

2.1 Introduction

Overwhelming evidence indicates that climate change will result in a significant increase of temperatures in Europe in the years to come (Alcamo et al., 2007; Rübbelke & Vögele, 2011b). Due to the close relationship between the electricity sector and climate, changes in the latter will affect the entirety of the electricity sector including production, imports and exports, distribution and consumption (McGregor et al., 2005; Michaelowa et al., 2010; Mimler et al., 2009; The World Bank, 2008a). Not every country will be affected in the same way due to a variety of factors that include not only temperature, but also different heating and cooling requirements and the variety of sources used for electricity generation among others (Eskeland & Mideksa, 2010).

A number of studies on the effects of climate change on electricity production have been conducted. A study by van Vliet et al. (2012) examined the susceptibility of the thermoelectric electricity production in the United States and Europe and found significant negative effects due to reduced river flows and increased river temperatures. Work done by Rübbelke and Vögele (2011b) characterized the European electricity system susceptibility to climate change based principally on the availability and temperature of cooling water used for nuclear power plants. Eskeland and Mideksa (2010) examined the relationship between temperature and electricity consumption demand on a European level. The study found that the net effect of climate change on electricity demand is small, but increases in summer electricity consumption and decreases in winter electricity consumption are likely, depending on the geographic location and climate of a given country. Further studies indicate that in the north and central parts of Europe, heating related electricity consumption will decrease due to warmer winter temperatures over the next decades, and will predominate over increases in cooling related electricity demand and consumption (Alcamo et al., 2007; Eskeland & Mideksa, 2010; Olonscheck et al., 2011). The opposite is true however for the south of Europe where increases in cooling related electricity consumption will outweigh any heating related decreases (Alcamo et al., 2007; Eskeland & Mideksa, 2010).

The aim of this study is to determine the relative electricity system susceptibility of 21 European countries to climate change using both quantitative and qualitative indicators, with the goal of ultimately providing a comparative analysis of the countries based on a number of influencing factors. We examine the relationship between the electricity system and temperature as well as other influencing factors and look at the effect of different components of the electricity system on each other. For the purpose of this study, the electricity system is defined as production and consumption only (transmission is not included) and although there are many effects of climate change including precipitation changes, and sea level rise, we only examine the air temperature change effects to maintain a reasonable scope for the study. In terms of susceptibility, a general definition that is used in this study is put forward by Costa and Kropp (2012) which characterizes susceptibility as a component of vulnerability that deals with "socio-economic and physical characteristics of a system that differentiate the magnitude of impacts for a given exposure". This concept can be linked to work by White et al. (2005) which puts susceptibility as a component of vulnerability in a risk-hazard context as well as the work of Turner et al. (2003) in terms of sensitivity in a sustainability context. The countries are referred to in this paper by their ISO 3166-1 alpha-2 abbreviations.

The influencing factors chosen for this study are by no means exhaustive, but were selected as being significant in terms of their impact on the electricity system and their ability to demonstrate potential susceptibilities. An important influencing factor is the direct effect of temperature, both current and projected, which, due to climate change, has an increasingly large impact on the electricity system as a whole (Eskeland & Mideksa, 2010; Mimler et al., 2009; Psiloglou et al., 2009; Rübbelke & Vögele, 2011b). The discrepancy between electricity production and consumption was considered in order to not only identify susceptibilities related to production shortfalls, but also to help characterize the electricity system (Rübbelke & Vögele, 2011b). The electricity production sources and their change over time of each country included in the study were also chosen as being an important influencing factor (Eskeland & Mideksa, 2010; Flörke et al., 2011a; Hoffmann et al., 2013; Rübbelke & Vögele, 2011b). Cooling electricity consumption is mainly dependent on air conditioner prevalence which was also included (Bertoldi & Atanasiu, 2009; Hekkenberg et al., 2009a; Olonscheck et al., 2011; Rademaekers et al., 2012; Rübbelke & Vögele, 2011a; van Vliet et al., 2012; Wilbanks et al., 2008).

This paper continues from this point with the Data and methods Section 2.2, followed by Section 2.3 where the results and findings of the study are presented. Section 2.4 includes the discussion of the results from the previous section along with a comparison of those findings with existing studies. The paper closes with the conclusions of the study in Section 2.5.

2.2 Data and methods

The methodology used in this study was an attempt to characterize the effects of climate change on the electricity system through the development of a ranked index. The ranked susceptibility index, as described in this section, is based on a number of influencing factors.

The daily mean temperature data (in °C) for the period 2000-2011 (European Climate Assessment and Dataset, 2012) with a resolution of 0.25° x 0.25° and covering an area of 25N-75N x 40W-75E was averaged by month and weighted by gridded population data (EUROSTAT, 2006) in order to account for the fact that electricity consumption, and to a lesser extent electricity production, are not distributed evenly across a country but are often concentrated in areas where people live. The population weighting of the temperature data was completed in ArcGIS (ESRI, 2011), with the first step being the allocation of the grid cells for both the temperature and population data sets into their respective countries. The weighting was then completed for each grid cell (i) in every country (j) using equations (2.1) and (2.2).

$$W_{i,j} = \frac{pop_{i,j}}{\sum_{i=1}^{n_j} pop_{i,j}} \tag{2.1}$$

$$T_{mean,j} = \sum_{i=1}^{n_j} T_{i,j} \cdot W_{i,j} \tag{2.2}$$

$W_{i,j}$: The relative population factor.
$pop_{i,j}$: The population.
n_j: The number of grid cells.
$T_{mean,j}$: The population weighted monthly mean temperature.
$T_{i,j}$: The mean monthly temperature.

The projected temperature increase data was available from the Tyndall Centre, which included data from 9 global climate models which we averaged (Mitchell et al., 2002). The data was a prediction of temperature changes for the years 1961-90 compared to 2070-99 for the IPCC A2 scenario.

Due to the non-linear nature of the correlation between electricity production or consumption and temperature, we divided the temperature data into three parts based on heating and cooling thresholds in between which no heating or cooling is required (Hekkenberg et al., 2009b; Sailor & Muiqoz, 1997; Valor et al., 2001). Heating is assumed below the mean temperature threshold of 12 °C (Christenson et al., 2006; Matzarakis & Thomsen, 2009), while cooling is necessary at 21 °C and above (Engle et al., 1992; Prek & Butala, 2010; Valor et al., 2001).

We used monthly electricity data per country (in GWh) for the time period January 2000 to December 2011 (IEA, 2012) that included production (combustible fuels, nuclear, hydro, other sources and total production), as well as imports, exports and total supply (determined by subtracting the exports from the sum of the production and imports). Due to a lack of data regarding the actual electricity consumption of a country, the electricity supplied to the grid is used as a proxy for consumption in this study and will be referred to as consumption from this point forward.

For the electricity production and consumption versus mean temperature plots created for this study, the difference from the annual mean of the electricity data was calculated. This calculation was necessary in order to facilitate the comparison between countries as well as to eliminate or minimize the overall increase in data values over the time period examined due to population and GDP changes along with other factors, which would bias the results. The residential air conditioner stock data (Adnot et al., 2008) by country was divided by annual actual and projected population data (EUROSTAT, 2012).

2.2.1 Influencing factors

Influencing factors considered for the ranked susceptibility index are described in the following sections. The influencing factors themselves were divided into groups for the sake of explanation.

2.2.1.1 Group 1: Production, consumption and mean temperature slope

Group 1 consists of four influencing factors. The slope values for data points both above and below the heating and cooling thresholds were determined for the electricity production and consumption percent difference from the annual average data against mean temperature. Countries reaching the cooling threshold were considered to be more susceptible currently, and those with steeper slopes have a higher susceptibility. Countries that do not reach the cooling threshold, or with fewer than 10 months that did, were deemed to be currently unaffected in terms of susceptibility. For the values below the heating threshold however, a steep slope was deemed to decrease susceptibility due to a more rapid decline of the winter peak as temperatures increase.

2.2.1.2 Group 2: Production and consumption

Group 2 includes four influencing factors: the correlation and the discrepancy between production and consumption calculated for the summer (June, July, August) and winter (December, January, February) months. In terms of susceptibility, stronger correlation between electricity production and consumption was determined to indicate lower susceptibility, as it implies a greater ability to deal with changes in the electricity system. The percentage discrepancy value characterizes the system by identifying countries that are net producers or consumers and to what extent. Net producing countries were determined to be less susceptible due to the fact that they meet or exceed their consumption demand with inland production on average.

2.2.1.3 Group 3: Thermal electricity production share

The thermal electricity production group includes two influencing factors: the current (2011) annual average percentage of total electricity production that is generated by thermal sources (combustible fuels and nuclear) and the difference between the 2011 and

2000 percentage of thermal source electricity production. The former being a measure of the current percent of production sources in a country that are deemed to be more susceptible and the latter was included in order to address changes in thermal electricity production share over time. Countries experiencing decreases in the share of thermal electricity production have lower susceptibility than those experiencing increases.

2.2.1.4 Group 4: Projected temperature increase

Summer temperature increases were assumed to increase susceptibility due to probable increases in consumption for cooling, while increases in winter temperatures were deemed to decrease susceptibility, as heating electricity requirements are likely to decrease.

2.2.1.5 Group 5: Air conditioner prevalence

The per capita air conditioner prevalence group included the projected 2030 air conditioner stock and the percentage increase of air conditioner stock between 2005 and 2030. The 2030 data gives an indication of the magnitude of potential warm weather electricity consumption in the future, while the growth data provides information on the potential change from the current consumption. Susceptibility increases with higher values for either influencing factor due to the increasing effects of air conditioner use on electricity consumption. It is important to note that the air conditioner factor is a proxy for all electricity cooling, including for example, industrial cooling for which there is no available data. There was no data for NO and CH, therefore both influencing factors in this group were excluded from the index calculations for those countries.

2.2.1.6 Group 6: Imports and exports

In order to take into account the magnitude of imports or exports per country we used the summer and winter absolute export values subtracted from the corresponding import values (2000-2011). The difference was then divided by total electricity production in order to determine the extent to which a country is a net importer or exporter. Countries reliant on electricity imports for part or all of the year were determined to be more susceptible as they often do not have the inland production capacity to meet their electricity demand and are therefore reliant on exports from other countries. Countries that are net exporters were assumed to be less susceptible because of their ability to meet or exceed their demand.

2.2.2 Influencing factor correlation

The correlation between all of the influencing factors was determined in order to identify and eliminate redundant factors (Table 2.1). Based on the results of the Spearman correlation, Group 6, which includes the summer (6.1) and winter (6.2) discrepancy between imports and exports correlated highly (over 0.95) with the summer (2.3) and winter (2.4) discrepancy between production and consumption and was therefore excluded from the ranked index calculations. This makes sense due to the inherent relationship between production and consumption, and imports and exports, as well as the calculations used to determine the consumption.

Table 2.1: Influencing factor correlation table. Note: Starred (*) influencing factors do not include CH or NO in their calculation due to lack of data availability. Red values indicate correlation above 0.95.

Influencing Factor	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4	3.1	3.2	4.1	4.2	5.1*	5.2*	6.1	6.2
1.1	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.2	0.73	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.3	0.02	0.08	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-
1.4	-0.03	0.09	0.94	1.00	-	-	-	-	-	-	-	-	-	-	-	-
2.1	0.11	0.02	-0.33	-0.33	1.00	-	-	-	-	-	-	-	-	-	-	-
2.2	0.26	0.12	-0.25	-0.23	0.89	1.00	-	-	-	-	-	-	-	-	-	-
2.3	-0.13	0.41	0.11	0.17	-0.21	-0.26	1.00	-	-	-	-	-	-	-	-	-
2.4	0.34	0.31	0.07	0.10	-0.13	-0.08	0.60	1.00	-	-	-	-	-	-	-	-
3.1	0.10	0.31	0.08	0.13	-0.19	-0.33	0.15	-0.20	1.00	-	-	-	-	-	-	-
3.2	0.48	0.29	-0.15	-0.18	0.36	0.36	0.05	0.50	-0.21	1.00	-	-	-	-	-	-
4.1	-0.16	-0.15	0.30	0.29	-0.39	-0.37	0.07	0.11	0.16	-0.38	1	-	-	-	-	-
4.2	0.39	0.25	0.26	0.35	0.13	0.27	-0.15	0.12	0.07	0.25	0.07	1.00	-	-	-	-
5.1*	0.02	0.13	0.60	0.53	0.17	0.07	0.15	0.12	0.02	-0.06	0.29	0.36	1.00	-	-	-
5.2*	-0.13	-0.18	-0.50	-0.54	0.21	0.12	0.18	0.17	-0.20	0.18	-0.28	-0.49	-0.22	1.00	-	-
6.1	-0.08	0.42	0.09	0.13	-0.16	-0.19	**0.98**	0.64	0.09	0.13	0.08	-0.14	0.15	0.14	1.00	-
6.2	0.30	0.28	0.08	0.11	-0.09	-0.06	0.60	**0.99**	-0.22	0.52	0.11	0.09	0.14	0.13	0.66	1.00

2.2.3 Final methodological structure

The remaining influencing factors (Groups 1-5) are presented in Figure 2.1. It is important to note that both influencing factors in Group 6 are not included in this figure as it is not part of the study from this point onward based on its exclusion due to the correlation calculations from the previous section.

2.2.4 Index calculations

The absolute influencing factor values were not used in the index calculation; instead each of the influencing factor values were normalized by the maximum value in the group. For indicators that have a potentially positive effect on susceptibility, the range from -1 to 0 is used. Similarly, for influencing factors that potentially have a negative effect on susceptibility, the range from 0 to 1 is taken. The susceptibility influencing factors were grouped based on similarities; of which three are current measures of susceptibility (Groups 1-3) while two are projected (Groups 4 and 5). Because the discrepancy influencing factors (2.3 and 2.4) could possibly increase or decrease susceptibility, the countries were first separated based on whether they were net producing countries (with values >1) or net consuming countries (with values <1). Both subgroups were then normalized by their maximum value respectively. The 14 influencing factors were averaged for each country giving a ranked susceptibility index (equation (2.3)).

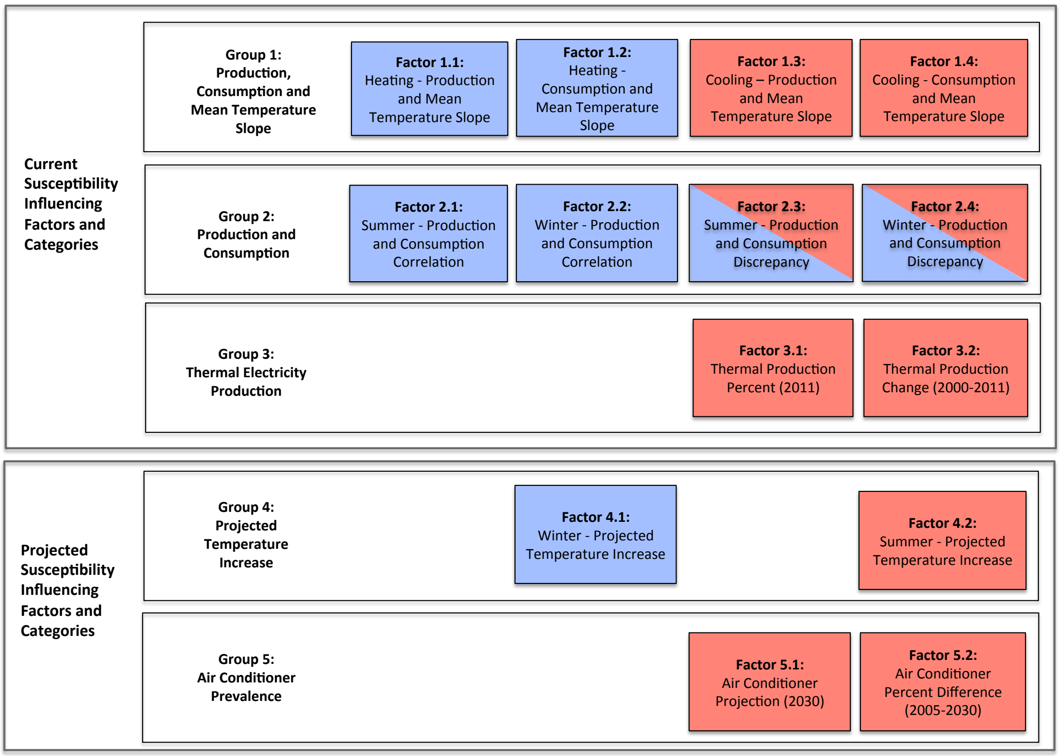

Figure 2.1: Influencing factors for determining susceptibility (Blue = influencing factors that decrease susceptibility, Red = influencing factors that increase susceptibility).

$$I = \frac{\sum_{x=1}^{k} v_n}{k} \tag{2.3}$$

I: The ranked index value.

v_n: Influencing factor n (index value).

k: The number of influencing factors.

Each of the influencing factors were weighted equally for the index calculation, the most common weighting for composite indicator calculations (Nardo et al., 2005). While statistical weighting of the influencing factors could have been possible, it does not add understanding or legitimacy to the index, as statistical approaches do not include content based argumentation. A review of possible statistical weighting options revealed that there are many possibilities available, leading to quite different ranked index results. Furthermore, a principal component analysis (PCA) was conducted on the data in order to determine if the influencing factors themselves were sufficiently independent and to identify the possibility of significant factor overlap (Lam et al., 2010; Nardo et al., 2005). The results of the PCA can be seen in the appendix, which show that the variation of the data can be explained using 5 composite component factors (representing only about 80 % of the variation in the data), and only a small number of influencing factors had factor loadings that were high enough to be noticeable. These results demonstrated the sufficient independence of the influencing factors, and therefore support the use of equal weighting among factors.

2.2.5 Sensitivity analysis

A sensitivity analysis of the influencing factors included in the ranked susceptibility index was conducted by calculating the sum of the squared difference between the original index value and the new index value (calculated using the average influencing factor value for all countries for the factor in question). The method was taken from a study by Fraiman et al. (2008) and calculated using equation (2.4).

$$S_i = \sum_{i=1}^{n} [I_{i,c} - I_c]^2 \tag{2.4}$$

S_i: Sensitivity value for influencing factor i.
n: The total number of countries.
$I_{i,c}$: Index value calculated with influencing factor i removed, for country c.
I_c: Original index value including all influencing factors for country c.

2.3 Results

2.3.1 Ranked index values

This section presents the results for each of the influencing factors included in the study, separated into groups. The ranked susceptibility actual and index values for each influencing factor can be seen in the appendix.

2.3.1.1 Group 1: Production, consumption and mean temperature slope

Influencing factors 1.3 and 1.4 show that GR, ES, IT and PT are highly susceptible due to the fact that they experience temperatures that surpass the cooling threshold (Figure 2.2). On the other hand, for influencing factors 1.1 and 1.2, the Scandinavian countries are among the least susceptible, however PT, FR and GB are also relatively less susceptible, due to steep slopes below the heating threshold (Figure 2.2).

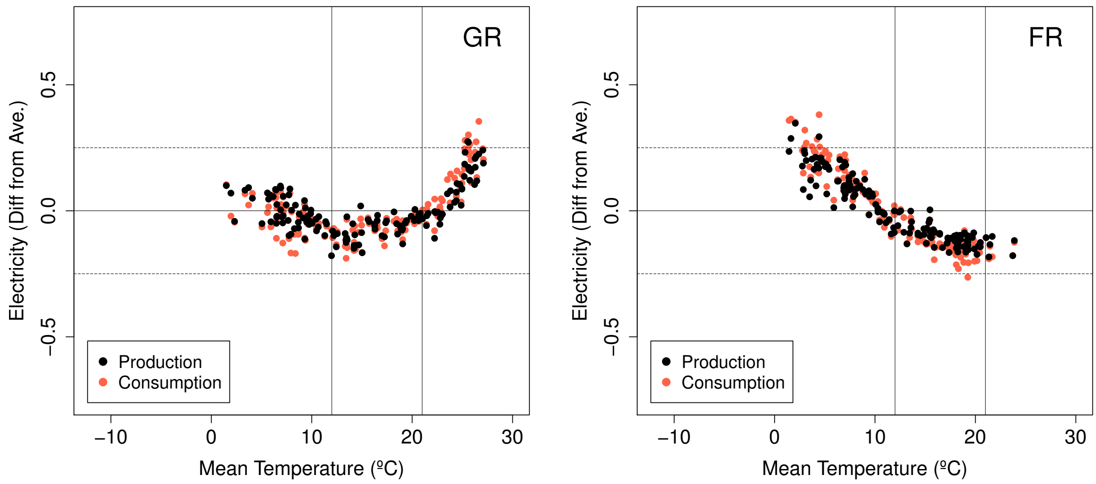

Figure 2.2: Production and consumption by mean temperature - Slope examples (All countries available in the appendix). Source: adapted from European Climate Assessment and Dataset (2012) and IEA (2012).

2.3.1.2 Group 2: Production and consumption

In terms of the production and consumption correlation, ES and GB are notable countries for both the summer and winter influencing factors (2.1 and 2.2) because they have consistently strong correlation between electricity production and consumption. On the other hand, SK and CH have a consistently weak correlation between production and consumption. Regarding the percentage discrepancy, LU is the most extreme example of a net consuming country for both summer and winter (influencing factors 2.3 and 2.4) (Figure 2.3).

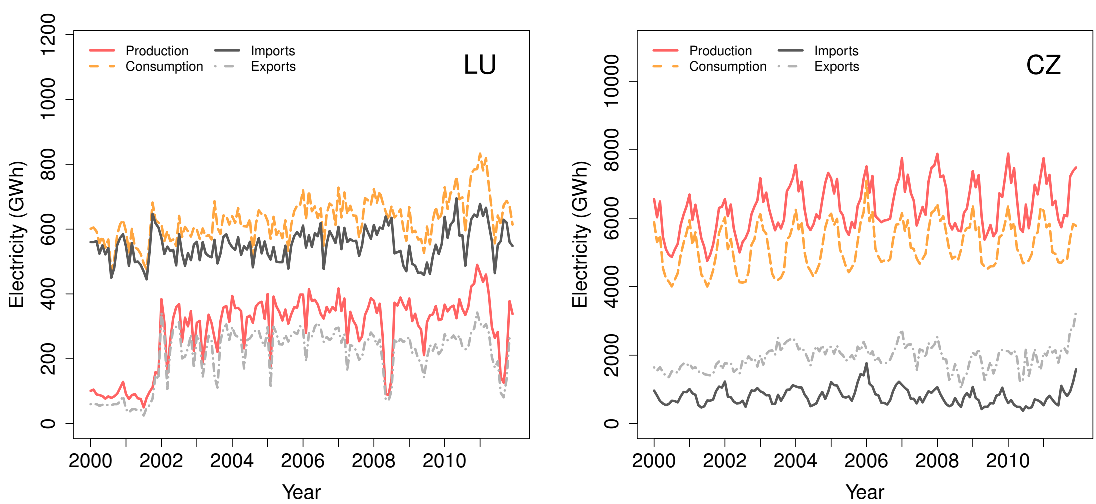

Figure 2.3: Monthly production, consumption, imports and exports over time - Percentage discrepancy examples (All countries available in the appendix). Source: adapted from IEA (2012).

2.3.1.3 Group 3: Thermal electricity production share

The thermal electricity production share (percentage of electricity production from combustible fuels or nuclear) provides information about the current susceptibility of a countries' inland electricity generation mix (Figure 2.4). DK and PT are the less susceptible, due to their decline in thermal share over time (influencing factor 3.2). HU, PL and NL produce greater than 95 % of their inland electricity from thermal sources and have the highest current influencing factor values (3.1).

All of the countries produce greater than 40 % of their electricity from thermal sources, with the exception of NO (<4 %). In terms of changes in the percent share of thermal production over time, LU has by far experienced the greatest rise in thermal use while DK, PT and IE have experienced the greatest decline.

Only half of the electricity consumption of LU is met by inland production. CZ and FR are notable as well due to their large production surplus that is consistent for both summer and winter (2.3 and 2.4) (Figure 2.3). The majority of the countries experience seasonal differences and parts of the year are net consumers and other times net producers, most notable are AT, CH and DK.

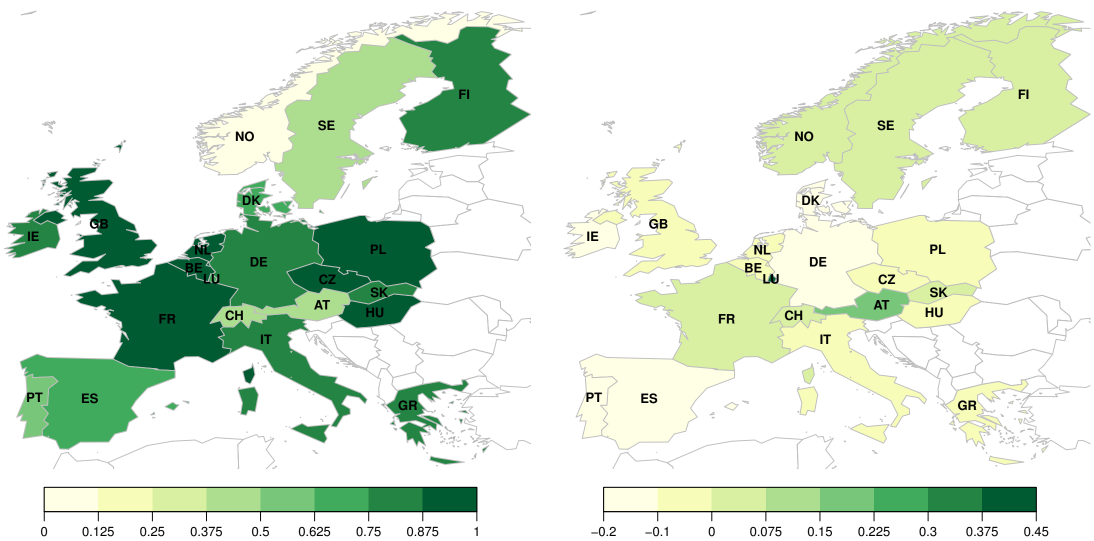

Figure 2.4: Thermal electricity production share (2011) (left) and percent change (2000-2011) (right) maps. Note: Darker colors indicate higher susceptibility. Source: adapted from IEA (2012).

2.3.1.4 Group 4: Projected temperature increase

The projected temperature increase influencing factors give a relative indication of the magnitude of temperature increase expected for both winter and summer (4.1 and 4.2). FI, SE and NO will see the greatest rise in winter temperatures (4.1), while ES, HU and CH will see the greatest rise in summer (4.2). IE and GB will experience the smallest future temperature changes for both seasons. The geographical susceptibility trend of the actual summer and winter temperature values is evident from the maps in Figure 2.5 where a clear north-south gradient is present.

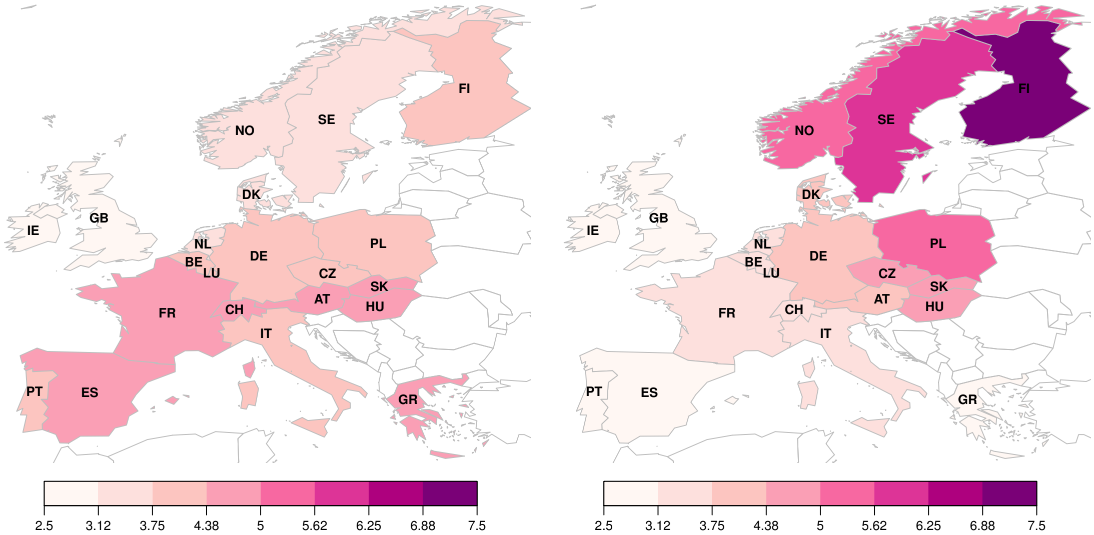

Figure 2.5: Actual summer (left) and winter (right) temperature increase maps (°C) (Scenario A2 1961-90 to 2070-99). Note: Darker colors indicate higher susceptibility for the summer map (left) but lower susceptibility for the winter map (right). Source: adapted from Mitchell et al. (2002).

2.3.1.5 Group 5: Air conditioner prevalence

Countries that historically reach the cooling threshold would logically be the most likely to have the highest air conditioner prevalence due to their warmer temperatures.

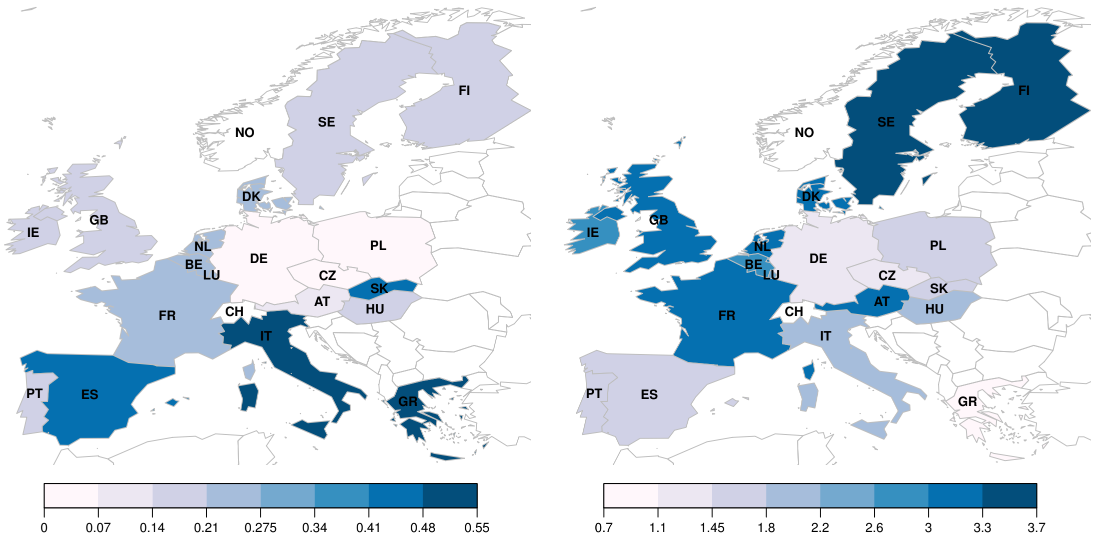

Figure 2.6: Projected air conditioner prevalence map (per capita, 2030) (left) and projected air conditioner percent difference (2005-2030) (right) maps. Note: No data was available for CH or NO. Darker colors indicate higher susceptibility. Source: adapted from Adnot et al. (2008).

This is not true in all cases however, PT being the exception with relatively few air conditioners, and limited growth projected in the future (influencing factor 5.2). IT, GR and ES are projected to have a large stock by 2030 (influencing factor 5.1), however with moderate or low growth (due to saturation). The countries with higher projected growth (for example FI, SE and GB) will likely see greater than three times the current air conditioner stock by 2030 (influencing factor 5.2). A map of the actual projected air conditioner prevalence and projected air conditioner stock difference can be seen in Figure 2.6.

2.3.2 Ranked susceptibility index

The ranked susceptibility index (Table 2.2, Figure 2.7) is an average of the influencing factor index values. The index is therefore a deductive relative indication of the susceptibility of each country to climate change with equal weighting of each of the 14 included factors.

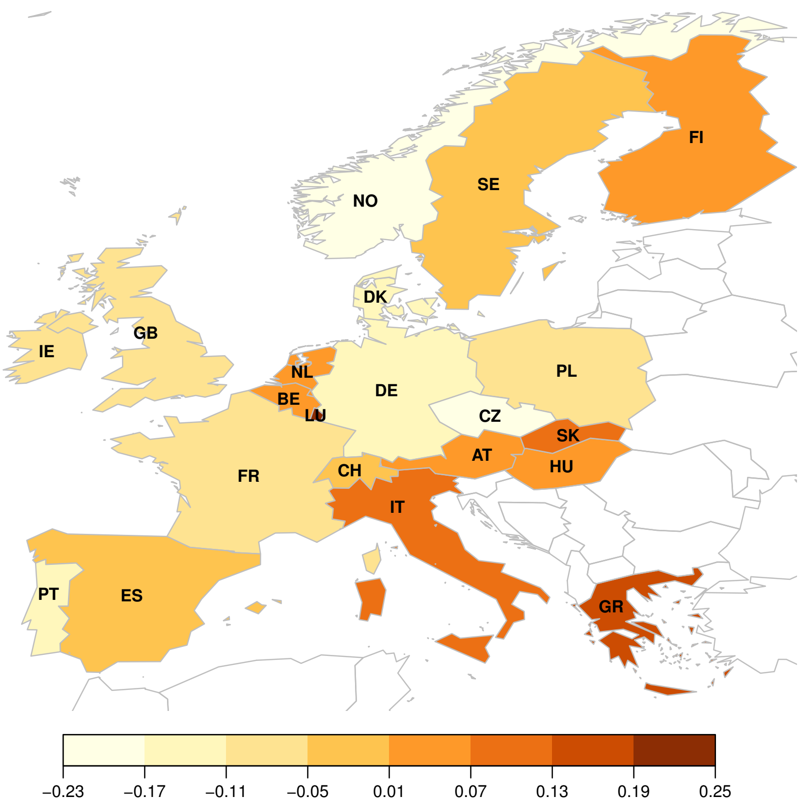

Figure 2.7: Relative ranked susceptibility index map. Note: Darker colors indicate higher susceptibility.

It is important to note that the least susceptible country in the index is the least susceptible relative to the other countries in the index, but does not necessarily have no susceptibility. LU is relatively the most susceptible country by a significant margin, followed by GR, while NO is the least susceptible in the index.

Table 2.2: Relative ranked susceptibility index.

Country	Mean Index Value
LU	0.249
GR	0.136
SK	0.091
IT	0.078
HU	0.065
NL	0.064
AT	0.047
FI	0.030
BE	0.022
SE	-0.020
CH	-0.029
ES	-0.041
GB	-0.078
PL	-0.093
FR	-0.100
IE	-0.103
DE	-0.112
DK	-0.136
PT	-0.163
CZ	-0.195
NO	-0.215

2.3.3 Sensitivity analysis

The sensitivity analysis completed for each influencing factor can be seen in Table 2.3, and shows the relative effect of each factor on the susceptibility index ranking and values. The index is most susceptible to the projected summer temperature increase (4.2). Both the slope for production and consumption with mean temperature for the cooling values (1.3 and 1.4) have the least effect on the index. Some countries are more susceptible to relative changes in their rank based on the effects of the influencing factors (this can be seen in the sensitivity analysis Figure 8.9 in the appendix). NO is consistently among the least susceptible for each influencing factor omission, while LU is consistently the most susceptible (see Figure 8.9 in the appendix).

Table 2.3: Sensitivity analysis values. Note: Factors are listed in increasing order, the index being the most sensitive to the last factor listed.

Influencing Factor	Sensitivity Value
1.3 Production and Mean Temperature Slope (Cooling)	0.0058
1.4 Consumption and Mean Temperature Slope (Cooling)	0.0061
2.4 Production and Consumption Discrepancy (Winter)	0.0189
2.3 Production and Consumption Discrepancy (Summer)	0.0192
1.1 Production and Mean Temperature Slope (Heating)	0.0216
3.2 Thermal Production Change (2000-2011)	0.0253
5.1 Air Conditioner Projection (2030)	0.0254
1.2 Consumption and Mean Temperature Slope (Heating)	0.0257
4.1 Projected Temperature Increase (Winter)	0.0375
5.2 Air Conditioner Percent Difference (2005-2030)	0.0442
2.1 Production and Consumption Correlation (Summer)	0.0567
2.2 Production and Consumption Correlation (Winter)	0.0636
3.1 Thermal Production Percent (2011)	0.0676
4.2 Projected Temperature Increase (Summer)	0.0707

2.4 Discussion

This section will attempt to identify and explain the underlying reasons for the relative susceptibilities of selected countries, discuss the reasons certain countries are more susceptible than others, and examine these results in comparison with existing findings. Due to the highly complex nature of the electricity system in general, and its very pronounced subjectivity to country specific conditions, explaining the behavior of the system is difficult and the findings presented in this report are an attempt to break down and characterize the effect of some of the most important influencing factors, but are by no means the entire picture (Schaeffer et al., 2012).

2.4.1 Discussion of the results

2.4.1.1 Discussion of selected countries

LU LU is, by a wide margin, the most susceptible country in terms of the ranked susceptibility index. Inland production in LU meets less than half of the consumption demand (influencing factors 2.3 and 2.4) which increases susceptibility, as well as makes the country reliant on imports (IEA, 2009a). This is most likely due in large part to the small size of the country as well as the high level of industrial electricity consumption (IEA, 2009a). In 2002, LU experienced a drastic shift in its electricity system due to a capacity increase when gas-fired electricity production was introduced which effectively increased production by 200 %, increasing the countries' susceptibility due to greater reliance on thermal electricity production (influencing factors 3.1 and 3.2) (European Commission, 2007). LU has one of the highest per capita electricity consumption rates in the world, and is securely positioned within the Central-West Europe electricity market which may account for the country putting little emphasis on increasing inland production (IEA, 2009a).

Additionally, LU primarily utilizes combustible fuel as its electricity production source which will likely experience climate change related decreases in capacity during prolonged heat waves or droughts (Hoffmann et al., 2013). However, almost a third of the country's production is from hydro, which may help increase electricity security depending on future precipitation patterns, which in northern Europe will likely be an increase, enhancing hydro capacity (IEA, 2007; Rübbelke & Vögele, 2011a; Semadeni, 2003). Between 2000 and 2011 however, the share of thermal electricity production of LU has increased by more than 40 % (IEA, 2009b).

Electricity production and consumption below the heating threshold in LU on the other hand are not particularly steep in terms of slope to temperature (influencing factors 1.1 and 1.2) and therefore the effects of projected temperature increases will not decrease susceptibility by a significant margin in terms of electricity savings from heating. Many of the countries examined, including LU, experience large volumes of tourists at different time periods in the year. The potential effects of the temporary increase or decrease in population due to tourism on electricity consumption could act as a small factor in decreasing consumption during summer months for LU where trips surpass arrivals during that period (EUROSTAT, 2012).

GR GR is the second most susceptible country in the relative index due to the fact that it already reaches the cooling threshold (influencing factors 1.3 and 1.4). Similar to LU, electricity production and consumption have a steep slope in relation to temperature, meaning that as temperatures rise, so too does electricity consumption, primarily due to the high number of air conditioners (influencing factors 5.1 and 5.2). Furthermore, the expected temperature changes due to climate change indicate a distinct warming during the summer that outweighs any winter warming meaning that cooling related electricity consumption will probably increase (influencing factors 4.1 and 4.2). GR is a net consumer of electricity in both summer and winter months and therefore a consistent net importer of electricity by a larger margin (influencing factors 2.3 and 2.4).

FR FR is considered to have moderate susceptibility in terms of the ranked index, which is not higher due largely to its production surplus (influencing factors 2.3 and 2.4). FR is striving for energy security and has an investment body, which identifies electricity production needs to aid in this endeavor (IEA, 2010a). Furthermore, and what might explain at least part of the production surplus in FR is that while base load electricity consumption can easily be met, peak consumption is ever increasing, which requires more production capacity (IEA, 2010a).

Currently, FR does not exceed the cooling threshold, however with projected temperature increases for summer months (influencing factor 4.2) and increases in air conditioner stock in the future (influencing factor 5.1), susceptibility will likely increase. FR may face further problems in the future due to its reliance on thermal electricity production, mainly nuclear (influencing factors 3.1 and 3.2). Over the past decade, a number of extreme weather events, which are likely to increase in frequency with climate change, were problematic to the FR electricity system (Eskeland & Mideksa, 2010; Rübbelke & Vögele, 2011b). The summers of 2003 and 2009 proved particularly problematic due to heat waves impacting cooling water for nuclear power plants in terms of amount and temperature (Flörke et al., 2011a; Rübbelke & Vögele, 2011b). In 2009, a third of the nuclear electricity plants in FR were shut down due to the summer heat wave, forcing FR to import electricity (Rübbelke & Vögele, 2011b).

CH CH is moderately susceptible relative to other countries in the ranked index and total values (no air conditioner data was available however), but behaves uniquely, with seasonal differences in the system. Electricity consumption and production in CH are highly correlated (influencing factor 2.1 and 2.2) and CH has a production surplus during summer months (influencing factor 2.3), due to its utilization and management of hydro. Hydro reservoirs are often filled during periods of higher precipitation and glacier melting (spring months) and stored in summer until times of need or for export during ideal market conditions (Paul et al., 2007; Semadeni, 2003). Electricity production for CH also varies greatly by year however, which is primarily due to precipitation changes affecting hydro electricity production, leading to further discrepancy between production from consumption (IEA, 2007). Nuclear electricity production decreases during summer months, while hydro production increases, indicating that nuclear is used to help meet the winter peak while hydro is used for export. This seasonal shift of production sources may add to the variability of the system, due to the fact that CH produces the most in times when it can easily meet its own consumption needs, and thus it has no electricity security issues for that period. Thus, CH is the only country with a positive correlation between electricity production and mean temperature for the values below the heating threshold.

CZ CZ is a less susceptible country in the index mainly due to a large production surplus (influencing factors 2.3 and 2.4). Furthermore, CZ is not expected to substantially increase its currently low air conditioner stock in the future (influencing factors 5.2), and will experience only a moderate temperature increase (influencing factors 4.1 and 4.2), which is greater in winter than summer. The combustible fuel and nuclear electricity production sources on which CZ is almost complete reliant (influencing factors 3.1 and 3.2) will likely be negatively affected by climate change in the future, which will inevitably increase susceptibility. However, CZ currently has a large reserve of domestic resources (primarily coal and uranium) that is easily accessible and readily used for electricity production, which will maintain electricity security in the near future (IEA, 2010b).

NO The least susceptible country in the ranked index is NO with low susceptibility in the majority of the influencing factors. It is important to note however, that there was no air conditioner data available for NO, and therefore, the index ranking value is lower. That being said NO has low relative susceptibility for influencing factors 1.1 and 1.2, meaning that as the climate changes, electricity production and consumption will decrease during the winter months. Furthermore, NO will benefit the most from the temperature changes, with the winter rise in temperature being far greater than the summer increase (influencing factors 4.1 and 4.2). NO has almost no electricity production from thermal sources (influencing factors 3.1 and 3.2), and relies almost exclusively on hydro electricity which will experience greater capacity due to precipitation increases in the future in the course of climate change, which will therefore be beneficial for electricity production in the country (Alcamo et al., 2007). Finally, NO is a net producer of electricity in both summer and winter (influencing factors 2.3 and 2.4) and therefore has the ability to export the excess.

Universal Trends All of the countries, to differing degrees, show an increase in monthly electricity consumption from February to March, which for most countries is against the generally decreasing electricity production and consumption trend in spring. This can be likely explained by the 1 hour clock change for daylight savings time, usually done in March (European Parliament and Council, 2001). Daylight savings is designed to increase the number of daylight hours and therefore reduce electricity consumption due to decreases in heating and lighting, however studies show that for the first few weeks after the change in spring, consumption increases due to earlier wake up times which require more heating (Kellogg & Wolff, 2007; Kotchen & Grant, 2008).

Day length (the number of daylight hours) varies seasonally and geographically, and has a potential significant effect on electricity consumption due to lighting requirements. Lighting accounts for approximately 10 % of household electricity use on average in European countries, however the monthly variation of consumption share is more important than the average (Bertoldi & Atanasiu, 2009). Koroneos and Kottas (2007) demonstrate that for GR, electricity consumption for lighting peaks in the months of January and December, and is the lowest in the months of June and July. Their study reinforces the seasonal variation and possible influence of lighting on electricity consumption, especially considering that GR is one of the southernmost countries examined in this study, which means it would experience the least variation of day length throughout the year.

The monthly electricity production and consumption from 2000-2011 demonstrates an overall increasing trend of the variables over time. This increase could be due to a number of factors, most notable are a rise in GDP and rise in population (except DE and HU experienced no consistent population increase during the time period) (EUROSTAT, 2012). However, the time frame of only 11 years (due to data availability) does not provide enough for a sound statement regarding an increasing trend especially due to the decrease seen among most countries (with the exception of BE) around 2008/2009, which is most likely due to the global financial crisis (European Commission, 2009).

2.4.1.2 Results correlation with existing studies

The ranked susceptibility index correlates well with a number of existing studies, however no previous work examines the electricity system in the same way or utilizes the same set of influencing factors. The index aligns well with a study by Eskeland and Mideksa (2010) which identifies the relative effects on heating and cooling due to climate change in Europe. The study concludes that climate change will induce less heating in northern European countries, while increasing cooling in southern European countries. Ultimately, the study identifies GR, IT and ES as countries that will experience cooling increases that outweigh heating decreases due to climate change. Thus correlating with the higher susceptibility ranking of GR and IT seen in our index. ES on the other hand is only moderately susceptible in our ranked index, something that is due to the inclusion of a wider range of influencing factors especially the production and consumption correlation, which decreases the susceptibility of ES.

A study by Gnansounou (2008) assesses the susceptibility of the energy sector as a whole (including the electricity sector) on a country level in terms of a much wider scale which take into account a number of influencing factors including energy intensity, oil and gas import dependency, CO_2 content of primary energy supply, electricity supply weaknesses and non diversity in transport fuels. Despite the very different influencing factors considered and wider range of countries examined, the ranked index of susceptibility presented in the study is similar to the findings of this study. GR, LU and IT were found to be very susceptible, while NO, FR and GB are considered relatively less susceptible. Obviously, due to the examination of the energy, as opposed to electricity sector, there are some differences to our relative index ranking, and only NO is consistent with the lower susceptibility, GB is more susceptible in our index mainly due to a strong projected increase in air conditioner stock in the future. The reasons for the increase of susceptibility in FR are explained in Section 2.4.1.1.

Studies by Rübbelke and Vögele (2011b) and van Vliet et al. (2012) examine the negative effects of climate change on the electricity production ability in Europe, specifically on the most susceptible electricity production source, thermoelectric generation. Southern and southeastern Europe are identified as being particularly susceptible to climate change related problems which correlates well with the index for GR and IT, however not for PT which has very low air conditioner stock (van Vliet et al., 2012). The potential issues are however, also present for any countries in the index that utilize thermoelectric production sources, which includes some of the least susceptible countries in the index, most notably CZ.

2.4.1.3 Sensitivity analysis

The goal of the sensitivity analysis is to identify the relative sensitivity of each influencing factor on the ranked susceptibility index. The sensitivity analysis helps identify which influencing factors have the most effect on the index value and therefore ranking. The index is the least sensitive to the slope of electricity and mean temperature for the cooling values (1.3 and 1.4). This may be explained by the fact that only five countries reach the cooling threshold. The projected temperature increase in summer (4.2) has the most effect on the index, likely due to the fact that summer temperature increases will have a profound effect on electricity consumption, partly due to air conditioner use for warmer countries, and decreases in heating trends in colder countries. In both cases, the summer temperatures will largely dictate future susceptibility. The thermal production percent (3.1) also has a large effect on the index; this can be explained by the higher susceptibility of countries with heavy reliance on thermal production.

2.4.2 Limitations

The major limitation of this study was the access and availability of data. The only available monthly electricity data for a wide range of European countries included only the period from 2000 to 2011, and did not cover the entire continent (only 21 countries). Daily electricity data for that period would have been quite useful however no such data was found. This is particularly pertinent due to the well documented 2003 summer heat wave in Europe which caused a number of problems for some countries in terms of meeting electricity demand and forced changes to the electricity system, but did not appear in the monthly data due to the shorter time scale of the event (Eskeland & Mideksa, 2010; Flörke et al., 2011a; Rebetez et al., 2008; Rübbelke & Vögele, 2011a).

One specific limitation was the air conditioner data, which was published in 2008, and therefore only the 2005 data values were measured, while the others were projections. Moreover, the data only reveal information about the number of air conditioners that exists in a country, and not how or when they are used. The assumption is then that countries with a lot of air conditioners put them to use when the temperature exceeds the cooling threshold, however this is not necessarily true. Furthermore, the air conditioner data did not provide values for CH and NO; meaning that the integration of that data could change the index.

Despite the fact that all electricity generation sources are affected in some way by climate change, there is no relative quantitative data on the effects on electricity production. Therefore, based on the available research, only thermal electricity production (combustible fuels and nuclear) was considered to be susceptible (Flörke et al., 2011a; Rübbelke & Vögele, 2011a). Studies concerning the 2003 heat wave in Europe cite thermal power plant output as being problematic (Förster & Lilliestam, 2009; Rübbelke & Vögele, 2011b, 2011a). Furthermore, and perhaps the most compiling evidence of the increased susceptibility of combustible fuel electricity production is the political and social objection to these emission intensive and controversial electricity production sources. Due to an increasing push for lower greenhouse gas emissions by a number of European countries as well as historical and recent nuclear power disasters, nuclear and fossil fuel phase out plans have been made. Most notably, DE has planned to close all of its nuclear power plants by 2022, along with the remaining black coalmines by 2018 (Breidthardt, 2011; Dougherty, 2007). Ultimately, even a country with ample electricity production now, may see its surplus diminish as thermal production decreases with growing environmental, social and political pressure, something that will probably not be the case for hydro or renewable production sources.

Hydro electricity generation is also susceptible to extreme events and changing precipitation patterns due to climate change, however research into the specific effects associated with this phenomenon yields contradictory results and the susceptibility may increase or decrease (Rademaekers et al., 2012; Rübbelke & Vögele, 2011a; The World Bank, 2008a). Furthermore, the complex interaction between climate and hydro electricity requires a detailed geographically specific analysis in order to quantitatively determine susceptibility.

The EU as a whole has been undertaking extensive integration of renewable electricity production, which exceeded 20 % in 2010, meeting a 2001 target (EWEA, 2012). An even more ambitious EU renewable electricity target for 2030 has been requested by industry, with the goal of decreasing emissions as well as improving energy security in the EU, both of which require a move away from traditional thermal electricity production (EWEA, 2012). It is likely that along with the planned electricity and energy targets for the EU, substantial electricity production changes will be undertaken in most countries in the upcoming years, unfortunately any kind of future calculations or quantification in terms of the projected impacts of those changes on the electricity system susceptibility would require extensive country specific analysis.

Electricity storage capacity could affect the susceptibility of the electricity system of a given country strongly, but was not integrated in this study due to lack of adequate data (Semadeni, 2003). CH utilizes hydro electricity greatly and has a number of planned and existing hydro pumped storage plants which, if integrated in this study would decrease its index susceptibility ranking (Huber & Gutschi, 2010). Besides hydro pumped storage there are a number of energy storage technologies which, if available, bridge production and consumption fluctuations (Naish et al., 2008).

2.5 Conclusions

Assessing the susceptibility of European electricity systems to climate change on a country level is a complex issue with a wide variety and number of influencing factors. It is clear however, that many countries are not only susceptible to climate related stresses currently, but will become more susceptible in the future. This study provides an overall outlook of the susceptibility of 21 European countries to climate change, something that has not been previously undertaken to this degree in terms of geographic scope and specific influencing factors examined, but builds on the findings of existing studies. Ultimately, a ranked susceptibility index was presented that provides a quantitative relative indication of susceptibility among the countries included. The study was successful in identifying those countries that are susceptible to climate change, along with the specific aspects of their electricity system that are vulnerable. No distinct pattern was evident in terms of electricity system characteristics or susceptibility influencing factors between countries ranked higher or lower in the index. This lack of similarity between countries highlights the complexity and distinct nature of each country's electricity system and its relation to climate. The index utilized influencing factors, both current and projected, all of the influencing factors were significant enough to affect the ranking.

The findings of this study are useful in a number of ways. In terms of decreasing susceptibility, policy makers, scientists and energy managers can examine the most important influencing factors that increase susceptibility and focus their adaptation efforts on those areas. Furthermore, due to the relative nature of the susceptibility index, countries with higher susceptibility can identify countries with less susceptible electricity systems and use them as a guide to decrease their own susceptibility. Further work incorporating more influencing factors such as the influence of prices and the electricity market on consumption, the political and social outlooks and decision making processes in regard to the electricity system, as well as specific energy plans for each country could all be beneficial. The inclusion of those additional factors would add an additional level of understanding to the overall understanding of susceptibility within the system. We feel that the findings of this study are an important first step towards a comprehensive analysis of the susceptibility of European countries to climate change.

3

Heating and cooling energy demand of the German residential building stock *

Abstract

The housing sector is a major consumer of energy. Studies on the future energy demand under climate change which also take into account future changes of the building stock, renovation measures and heating systems are still lacking. We provide the first analysis of the combined effect of these four influencing factors on the future energy demand for room conditioning of residential buildings and resulting greenhouse gas (GHG) emissions in Germany until 2060. We show that the heating energy demand will decrease substantially in the future. This shift will mainly depend on the number of renovated buildings and climate change scenarios and only slightly on demographic changes. The future cooling energy demand will remain low in the future unless the amount of air conditioners strongly increases. As a strong change in the German energy mix is not expected, the future GHG emissions caused by heating will mainly depend on the energy demand for future heating.

*This chapter has been published as: Olonscheck M., Holsten A., Kropp J.P. (2011): Heating and cooling energy demand and related emissions of the German residential building stock under climate change. Energy Policy, 39/9, 4795-4806.

3.1 Introduction

The provision of energy, which globally still relies predominantly on non-renewable energy sources, leads to an increasing concentration of greenhouse gases (GHG) in the atmosphere and thus contributes to climate change. To develop readjustment and mitigation strategies, estimates regarding future energy consumption and resulting GHG emissions will be essential. In this regard, particular attention should be given to the household sector as a major consumer of energy. In 2007, the residential building sector accounted for 12 % of world energy consumption (EIA, 2010). In Germany households account for 15 % of total energy consumption, of which about three quarters stem from heating (FMET, 2009). In 2009, heating of German residential buildings caused 121 million tons CO_2 emissions (DESTATIS, 2011).

The energy consumption patterns of households can be determined by a combination of climatic, demographic, economic and lifestyle factors. Commonly the effect of temperature is considered (Amato et al., 2005; Cartalis et al., 2001; Eskeland & Mideksa, 2009; Howden & Crimp, 2001), whereas some studies include other meteorological parameters like humidity or specific enthalpy (Gertis & Steimle, 1989; Howden & Crimp, 2001; Sailor, 2001). Yet Scott et al. (1994) found that even a 20 % change in solar insolation, wind speed, or humidity alters overall building energy demand only slightly.

A number of recent studies show that large energy reductions can be achieved by renovation. By means of a building simulation model, Scott et al. (1994) show that independent of climate change, an improvement in the building design could substantially reduce heating energy consumption of U.S. commercial buildings. Yet analysing the same sector in the U.S., Belzer et al. (1996) conclude that even with substantial improvements in building energy performance climate change will lead to an increase in cooling energy consumption that is nearly as large as the decrease in heating energy consumption in the same period. In the U.S. energy saved by efficiency programmes more than offsets the increase in energy consumption for room conditioning due to climate change and growth in building stock (Scott et al., 2007). Under warmer conditions, residential air conditioning market saturation generally increases. Analysing 12 cities in four states in the U.S., Sailor and Pavlova (2003) estimate that increases in cooling energy demand due to a warmer climate could be outbalanced by long-term adaptive behavioural responses. The disproportional growth of air conditioner use might lead to an even higher cooling energy consumption.

For Germany, Diekmann et al. (2005) examine heating energy demand and CO_2 reduction strategies using a space heating model which accounts for different insulation measures and heating installation improvements. For the heating energy demand of households they estimate an increase of 5 % or an decrease of 29 % by 2030 compared to 1990. The total CO_2 emissions of households will decrease between 8 % and 38 %. Using the same approach, Kleemann et al. (2000) calculate a considerable reduction potential for a single-family building by implementing heat insulation measures. However, the model does not account for climate change effects. Loga et al. (2007) investigate energy efficiency measures for the German building stock and find reduction potentials of 0.7 % and 1.7 %/yr for a renovation rate of 0.75 % and 2.5 %/yr, respectively, and insulation standards according to the German Energy Saving Regulation 2007. The corresponding reduction in CO_2 equivalent emissions will be 1.2 % and 3.0 %/yr. Buchert (2009) concludes that the German residential heating and water heating sector offer large CO_2 reduction potential in the next decades.

Nevertheless there is still a lack of studies analysing the impact of a changing climate on the heating and cooling energy demand and resulting GHG emissions considering changes in the residential building stock, renovation measures and market penetration of conditioning systems. Thus, we developed a model based approach simulating the energy demand of German households for room conditioning including the influence of warming, upcoming renovation regulations, demographic changes and different heating systems until 2060. In particular we will answer the question of how the heating and cooling energy demand of German households for room conditioning will change in the future. Moreover we also show which additional factors - beside rising temperatures - will have an influence on this demand. Finally, we calculate the resulting GHG emissions.

In the following (Section 3.2), we introduce the analysed building data and the method to include the effect of retrofit measures. Moreover, we detail the concept of heating and cooling degree days and the formulae used to calculate the useful energy demand of residential buildings. Taking into consideration different heating systems, we compute the end energy demand and resulting GHG emissions. In Section 3.3 the results are presented. Thereafter follows a discussion of the results and a comparison with previous studies (Section 3.4). A summary concludes our findings (Section 3.5).

3.2 Data and methods

3.2.1 Data

The German building stock comprises about 18 million residential buildings with approximately 40 million dwellings (FMTBUD, 2009). For the analysis we use data from the German Building Typology "Taxonomy and data sets" and "Occurrence of building types with different age of structure" of the Institute for Building and Environment (IWU) for the period 1954-2006. This classification comprises 43 building types by year of construction, number of dwellings in one building of each type and per building type, the volume and the size and insulation standard of the main building components. The insulation standard is expressed by heat transmission values (U-values) which indicate the thermal balance of a building component in W/m^2 component surface and per degree Kelvin temperature difference between indoor and outdoor temperature (Laustsen, 2008).

The climate data were obtained from two different model approaches. We use projections of the regional statistical climate model STAR II (Orlowsky et al., 2008). It is based on observed meteorological data from 2 335 meteorological stations of the German Weather Service (DWD) and covers a time horizon from 1951-2006. This data is re-sampled using cluster-analysis to provide scenario data up to 2060. Thereby, seven different temperature trends were imposed assuming warming of 0.0 °C to 3.0 °C. For our analysis we use projections representing a 1 °C, 2 °C and 3 °C warming trend for Germany. Out of 100 random realisations of this statistical model we selected those with the median of the climatic water balance (Werner & Gerstengarbe, 1997). Further, we use data from the regional dynamic model CCLM under scenario A1B covering the period of 1960-2100 (Lautenschlager et al., 2009). This is a non-hydrostatic model which is forced by the global coupled atmosphere-ocean-model ECHAM5/MPI-OM (GKSS, 2010). For comparison of both models we restrict the time horizon to 101 years, 1960-2060, and average model runs.

3.2.2 Methodological concept

As the building typology does not contain annual data about the age of a building, but only building classes with different bins of years, we assumed an equal distribution for every class. The annual total sum of the residential building stock calculated according to the building typology slightly deviates from the official statistics of the Federal Statistical Office (DESTATIS, 2010). Thus, we applied the annual number of residential buildings according to the Federal Statistics while assuming the share of building types according to the IWU data. For missing years between 1954 and 1993, we linearly interpolated data on the stock of residential buildings in the former German Democratic Republic (calculated on basis of DESTATIS (2010)).

In order to determine the future total living space demand, we combined population forecasts until 2060 of the Federal Statistical Office (DESTATIS, 2009) with extrapolated data on the per capita living space demand in the future. We chose the population forecasts 5-W1 (low), 6-W2 (medium) and 4-W2 (high) since they provide a wide span of possibilities (decline in population until 2060: 20 mio., 12 mio., 5 mio. respectively, from a current population of 82 million). The per capita demand of living space was extrapolated (based on the available data covering 1994-2008) employing a functional form which increases and exponentially approaches a constant value. According to the obtained parameters the per capita demand grows from 36.2 m^2 in 1994 to 47.2 m^2 in 2060. This represents changes in life style. The total living space demand was assigned to the different building types according to their mean share and size in the past. We compared this calculated total number based on living space demand and population with the number of buildings according to the Federal Statistics for 1994-2008. We found a good agreement with a deviation of 10 %, which we applied for the projection of the future building stock.

For determining the number of new residential buildings in the future, we extrapolated the trend of the available data from 1996-2007 assuming a decrease with bases of 94,000, 105,000 and 116,000 buildings. These bases represent the lowest ratio of the number of new residential buildings and the population in this period applied to the population forecasts in 2060. Thereby, we assumed that only single-family houses, row houses and multi-family houses as the main residential building types in the past will be erected in the future. Their share in the stock of new residential buildings as well as their component sizes are obtained by averaging the characteristics of buildings erected between 1984 and 2006 for the respective types.

We assumed that only buildings aged 30 years or older in the considered year are at disposal for demolishing. The number of demolished buildings is derived by subtracting the number of new buildings from the total stock in a respective year. We calculated the number of demolished buildings per type based on the mean share of building types in the total stock. As the share of high-rise buildings in the total stock is very low, the resulting number of demolished residential buildings is always lower than 0.5 and therefore assumed to be zero.

The applied building typology only describes the original state of residential buildings and does not take into consideration later renovation measures (Diefenbach & Born, 2007). Hence, we first updated the typology under the viewpoint of past renovation measures. These are dependent on both the intensity of energetic improvements (U-values of building components) and on the annual share of residential buildings that have been renovated (renovation rate). For determining the intensity of energetic improvements, we considered U-values for different building components from ordinances in the past and planned regulations in the future (Table 3.1). Under the assumption that all required U-values in the ordinances valid at the respective time were followed, the extent of energetic improvement of residential buildings in the past was determined.

Buildings constructed after 2012 are assigned U-values according to energy standards as defined in the Integrated Energy and Climate Program of the Federal Government from 2007 (Jochem et al., 2008). As the European Union instructs clients to design buildings in compliance with passive house standards from 2021 on (EU, 2009), we assumed that single-family houses erected after 2020 meet this standard with regard to their U-values.

Table 3.1: U-values [in W/m^2K] according to the German heat insulation regulations (Wärmeschutzverordnung, WSchV) and energy saving regulations (Energieeinsparverordnung, EnEV) for renovation of residential buildings over time by component (IWU, 2007).

Building component	U-values WSchV 1982	U-values WSchV 1995	U-values EnEV 2002	U-values from 2010 on (EnEV 2009)	Possible U-values from 2013 on	Possible U-values from 2020 on
Roof	0.45	0.3	0.3	0.24	0.17	0.1
Wall	0.6	0.5	0.45	0.24	0.17	0.15
Basement	0.7	0.5	0.5	0.3	0.21	0.12
Window	3.1	1.8	1.7	1.3	0.9	0.8

There is a lack of data regarding annual renovation rates in Germany for the past (Diefenbach & Born, 2007). According to estimates it amounts to around 2.5 % (Jochem et al., 2008). However, as most of these renovations do not incorporate the total renovations in an energetic sense, but often only parts of a building are improved energetically, the quota of energetically renovated residential buildings per year is considered to be much lower (Diefenbach & Born, 2007). Diefenbach et al. (2005) suppose an annual energetic renovation rate of 0.75 % to 1.5 % and use 1 % as a general estimate, which we apply in this study.

Due to a lack of detailed data on the type of residential buildings which have been renovated, we assume that in each considered year only those buildings that are 30 years or older and that are not yet demolished are improved (Boermans & Petersdorff, 2007). In order to obtain the annual number of redeveloped buildings per building type, the share of each type subjected to renovation measures in the overall number of residential buildings subjected to renovation measures was multiplied by 1 % (renovation rate) of the total stock of buildings in the considered year. For the future we apply the renovation rates according to the considered scenarios (see Section 3.2.5). The number of renovated buildings is then cumulatively summed over the years of consideration. The considered time frame of 101 years leads to buildings being renovated more than once after 2014. Thus, after 2014, the renovation rate was split up equally to one-time and second renovations.

If for one building type the number of one-time renovated buildings exceeded the stock of buildings in one year before 2014, we apportioned the surplus to the other building types according to their share in the total stock. If this case occurred for years after 2014 (when second renovations are considered), we set the cumulative number of (one-time) renewed buildings to the total number of that building type.

If the calculated cumulative number of one-time renovated buildings of a type was larger than the actual stock of buildings of that type (as occurs due to an assumed constant yearly retrofit rate), we limited it to the stock of that type in the respective year. Moreover, the total renovation rate was assigned solely to the second renovation.

The cumulative number of second-time renovated buildings per type can neither exceed the existing total building stock of that type nor exceed the total number of improvable buildings of that type in a considered year. If the smaller value limits the cumulative number of buildings to be renovated a second time, an apportionment to other building types is carried out until the cumulative number of buildings to be renovated a second time is equivalent to the minimum and therefore set to the minimum. Thus, the cumulated number of second-time renovated buildings always stays below the cumulated number of renovatable buildings or those to be renovated a second time.

3.2.3 Calculation of the useful heating and cooling energy demand

To assess the impact of temperature on the heating and cooling energy demand, we applied the common concept of heating and cooling degree days (Amato et al., 2005; Cartalis et al., 2001; Eskeland & Mideksa, 2009; Howden & Crimp, 2001; Prettenthaler & Gobiet, 2008). A degree day is defined as the °C difference between an indoor comfort temperature and the mean daily outdoor temperature, if the latter does not exceed a certain threshold, and is especially dependent on the insulation standard of the considered building. For Germany this comfort temperature is defined in the industrial standard DIN 4108-6 (German Institute for Standardization) as 19 °C (DIN, 2003).

We considered different heating thresholds for different types of insulation. As this differs strongly between building type, we assumed the two thresholds of 10 °C and 12 °C as applied in Christenson et al. (2006) and Prettenthaler and Gobiet (2008). We assigned them to each building type according to its heat loss per volume based on standard DIN V 4108-6 (DIN, 2003) and the German Energy Saving Regulation 2007 (FG, 2007). We found that for residential buildings that are not yet retrofitted, heating thresholds of 10 °C and 12 °C are suitable. Newer buildings do have lower, older ones higher thresholds. From 1995 on, when the heat insulation regulation (Wärmeschutzverordnung) came into force, for all building types we use a heating threshold of 10 °C for the determination of heating degree days.

As there is no European Standard for computing cooling degree days, European studies usually apply a common U.S. definition with a comfort temperature of 18.3 °C (65 F) (Aebischer et al., 2007; Christenson et al., 2006; Prettenthaler & Gobiet, 2008). The application of this internationally prevailing base temperature is not plausible in this study as the indoor comfort temperature is assumed to be 19 °C. In this study, we therefore implemented a cooling threshold of 22 °C as a realistic upper limit, which has been used by Benestad (2008) and Matzarakis and Thomsen (2009). Thus, heating degree days

(HDD) are calculated by:

$$\mathrm{HDD} = \sum_{i=1}^{n} (19\ ^\circ\mathrm{C} - \theta) \text{ for n} = \text{days per year and}\, \theta \leq 10\ ^\circ\mathrm{C}, \text{or}\ 12\ ^\circ\mathrm{C} \tag{3.1}$$

and cooling degree days (CDD) by:

$$\mathrm{CDD} = \sum_{i=1}^{n} (\theta - 19\ ^\circ\mathrm{C}) \text{ for } n = \text{ days per year and } \theta \geq 22\ ^\circ\mathrm{C}. \tag{3.2}$$

The residential building stock is not equally distributed over Germany. For this reason we weighted heating and cooling degree day data from both models according to spatially distributed population density based on CORINE Land Cover (CLC) data (Gallego & Peedell, 2001). Thereby, we weighted the degree day values by the population in the vicinity of the respective climate station based on Thiessen polygons (for the STAR II model) or by the population within the respective grid cell (for the CCLM model).

The heating energy demand corresponds to the heat that the heating system must supply to a building to attain a certain comfort temperature. It is influenced on the one hand by heat losses through outer surfaces and ventilation of a building (both are influenced by the number of degree days) and on the other hand by gains of heat through insolation and waste heat of internal heat sources like electric equipment and residents (Jungmann & Lambrecht, 2008). When outdoor temperatures lie above indoor temperatures, the transmission and ventilation heat fluxes are simply reversed (DIN, 2007). Thus, the heat supplied to the building results in a certain cooling energy demand.

The annual heating energy demand Q_h of each residential building was calculated on the basis of the German DIN standard V 4108-6 (DIN, 2003), given the formula:

$$Q_h = 24 \cdot 10^{-3} \cdot f \cdot \mathrm{HDD} \cdot (H_T + H_V) - \eta \cdot (Q_S + Q_I)\ [\mathrm{kWh/a}], \tag{3.3}$$

where

f = Factor for inclusion of a night setback of the heating system temperature = 0.95 [kh/d],

H_T = Transmission heat losses,

H_V = Heat ventilation losses,

η = Factor for inclusion of the utilisation factor of internal and solar heat gains,

Q_S = Usable solar heat gains (constant value),

Q_I = Usable internal heat gains (constant value).

Transmission heat losses derive from heat conduction in the building components as well as heat transfer to the outer surfaces of the components. Thus, they are a measure of the heat insulation quality of the building envelope and depend on the U-values of the building components; the smaller the U-values, the better their energetic state (Jungmann & Lambrecht, 2008). Transmission heat losses H_T are calculated with the following equation.

$$H_T = \sum_{i=1}^{4} (F_{xi} \cdot U_i \cdot A_i) + A \cdot \Delta U_{TB} \text{ [W/K]}, \tag{3.4}$$

where

F_{xi} = Temperature correction factor (depending on the kind of building component),

F_{xi} [wall, window, roof] = 1, F_{xi} [basement] = 0.6,

U_i = Mean U-value of a building component [W/(m^2· K)],

A_i = Surface area of each building component [m^2],

A = Heat transmitting surrounding area [m^2],

ΔU_{TB} = Thermal bridge correction factor = 0.05 [W/(m^2· K)].

The replacement of warm ambient air by cold outdoor air results in heat ventilation losses H_V. For calculation of these losses, differences in the leak tightness of buildings are neglected, thus

$$H_V = 0.19\,[\text{W/K} \cdot \text{m}^3] \cdot V\,[\text{m}^3], \tag{3.5}$$

where V = Heated building volume (constant per building type).

Usable solar heat gains Q_S are mainly conveyed via windows and other glazings and depend on the total energy transmittance g of the in-built glass, the glass surface, and the intensity of radiation. Assuming buildings are fully exposed to radiation, usable solar heat gains are calculated by

$$Q_S = \sum_{i=1}^{4} 0.567 \cdot I_i \cdot g_i \cdot A_i \text{ [kWh/a]}, \tag{3.6}$$

where

I_i = Intensity of radiation (depending on orientation: $I_E = 155$, $I_S = 270$, $I_W = 155$, $I_N = 100$) [kWh/(m^2· a)],

g_i = Total energy transmittance of glazing type in case of vertical insolation [-],

A_i = Area of windows [m^2].

Electrical equipment, lighting, and attendant residents cause internal heat gains depending on the amount, the frequency of use, the efficiency of the devices and the degree of activity of the residents. As these influences cannot be quantified generally the regulation assumes a mean value of internal heat gains Q_I:

$$Q_I = 22\,[\mathrm{kWh/m^3a}] \cdot 0.32 \cdot V\,[\mathrm{m^3}]\,. \tag{3.7}$$

The DIN standard 18599 (DIN, 2007) allows for a complex and detailed determination of the heating and cooling energy demand of buildings. However, for comparability reasons a simplified approach for calculating the heating energy demand in DIN 4108-6 was chosen here and applied to the determination of the cooling energy demand Q_C. Thus the cooling energy demand [in kWh/a] was calculated as follows:

$$Q_C = (1-\eta_{HP}) \cdot \Big(0.024 \cdot \mathrm{CDD} \cdot \big(\sum_{i=1}^{4} F_{xi} \cdot U_i \cdot A_i + 0.05 \cdot A + 0.19 \cdot V\big) + \big(\sum_{i=1}^{4} 0.567 \cdot I_i \cdot g_i \cdot A_i + 22 \cdot 0.32 \cdot V\big)\Big)\,. \tag{3.8}$$

Due to the fact that the provision of residential buildings with air conditioners is much smaller than the provision with heating systems, we multiplied the calculated annual cooling energy demand by the share of households with air conditioners resulting in the actual cooling energy demand. Further, we assume an equal distribution of these cooling systems over all building types.

3.2.4 Calculation of the end energy demand

So far, we have calculated the useful energy demand defined as the energy that a heating or cooling system must theoretically supply to a building. However, it does not consider how efficient this demand is supplied. We therefore further calculate the end energy demand which is the amount of energy necessary to meet the useful energy demand after deducting transport, static, exhaust gas, radiation and transformation losses. These losses are considered by the annual utilisation rate of a certain heating system defined as the ratio between generated heat and necessary input energy. This value indicates the efficiency over a certain time period under practical conditions and thus also considers static and standing losses (FMENCNS, 2005). Thus, the end energy demand is given by:

$$E = Q_h/\varepsilon\ [\mathrm{kWh/a}] \tag{3.9}$$

where

E = End energy demand [kWh/a],

ε = Annual utilisation rate [-].

Table 3.2: Annual utilisation rates (Beer et al., 2009) and CO_2 equivalent emission factors (including upstream chains)(Memmler et al., 2009) for different type of heating system according to the respective energy sources.

Type of heating/ energy source	Annual utilisation rate	CO_2 equivalent emission factor
Coal boiler	0.79	0.43
Heat oil boiler	0.75	0.32
Gas boiler	0.79	0.25
Biomass boiler	0.79	0.01
Solar heat and heat pump	2.25	0.14
Electric heating	0.99	0.67
District and local heating	0.98	0.32

Table 3.3: Heating (left) and cooling energy demand scenarios (right).

	Heating			Cooling		
Assumptions/ Scenario	High	Medium	Low	High	Medium	Low
Future renovation rate	1 %	2 %	3 %	1 %	2 %	3 %
Future building stock	High	Medium	Low	High	Medium	Low
Projected temperature increase until 2060	1 °C	2 °C	3 °C	3 °C	2 °C	1 °C
Market saturation of heating (left) and cooling (right) devices	100 %	100 %	100 %	13 %	2.5 %	1 %

The annual utilisation rate differs between energy source and the heating system. We vary energy sources and heating systems over time while assuming constant annual utilisation rates. The annual utilisation rates applied for different types of heating are summarised in Table 3.2. As no data is available about the share of solar heat or heat pumps in the energy source "solar heat and heat pumps", an equal distribution is assumed.

3.2.5 Derivation of future scenarios

Since the future energy demand is associated with high uncertainty, we develop scenarios: a medium scenario and two extreme scenarios, thus covering the scope of possible and plausible future developments of the useful energy demand (Table 3.3). Within the scenarios the development of the number of households through the construction activity, the renovation activity, temperature changes and the market saturation of room conditioning devices are considered. Possible future changes of further influencing factors are neglected.

We assume the future renovation rate to range between 1 % (continuation of past development) and 3 %, as agreed in the Integrated Energy and Climate Protection Program (IEKP) of the Federal Government of Germany from 2007 (FMTBUD, 2009). Scenarios for the future stock of buildings are based on the extrapolated living space demand and the three population forecasts. Increases in the projected temperature are assumed to range between 1 °C and 3 °C, which corresponds approximately to the emission scenarios

B1, A2 and A1FI, respectively. Temperature data based on the CCLM model correspond to a warming of around 1 °C. Thus, for comparability the high scenario for heating and the low scenario for cooling were calculated on the basis of both climate models. While full market saturation was presumed for heating systems, a lower saturation of 1 % (constant value according to Adnot et al. (2008)), 2.5 % (values estimated by Adnot et al. (2008) for 2030) and 13 % was assumed for cooling systems. The last value is based on the actual number of air conditioners in Italy (Adnot et al., 2008), whose climate is projected for Germany in the future by Kopf et al. (2008) based on heating and cooling degree days. The total heating and cooling energy demand of residential buildings in Germany was calculated for not yet renovated and one-time and second-time renovated residential buildings with the statistical software R (RDCT, 2013) according to Eqs. (3.3) and (3.8) respectively.

For the future trend of different energy sources in all heating systems we apply two existing scenarios for Germany: "business-as-usual" (low sustainability scenario in the original study) and "regionalisation" (high sustainability scenario) to the end energy demand of households in Germany by energy source until 2050 (Beer et al., 2009; Beer, 2011) (Figure 3.1). Both scenarios are based on projections. As the scenario expressing medium sustainability only slightly differs from the high sustainability scenario, we only applied the two extreme scenarios. We hold values constant for the period 2050 to 2060 and linearly interpolated missing values between the data given on a 5-year basis.

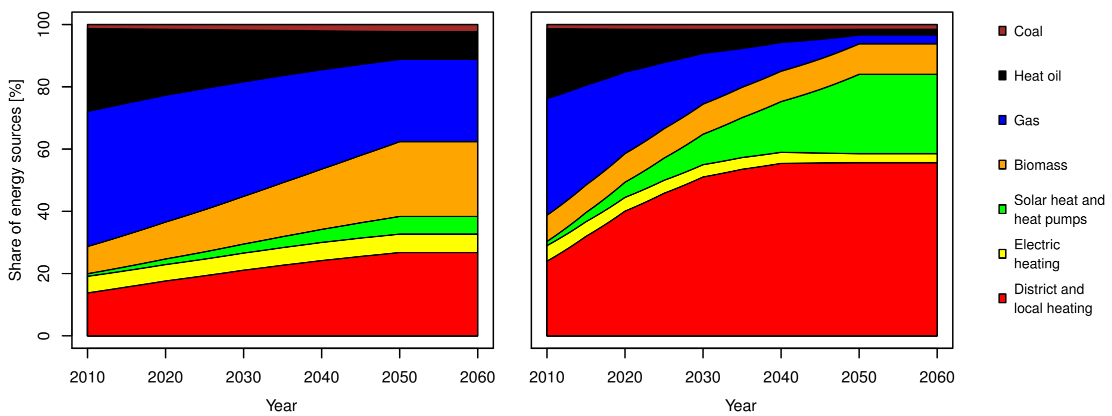

Figure 3.1: Share of energy sources used for heating of residential buildings in Germany according to scenario "business-as-usual" (left) and "regionalisation" (right) based on Beer et al. (2009).

3.2.6 Calculation of GHG emissions caused by heating

Multiplying the calculated annual end energy demand of German residential buildings per fuel by the specific CO_2 equivalent emission factor provides the amount of GHG emissions caused by different heating systems. We apply the CO_2 equivalent emission factors of Memmler et al. (2009) that are given in Table 3.2. Due to the great current uncertainty regarding the energy sources contributing to the future electricity mix, we restrict our analysis to the GHG emissions caused by heating.

3.2.7 Validation

For validation the calculated useful heating energy demand was compared with the heating energy consumption of German households for room conditioning in the period 1995 to 2008 (Figure 3.2). Our calculated theoretical heating energy demand exceeds the real

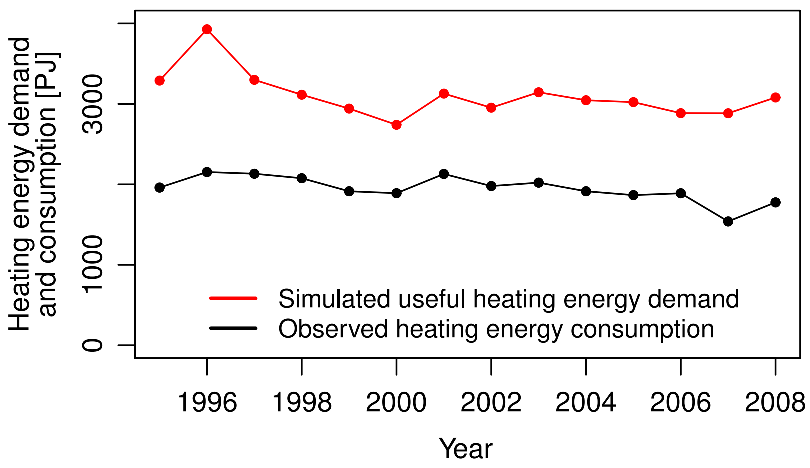

Figure 3.2: Comparison of calculated useful heating energy demand and observed heating energy consumption according to the Federal Statistical Office.

consumption. This is due to various factors, which have not been included in our simulations. First, increasing energy prices normally lead to a reduction in energy consumption. Since energy prices steadily increased in recent years (FMET, 2009), residents reduced their heating activity. Second, it is assumed that all residential buildings are occupied. However, in the past an average of 8 % of the dwellings in Germany were unoccupied (DESTATIS, 2010). Moreover, one million second residences and one million holiday flats are not constantly occupied (Kott & Behrends, 2009) and are therefore heated only part of the time. Yet this temporary occupation is not accounted for and it is assumed that room conditioning applies for the whole building volume. Third, the calculations do not allow for the specific characteristic of the urban building density and the related interaction between buildings and their environment, as the building typology only considers free-standing buildings. Yet in a city considerably less outer surfaces exist than denoted in the building typology due to adjacent buildings. It is therefore plausible that the real energy consumption is lower than the simulated demand, as 88 % of the German population lives in urban areas (OECD, 2007). Finally, in reality, not all rooms of a residential building are continuously heated to the same assumed indoor temperature. This leads to a lower annual heating energy consumption than that theoretically needed.

Bearing these factors in mind, it is plausible that the calculated energy demand exceeds the energy consumption. What is important is that the courses of the curves are quite similar. Due to a lack of data on the cooling energy consumption of German households in the past, it is not possible to validate the results concerning the useful cooling energy demand.

3.3 Results

3.3.1 Estimation of the useful energy demand

The heating energy demand displays a strong inter-annual variability. However, independent of the scenario, a clear downside trend of the heating energy demand is observable in the future with decreases of around 81 % (from 759 TWh to 143 TWh between 2010 and 2060) under the scenario "Low energy demand" and around 57 % (from 936 TWh to 400 TWh) under the scenario "High energy demand" (Figure 3.3). Calculations based on CCLM data yield a future decrease of the heating energy demand of 55 % from 843 TWh to 376 TWh in the high scenario.

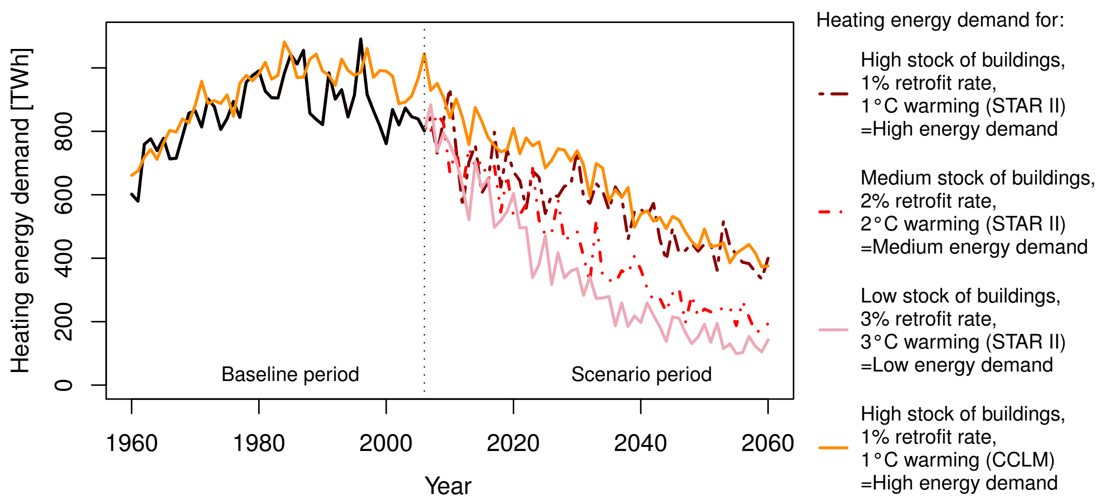

Figure 3.3: Heating energy demand of German households in the past and according to the four future scenarios, based on climate data of the models STAR II and CCLM and observed climate data (solid black).

The actual cooling energy demand strongly depends on the assumed share of residential buildings with air conditioners (Figure 3.4). Whereas the actual cooling energy demand slightly decreases from 0.07 TWh to 0.05 TWh in scenario "Low energy demand" between 2010 and 2060, it increases by 235 % from 0.26 TWh to 0.86 TWh in scenario "High energy demand" based on data from the climate model STAR II. All actual cooling energy demand curves converge in the mid 2030s as the share of households with air conditioners is assumed to stay constant from 2030 and beyond. Assuming that all households have air conditioners, the cooling energy demand roughly remains at the same level under the scenario “High energy demand” and decreases by 27 % (from 7.2 TWh to 5.3 TWh) under the scenario “Low energy demand” between 2010 and 2060. Calculations based on CCLM data yield a future decrease of the cooling energy demand of 23 % from 7.5 TWh to 5.8 TWh in the low scenario.

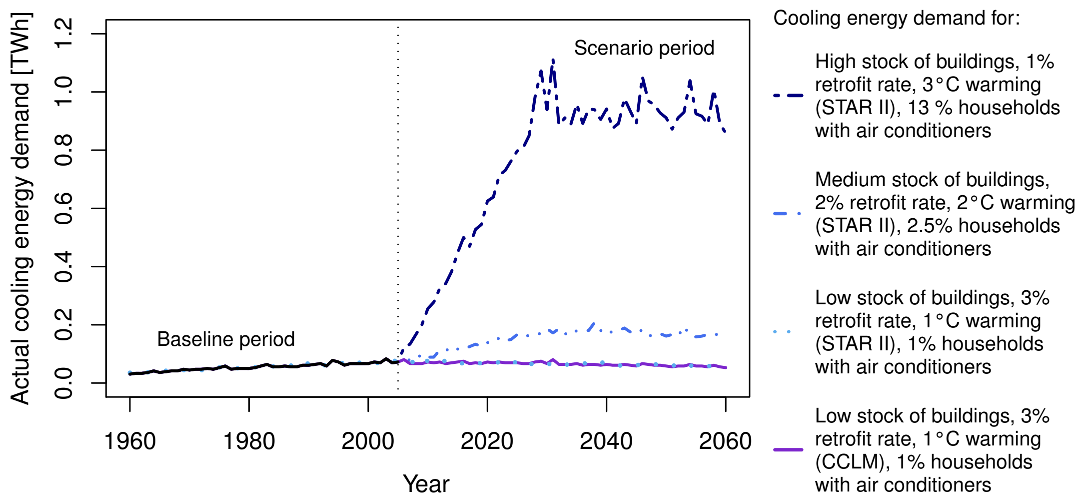

Figure 3.4: Actual cooling energy demand of German households in the past and according to the four future scenarios, based on climate data of the models STAR II and CCLM and observed climate data (solid black).

3.3.2 Influencing factors on the future useful energy demand

The effect of the considered factors on the useful energy demand is exemplarily shown by the medium scenario for the climate model STAR II (Figure 3.5). As the number of air conditioners cancels out the effect of all other factors it is presumed for this comparison that all residential buildings are provided with air conditioning systems.

In Figure 3.5a and b it is shown that the annual variability of the energy demand depends on the annual fluctuations of the degree days and thus the projected temperature. In order to quantify this relation, we calculate the Pearson correlation coefficient (PCC) between both records. Since the data is dominated by trends, we consider the year-to-year differences and accordingly quantify correlations in the annual variability. These derivatives lead to a correlation coefficient of 0.96 for heating and 0.64 for cooling. The initial increase in the heating energy demand until the end of the 1980s and the later decrease of both the heating and cooling energy demand cannot be explained by this factor alone. The fact that the heating energy demand decreases from the 1980s on despite an initially still increasing stock of residential buildings (Figure 3.5c) and that the PCC is only -0.54 reveals that the heating energy demand is superimposed by another factor, renovation. The cooling energy demand resembles the residential building stock (PCC: 0.92). However, between the beginning of the millennium and 2038 an initial increase and later decrease in the stock of buildings was accompanied by a rather constant development of the cooling energy demand (Figure 3.5d).

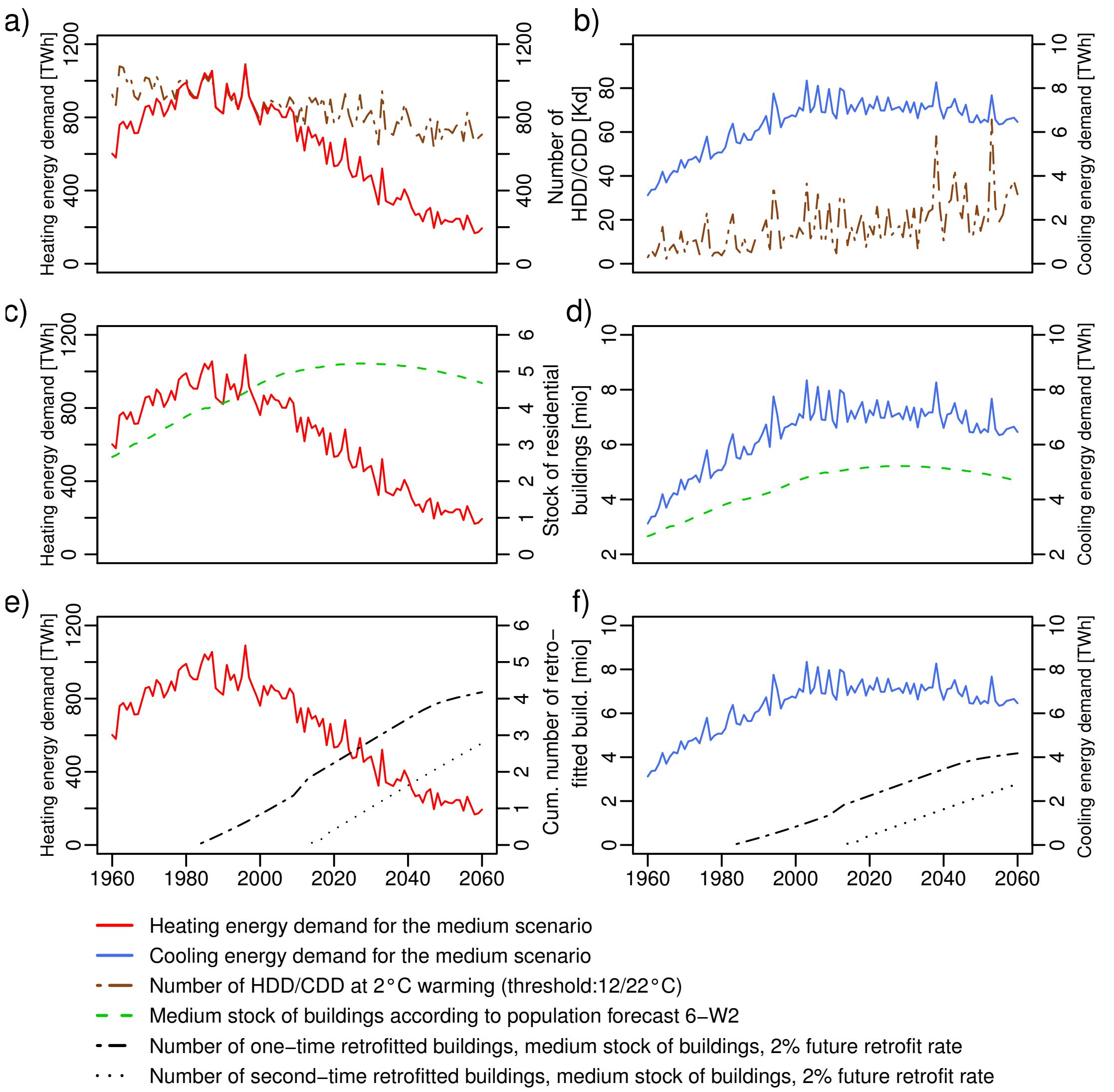

Figure 3.5: Relation between influencing factors and heating/cooling energy demand of German households, based on climate data of the model STAR II.

From 2010 the gradient of the curve of one-time renovated residential buildings doubles, as the renovation rate increases from 1 % to 2 %. However, from 2014 the quota is reduced to half the initial value as an equal apportionment of the renovation rate is assumed. From the middle of the 2040s the curve of one-time renovated residential buildings converges due to the limited number of renovatable buildings. Thus, the trend of the heating energy demand is mostly influenced by performed one-time renovation measures (PCC of -0.97 for 1984-2060) and to a lesser extent by second-time renovations (PCC of -0.9 for 2014-2060) (Figure 3.5e). This is due to the fact that the U-values only slightly differ between one-time and second-time improvements. Thus further renovation measures hardly influence the heating energy demand. Unlike with the development of the heating energy demand, there is no obvious relation between the beginning of renovation measures and changes in cooling energy demand (PCC of 0.2 for one-time renovations in the period 1984-2060 and -0.54 for second-time renovations in the period 2014-2060, Figure 3.5f). An increasing number of CDD (causing an increase in the cooling energy demand) interacts with more renovated buildings (causing a decrease in the cooling energy demand). Further, the development of the stock of residential buildings leads to an increase or decrease in the cooling energy demand - depending on the scenario and the period under consideration.

The effect of temperature increase, building stock, and renovation rate on the energy demand is further examined by varying specific factors while all other factors keeping constant (Figure 3.6). By this sensitivity analysis it can be shown that the development of the residential building stock has only a slight influence on the energy demand until the beginning of the 2020s, since the building stock changes start to differ clearly from each other only afterwards. Concerning a 1 °C warming and a renovation rate of 1 %, the strongest influence of the residential building stock on both heating and cooling energy demand becomes obvious. With regard to the heating energy demand this difference decreases under the projected increased warming and future renovation rate (Figure 3.6a). In contrast, changing other factors hardly reduces the strong influence of the building stock development on the future cooling energy demand (Figure 3.6b).

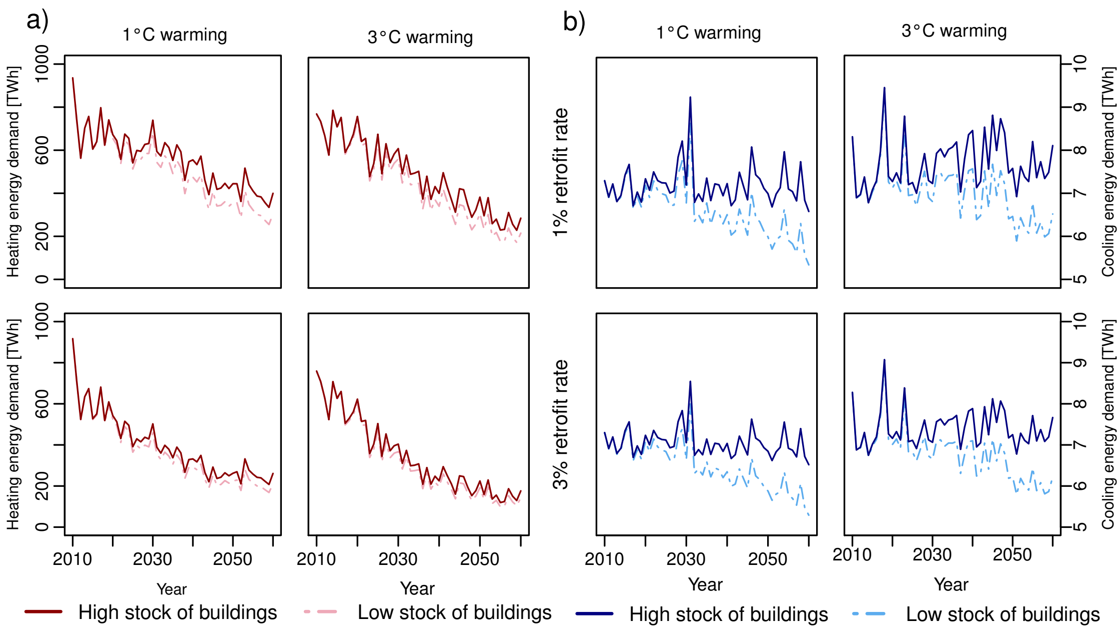

Figure 3.6: Sensitivity analysis of heating (left) and cooling (right) energy demand, based on climate data of the model STAR II.

Considering the same renovation rate and the same development of the stock of residential buildings, the heating energy demand is roughly 30 % lower and the cooling energy demand less than 10 % higher at the end of the considered period in the scenario given a warming of 3 °C than for 1 °C. Until the end of the examined period the same temperature and building stock development results in a heating energy demand 35 % lower and a cooling energy demand 5 % lower under a 3 % future renovation rate than under a renovation rate of 1 %. Thus, while the heating energy demand is strongly affected by performed renovation measures, the cooling energy demand is mainly influenced by the future stock of buildings.

For the same scenarios the future heating energy demand based on CCLM data is on average higher and the future cooling energy demand is lower than that projected based on STAR data, because the CCLM model projects colder conditions. Nevertheless, the findings regarding the effect of influencing factors on the future energy demand apply analogously for calculations based on CCLM data.

Table 3.4 summarises the percentage change in heating and cooling energy demand in the different scenarios for 1961-1990 compared to 2031-2060. Heating energy demand declines on average by 44 % in scenario "High energy demand" and by 78 % in scenario "Low energy demand" when comparing the period 1961-1990 with 2031-2060. Again, the strong effect of renovation measures becomes obvious. In the same period, the cooling energy demand will increase by 59 % in scenario "High energy demand" and increase by 25 % in scenario "Low energy demand".

Table 3.4: Percentage change in heating (left) and cooling (right) energy demand between 1961-1990 and 2031-2060 under different scenarios with regard to warming, renovation rate and building stock (high/low), based on climate data of the model STAR II.

	Heating			Cooling		
Percentage change in average energy demand	1 °C warming	2 °C warming	3 °C warming	1 °C warming	2 °C warming	3 °C warming
1 % future renovation rate	(-44/-53)	(-51/-59)	(-56/-64)	(46/28)	(53/33)	(59/39)
2 % future renovation rate	(-59/-65)	(-64/-70)	(-69/-74)	(43/26)	(49/30)	(53/34)
3 % future renovation rate	(-66/-72)	(-71/-75)	(-75/-78)	(42/25)	(47/29)	(51/32)

3.3.3 Estimation of GHG emissions

The future GHG emissions will significantly decrease in all scenarios. The range will be between 86 % (from 255 Mt CO_2 eq. to 35 Mt CO_2 eq.) in scenario "Low energy demand"/"regionalisation" and 66 % (from 319 Mt CO_2 eq. to 108 Mt CO_2 eq.) in the scenario "High energy demand"/"business-as-usual". The development of emissions is strongly influenced by the climate-related inter-annual variability. In order to examine the effect of different scenarios regarding the energy mix, we also combined the scenario "Low energy demand" with the energy source scenario "business-as-usual" and the scenario "High energy demand" with the energy source scenario "regionalisation" (Figure 3.7). It can be seen that the effect of changing energy sources is small compared to the effect of changing energy demand.

This is due to the fact that the energy mix is not expected to drastically change in the future with regard to emissions. Although there will be a shift to more district and local heating (with a higher annual utilisation rate but a CO_2 equivalent emission factor comparable to that of heating with oil), in both energy source scenarios, the share of renewables is expected to be still less than 40 %. Assuming a 100 % share of biomass in 2060, would reduce the emissions caused by heating of residential buildings to a low value of 2.5 Mt CO_2 eq. in scenario "Low energy demand" and 7 Mt CO_2 eq. in scenario "High energy demand". The corresponding values for an assumed share of 100 % solar heat and heat pumps would be 8.9 Mt CO_2 eq. and 25 Mt CO_2 eq., respectively.

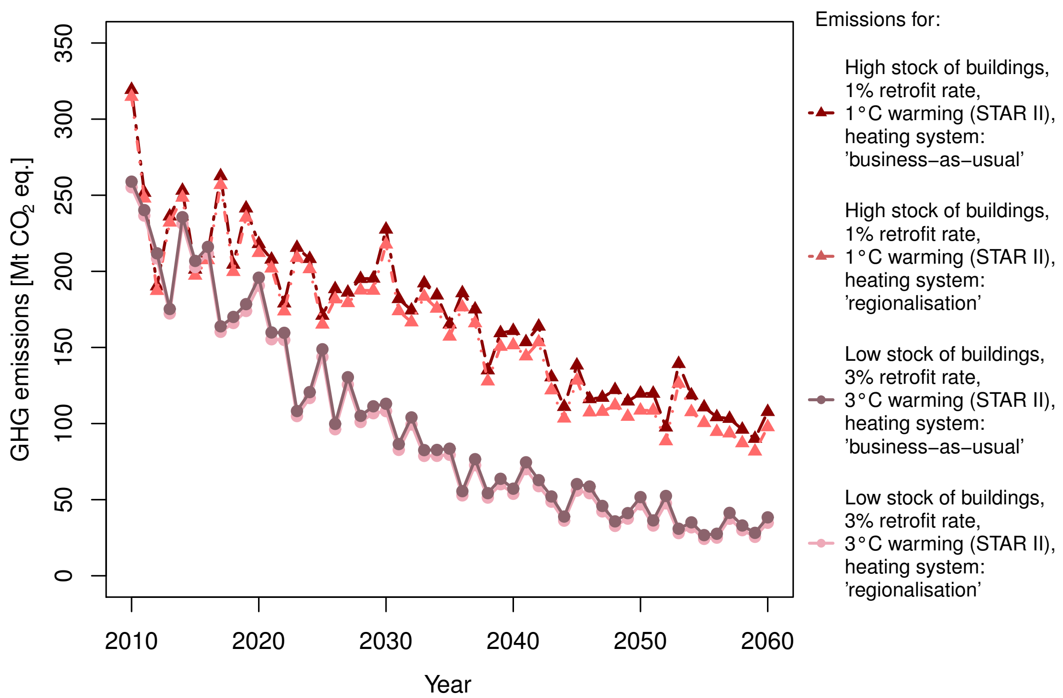

Figure 3.7: GHG emissions from heating of German households according to the future scenarios, based on climate data of the model STAR II. Results are based on projections.

3.4 Discussion

We calculated the future heating and cooling energy demand and resulting GHG emissions of households by means of different scenarios concerning warming, renovation, building activity, market penetration of room conditioning systems and energy sources used for heating. This is the first integrated approach to analyse the impact of these factors on the future energy demand and emissions of households for room conditioning in Germany. However, the results of this study agree with a number of international studies showing a reduction of the future heating energy demand and an increase in the future cooling energy demand. We find a reduction of the heating energy demand of 44-78 % when comparing 1961-1990 with 2031-2060, while Aguiar et al. (2002) determine a decline in the future heating energy demand of residential buildings in Portugal of 34-60 % when comparing the period 1958-99 with 2070-99. Although both studies examine a similar decrease, a comparison is only possible in a limited extent due to different considered time periods and geographical regions. Moreover, Aguiar et al. (2002) as well as Amato et al. (2005) and Christenson et al. (2006) assume fixed characteristics of the building stock in Portugal, the U.S. and Switzerland, while we take into account considerable future building stock changes. Prettenthaler and Gobiet (2008) study the influence of climate change on the energy demand for heating and cooling of buildings in Austria and find a climate-induced decrease of the average demand for heating of 20 % until 2050. The lower reduction than that we found for Germany is mainly due to the fact that the authors do not include building stock changes and renovation measures. However, they account for different heating systems on a highly regionalised level.

Examination of all the considered factors shows that renovation measures have the strongest influence on future heating energy demand of buildings. This underlines the role active policy making in this sector can play in regard to an ambitious climate protection policy. Independent of climate change, an increase in the annual renovation rate from 1 % to 3 % could lead to a heating energy demand decline for German households of between 14 % and 22 % (Table 3.4). For U.S. commercial buildings Scott et al. (1994) find an even stronger reduction potential of building efficiency improvements of 30-40 %. They also show that tripling of insulation would allow for a cooling energy demand reduction of 28-60 % but by examining only the effect of increased qualitative renovation. We try to show the influence of better insulation and increased renovation rates, which are increasingly a target of environmentally friendly policy making in the building sector.

Few studies determine the impact of insulation measures on the future energy demand of households in Germany. Kleemann et al. (2000) calculate a reduction potential of 70 % for insulating an un-renovated single-family building according to EnEV 2002 standards. Comparing the years 2000 and 2025, Buchert (2009) concludes that the heating energy demand of residential buildings in Germany will decrease by 8 % without renovation measures and by 35 % with insulation measures, considering future building stock changes but disregarding climate change. Loga et al. (2007) apply the same building typology as we did and find that an increase of the renovation rate to 2.5 % yields an annual reduction potential for energy of 1.7 % and for emissions of 3 %. For Germany we find a mean annual heating energy demand decrease of 0.35 % - 2.0 % and a mean reduction in emissions of 1.5 % - 2.0 % in the period 2010 to 2040. The Energy Concept of the Federal Government (FG, 2010) aims at reducing the heating energy demand of residential buildings by 20 % until 2020. Assuming the year of publication as the reference year, we find a heating energy demand decrease of 22-31 % between 2010 and 2020 depending on the scenario. Whereas this political aim seems within reach, our results for the emission reduction raise doubts about the feasibility of the Federal Government's plan (FG, 2010) to achieve an almost climate neutral residential building stock in Germany in 2050. Based on our scenarios, which include rather ambitious developments regarding the renovation rate, we calculated GHG emissions from heating of 61 to 139 Mt CO_2 eq. by 2050, representing reductions of 60-78 % compared to 2010.

While we neglect the influence of energy prices and income since we focus on energy demand, Eskeland and Mideksa (2009) conclude that the responsiveness of electricity consumption to changes in income is much greater than the effects of climate warming and energy prices in Europe. Doubling prices would only lead to a 20 % reduction in energy consumption. We found that the future development of the cooling energy demand strongly depends on the scenario considered. For the U.S., Scott et al. (2007) determine increases in residential cooling energy demand of 6-27 % between 2005 and 2050. Cartalis et al. (2001) examine an increase in cooling energy demand of 15-28 %. However, in contrast to these studies, we take into consideration changes in the number of air conditioners and come to the conclusion that such future increases will have a strong impact on the actual cooling energy demand. Assuming an increase in the share of households with air conditioners from 1-13 % we obtain a future increase of the actual cooling energy demand of more than 200 %. Aguiar et al. (2002) underline the profound impact of the number of air conditioners and estimated that the cooling energy demand increases in the Portuguese building stock by 130-525 % until the end of the century and if one-third of the residential floor area is air-conditioned 4.5 to 6 hours per day. Sailor and Pavlova (2003) also find that adoption of air conditioners as an adaptive response of households to temperature increase might have a much larger impact on energy consumption than warming itself.

In conclusion, existing studies on the future energy demand of German residential building only account for renovation measures and/ or building stock changes. None of these studies examine the combined influence of a projected temperature increase, renovation measures, and building stock changes on the future energy demand of households for room conditioning.

In our study we show how the future energy demand for room conditioning of residential buildings develops in Germany based on various influencing factors. However, there are some limitations:

The applied building typology of the German Institute for Building and Environment (IWU) is only an approximative representation of the German building stock. Moreover, buildings that are used for multiple purposes are classified as residential buildings if they account for more than 50 % of the used area. Especially in cities the share of residential buildings with shops on the ground floor can be large.

In reality there is no linear relationship between the number of degree days and the required energy to overcome a certain temperature difference (Scott et al., 1994). The use of constant threshold temperatures neglects possible differences in the diurnal variation in temperature as well as the fact that a heating system would not be turned on if the temperature falls below the threshold only one day. We presume that residential buildings are heated or cooled 24 hours to the same comfort temperature. However, indoor comfort temperatures vary between 6 °C and 30 °C (Shove, 2003) and are expected to change under changing climatic conditions (Chappells & Shove, 2005). We also assume that both the comfort sensation of residents and the heating and ventilation behaviour only depend on temperature and we thus disregard other factors such as the surface temperature of the components, humidity and different physical activity of people. The resident's possibility of exerting influence on the indoor comfort temperature affects the comfort. The more control they can exercise, the more comfortable the residents feel and the more they are willing to tolerate deviations from the indoor comfort temperature (Roberts, 2008).

We did not consider future changes in the efficiency rate of different heating systems. There is a trend from "constant-temperature" and "low-temperature" boilers to "condensing" boilers both for oil and gas but useful quantitative data are not available.
Our methodology could be applied to a more regional resolution, i. e. in terms of the local characteristics of climate and building stocks depending on data availability.

3.5 Conclusion

As there is a lack of information on the development of the future heating and cooling energy demand of German households under a changing climate, insulation improvements and population changes, we introduced a modelling approach allowing for the assessment of the combined effect of projected temperature increases, renovation measures and building stock changes. This was a considerable extension of currently existing approaches for Germany. Our analysis allows for cross-checking of policy goals in Germany. As a further benefit the approach could be transferred to other countries.

We showed that a strong future decrease in the heating energy demand of the German residential building stock will be accompanied by an increase in the cooling energy demand. The latter is strongly dependent on the assumed future share of households with air conditioners. Our results indicate significant consequences for energy production and supply systems especially since heating and cooling are provided by different energy sources. We therefore expect a strong future shift of energy demand from primary energy towards electricity.

It was clearly shown that the future heating energy demand is mainly influenced by performed renovation measures which underlines the importance of renovation for reducing the energy demand. Political action regarding the support of renovation measures represents a win-win-strategy regarding climate mitigation and energy saving. For example, the minimisation of cooling requirements can be encouraged by further building regulations and sustainable urban planning. Without drastic changes in the energy mix, a reduction of GHG emissions caused by heating of residential buildings can mainly be achieved by reducing the demand for energy. We feel that our approach can pave the road towards to deeper insights into the internal dynamics of the building sector in regard to its climate relevance.

4

Feasibility of energy reduction targets under climate change [*]

Abstract

In order to achieve meaningful climate protection targets at the global scale, each country is called to set national energy policies aimed at reducing energy consumption and carbon emissions. By calculating the monthly heating energy demand of dwellings in the Netherlands, our case study country, we contrast the results with the corresponding aspired national targets. Considering different future population scenarios, renovation measures and temperature variations, we show that a near zero energy demand in 2050 could only be reached with very ambitious renovation measures. While the goal of reducing the energy demand of the building sector by 50% until 2030 compared to 1990 seems feasible for most provinces and months in the minimum scenario, it is impossible in our scenario with more pessimistic yet still realistic assumptions regarding future developments. Compared to the current value, the annual renovation rate per province would need to be at least doubled in order to reach the 2030 target independent of reasonable climatic and population changes in the future. Our findings also underline the importance of policy measures as the annual renovation rate is a key influencing factor regarding the reduction of the heating energy demand in dwellings.

[*]This chapter has been published as: Olonscheck M., Walther C., Lüdeke, M., Kropp, J. P. (2015): Feasibility of energy reduction targets under climate change: The case of the residential heating energy sector of the Netherlands. Energy, 90, 560-569.

4.1 Introduction

In order to meet global climate targets, the building sector needs to reduce energy consumption by 60 % worldwide by 2050 (World Business Council for Sustainable Development, 2009). However, to increase the chances of successful and far-reaching measures on a national level, reliable estimates regarding the future energy demand are required. We take the Netherlands as a case study and assess the nation's ability to achieve given national heating energy saving targets. The Netherlands are a small country with 17 mio. inhabitants but belong to the 25 countries worldwide with the largest CO_2 emissions. Thus, the country can make a considerable contribution to climate mitigation. Furthermore, the Netherlands could be representative for regions such as Belgium, Great-Britain, Luxembourg and huge parts of France that have the same maritime temperate climate (Köppen, 1923) and similar population projections for the future (The World Bank, 2011).

To avoid adding one more example to the large number of published assessments in this field, we went through the literature, categorized existing studies and chose on this basis an appropriate approach for our case study. Publications considering the impact of climate change and other future changes on the energy demand of buildings are shown in Table 4.1 which is partly based on Li et al. (2012) and Yang et al. (2014) who reviewed existing papers regarding the impacts of climate change on energy use in the housing sector.

Concerning the modeling approach, we find statistical models (S) which relate heating energy consumption with driving forces like temperature on the basis of observed, historical data. Here the difficulty lies in the correct statistical distinction between the weather influence and the other independent variables (insulation etc.) due to the restriction to historical data which may not contain all relevant combinations of these variables. This can cause problems for the application of the statistical model in the scenario calculations. In contrast, mechanistic approaches rely on the representation of the physical processes of heat transfer which are all well known. The achievable level of detail in these models depends on the availability of detailed building properties. Therefore, these detailed models (MD) are applied mainly in small scale studies (see Table 4.1). The application on more aggregated mechanistic models of intermediate complexity (MI) might be advantageous in data sparse situations compared to MD-models where unknown parameters are simply fixed to a roughly estimated value. The spatial scale of the considered studies is typically either global (G), national (N), or regional/local (L) and related to the model type as mentioned above. Most studies calculate the energy demand annually (a) which may induce complications in case of the presence of non-linear relationships between weather variables and heat flows - here a monthly temporal scale (m) would be more appropriate. The studies vary widely in the consideration of relevant influencing factors and their trends, including climatic changes, thermal renovation measures, and population changes. Table 4.1 shows that only a few studies consider all factors simultaneously. Regarding the building sector, most studies deal with the residential (R) or the commercial (C) sector, few with both. Some studies consider a comprehensive stock of buildings, while others only use a limited number of prototype buildings and their respective distribution over the whole housing stock leading to a more coarse grained representation of the relevant parameters.

For our case study country, a statistical model is not possible as sufficiently long-term historical time series are not available to determine and discriminate the influence of the different driving factors. Therefore, a mechanistic approach is needed. The available Dutch housing typology covers the whole country and comprises 18 dwelling types by year of construction, size, and insulation standard of the main dwelling components. It does not allow for an application of a data demanding model (MD) that normally requires parameters like the exact location of windows and doors to model the energy demand of a specific building. However, using the heat flux components as defined in the national building standards for the modeling of the monthly heating energy demand of dwellings together with regional population and climate data, the available housing typology allows for the establishment of an intermediate complexity model (MI) with a monthly (m) and local/regional (L) resolution for the residential sector.

Table 4.1: List of papers that deal with the impact of climate change on the future energy demand or consumption of buildings. We give an overview over the modeling approach they use, which scale they analyse and which future influencing variables they consider. S=Statistical models, MD=Data demanding models, MI=Intermediate complexity models, R=Residential, C=Commercial, a=Annual, m=Monthly, G=Global, N=National, L= Regional/ Local, Compreh.=Comprehensive.

Paper	Modeling approach	Sector	Temporal scale	Spatial scale	Climatic changes	Renovation measures	Population changes	Compreh. stock
Aguiar et al. (2002)	MD	R+C	m	N+L	x	-	-	-
Jenkins et al. (2008)	MD	C	a	L	x	-	-	-
Zmeureanu and Renaud (2008)	S	R	a	L	x	-	-	-
Lam et al. (2010)	MD	C	a	L	x	-	-	-
Dolinar et al. (2010)	MD	R	a	L	x	-	-	-
Wan et al. (2011b)	MD	C	a	L	x	-	-	-
Wang et al. (2010)	MD	R	a	L	x	x	-	-
Scott et al. (1994)	MD	C	a	L	x	x	-	-
Gaterell and McEvoy (2005)	MD	R	a	L	x	x	-	-
Wan et al. (2011a)	MD	C	a	L	x	x	-	-
Chow and Levermore (2010)	MI	C	a	L	x	-	-	x
Collins et al. (2010)	MD	R	a	L	x	-	-	x
Isaac and van Vuuren (2009)	MI	R	a	G+N	x	-	x	-
Frank (2005)	MD	R+C	a	L	x	x	-	-
Zhou et al. (2013)	MI	R+C	a	N	x	-	x	x
Belzer et al. (1996)	S	C	a	N+L	x	x	x	x
Olonscheck et al. (2011)	MI	R	a	N	x	x	x	x
Yu et al. (2014)	MI	R+C	a	N+L	x	x	x	x
This study	MI	R	m	N+L	x	x	x	x

By using the monthly resolution, we consider possible non-linear effects which would be masked by an annual time resolution. The data situation enables us to consider temperature projections, population trends, and future renovation measures on a regional level. Our study simulates for the first time the combined effect of these factors on the monthly space heating energy demand of the housing stock of each Dutch province.

Belzer et al. (1996) and Yu et al. (2014) who did similarly comprehensive studies (Table 4.1), only analyze the heating energy demand on an annual level. There are some studies for the Netherlands that deal with energy use in the building stock which are discussed in Section 4.4. Only one of these Dutch studies took future changes in climate and the housing stock into consideration. We limit the analysis to the calculation of the useful heating energy demand which is defined as the energy that a heating system must theoretically supply to a building. This useful heating energy demand does not say anything about how efficient this demand is supplied. Moroever, as cooling has only a share of 6 % in the energy consumption of the Netherlands at the moment, we focus on the calculation of the future heating energy demand.

National targets of the Dutch government aim to achieve an energy neutral building stock in 2050 (SER, 2013) which is somewhat more ambitious than the EU target of 80 % reduction in energy consumption of buildings by that same year (Klinckenberg et al., 2013). By 2030, the energy consumption of the Dutch building sector should be reduced by half when compared to 1990 (VROM, 2009). For two reasonable future scenarios, we calculate whether it is possible to decrease the heating energy demand of the Dutch housing stock to these two aspired levels and give recommendations regarding the required annual renovation rate per province in order to achieve these goals. Furthermore, we are able to determine which influencing factor - population development, temperature changes or annual renovation rate - has the strongest effect on the future heating energy demand which might be policy relevant.

In Section 4.2, we introduce the used housing stock data and the method to determine its quantitative (number of dwellings) and qualitative (renovation measures) change over time. Moreover, we present the equations used to calculate the heating energy demand of dwellings. The results are described in Section 4.3. The discussion in Section 4.4 is followed by a conclusion and an outlook in Section 4.5.

4.2 Data and methods

The Netherlands are characterized by some differences regarding the share of different dwelling types per province, the future population development on a regional level and the projected change of the outdoor temperature (Table 4.2, Table 8.13 and Table 8.14 in the appendix). While this future temperature is varied per province and per month, the mean amount of energy of incoming sun rays [in W/m^2] was assumed to be constant over time. There are about 7.2 million dwellings in the Netherlands of which roughly 26 % are situated in freestanding and semi-detached houses and about 40 % in row houses (CBS, 2013).

For the analysis we used data from the Dutch Building Typology 'Exemplary apartments 2011' of Agentschap NL, which is part of the Ministry of Economy, Agriculture and Innovation (AgentschapNL, 2011). The insulation standard of the main dwelling components is expressed by heat transmission values (U-values). These change in the case of a renovation. Past data on population, housing stock and the number of new and demolished dwellings on national and province level were derived from Federal Statistical Office data (CBS, 2013).

Table 4.2: Population and projected population changes between 1991-2000 and 2051-2060 according to the forecast and the lower and upper 95 % forecast interval in the different provinces as well as share of dwellings in freestanding buildings in the total number of dwellings in 2012 (CBS, 2013) and projected temperature changes between 1991-2000 and 2031-2040 resp. 2051-2060 according to the RCP scenarios 8.5 and 2.6 (Van Vuuren et al., 2011).

	Population in mio. in 2012	Population changes btw. 1991-2000 and 2051-2060 in % according to			Share of dwellings in free-standing buildings in %	Projected annual mean temperature changes in K compared to 1991-2000			
		the lower 95% forecast interval	the population forecast	the upper 95% forecast interval		2031-2040 (RCP8.5)	2051-2060 (RCP8.5)	2031-2040 (RCP2.6)	2051-2060 (RCP2.6)
Groningen	0.58	-2.30	4.21	11.57	24.4	1.41	2.12	0.88	0.94
Friesland	0.65	0.68	7.38	14.97	31.7	1.38	2.06	0.85	0.92
Drenthe	0.49	-3.24	3.20	10.49	29.7	1.40	2.11	0.87	0.92
Overijssel	1.14	5.16	12.17	20.09	19.6	1.36	2.09	0.86	0.93
Flevoland	0.40	72.55	84.05	97.05	8.9	1.34	2.04	0.84	0.92
Gelderland	2.02	1.94	8.73	16.41	18.7	1.33	2.10	0.88	0.95
Utrecht	1.25	22.00	30.12	39.31	6.9	1.31	2.07	0.88	0.94
Noord-Holland	2.72	12.96	20.48	29.00	8.1	1.33	2.01	0.84	0.91
Zuid-Holland	3.56	9.10	16.37	24.59	5.3	1.28	2.02	0.86	0.89
Zeeland	0.38	-5.09	1.23	8.39	23.4	1.22	2.01	0.86	0.89
Noord-Brabant	2.47	5.64	12.67	20.63	17.9	1.29	2.08	0.91	0.95
Limburg	1.12	-12.78	-6.97	-0.40	19.5	1.29	2.13	0.96	0.99
The Netherlands	16.8	-4.10	14.19	36.27	14.1	1.33	2.07	0.87	0.93

4.2.1 Calculation of the heating energy demand

Motivated by the available data and building regulations we decided to use a MI. The monthly heating energy demand Q_h of each dwelling is calculated with the statistical software R (RDCT, 2013) on the basis of the Dutch NEN standard 7120:2011 if not stated differently, given equation (4.1). It considers heat losses via transmission and ventilation and heat gains from internal heat sources and the sun multiplied by an utilisation factor. Figure 4.1 provides an overview on the main heat fluxes.

The most important equations are described below. The full details can be found in the appendix.

$$Q_h = (Q_{H,ht} - \eta_{H,gn} \cdot Q_{H,gn}) \text{ [MJ/month]} \tag{4.1}$$

where
$Q_{H,ht}$ = Total heat losses [MJ],
$\eta_{H,gn}$ = Utilisation factor for heat gains [-],
$Q_{H,gn}$ = Total heat gains [MJ].

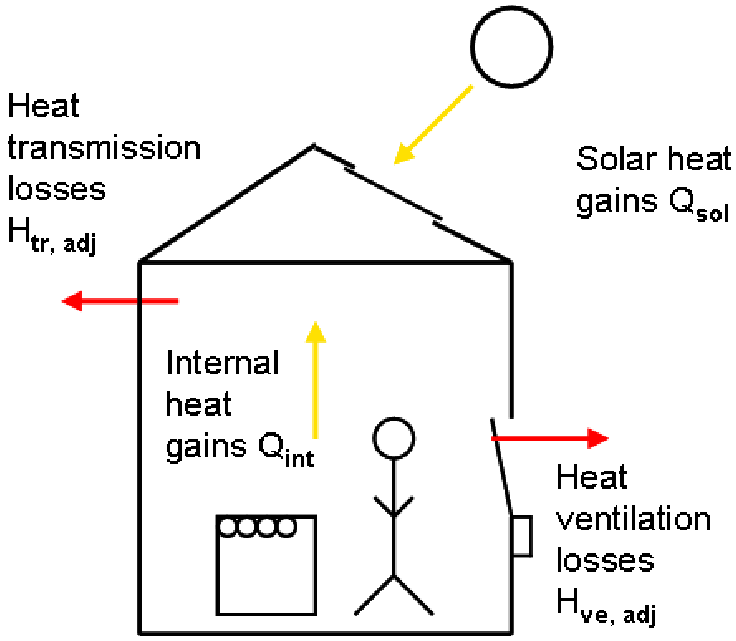

Figure 4.1: Heat fluxes that determine the heat balance of a building.

4.2.1.1 Calculation of heat losses

Total heat losses of a dwelling are affected by changing outdoor temperatures and vary in the course of the year due to the different length of months. We calculated them according to equation (4.2).

Total heat losses $Q_{H,ht}$ were calculated by:

$$Q_{H,ht} = (H_{tr,adj} + H_{ve,adj}) \cdot f_{int,set,H,adj} \cdot a_{H,red,night} \cdot (\theta_{int,set,H} - \theta_e) \cdot t \tag{4.2}$$

where

$H_{tr,adj}$ = Heat transfer coefficient for transmission [W/K],

$H_{ve,adj}$ = Heat transfer coefficient for ventilation [W/K],

$f_{int,set,H,adj}$ = Correction factor for levelling the temperature in a dwelling [-] (for details see appendix),

$a_{H,red,night}$ = Reduction factor for night setback of the temperature [-] (for details see appendix),

$\theta_{int,set,H}$ = Indoor temperature = 20 [°C],

θ_e = Outdoor temperature [°C],

t = Value for the length of the considered month = 2.6784 in every second month starting with January; 2.5920 in every second month starting with April; 2.4192 in February [Ms].

The heat transfer coefficient for transmission $H_{tr,adj}$ was calculated over the dwelling components i (roof, wall, basement, windows) by equation (4.3). It is mainly dependent on the surface and the U-value of a component and differs per dwelling type.

$$H_{tr,adj} = \sum_{i=1}^{4} (A_{T,i} \cdot (U_i + \Delta U_{for,i})) \tag{4.3}$$

where

$A_{T,i}$ = Surface of the considered component [m^2],

U_i = Heat transition coefficient [U-value] of a dwelling component [$W/m^2 \cdot K$],

$\Delta_{U_{for,i}}$ = Value for the consideration of thermal bridges = $-0.15 \cdot (U_i - 0.4)$ [$W/m^2 \cdot K$].

The heat transfer coefficient for ventilation $H_{ve,adj}$ was calculated by:

$$H_{ve,adj} = \frac{\rho_a \cdot c_a}{1000} \cdot q_{ve,mn} \tag{4.4}$$

where

ρ_a = Density of air = 1.205 [kg/m^3],

c_a = Specific heat capacity of air = 1008 [$J/kg \cdot K$],

$q_{ve,mn}$ = Time and temperature weighted air volume supply and return flow [dm^3/s] (for details see appendix).

Due to a lack of information, we assumed a mean specific internal heat capacity of 'traditional, mixed heavy' and 'mixed light' dwelling types. $q_{ve,mn}$ mainly considers the air volume flow resulting from the ventilation system. It differs per dwelling type. The detailed calculation can be found in the appendix.

4.2.1.2 Calculation of heat gains

Total heat gains within one month are approximated by equation (4.5). They consist of internal heat gains which are represented via a constant factor dependent on the base area and solar heat gains that differ e. g. per size of the component i.

Total heat gains $Q_{H,gn}$ were calculated by:

$$Q_{H,gn} = Q_{int} + Q_{sol} \tag{4.5}$$

where

Q_{int} = Internal heat gains [MJ],

Q_{sol} = Solar heat gains [MJ].

Internal heat gains Q_{int} were calculated by:

$$Q_{int} = (230 + 1.8A_g) \cdot t \tag{4.6}$$

Solar heat gains Q_{sol} were calculated by:

$$Q_{sol} = \sum_{k=1}^{4} (\phi_{sol,k} \cdot t) \tag{4.7}$$

where

$\phi_{sol,k}$ = Heat flow caused by incoming sun rays [W] (for details see appendix).

The utilisation factor for heat gains $\eta_{H,gn}$ depends on the heat balance ratio γ_H between total heat gains $Q_{H,gn}$ and losses $Q_{H,ht}$ as well as on a numerical parameter a_H that is up to the inertia of the building.
As:

$$\gamma_H \neq 1 \; and \; \gamma_H > 0: \qquad \eta_{H,gn} = \frac{1 - \gamma_H^{a_H}}{1 - \gamma_H^{a_H+1}} \tag{4.8}$$

where

a_H = Numerical parameter depending on the time constant $= 1 + \frac{\tau_H}{15}$.

Based on these equations we calculated the total heating energy demand of dwellings in the Netherlands and its provinces for not yet renovated and renovated dwellings.

4.2.2 Projection of the future number of dwellings

For determining the future annual housing stock on the national level, we applied the population forecast as well as the 95 % forecast intervals given by the Federal Statistical Office (CBS, 2013) since these represent a reasonable large range of possibilities (until 2060: nationwide population increase to 21.5 mio., 17.7 mio. or decrease to 14.6 mio. from a value of 16.8 mio. in 2012). Population forecasts on a regional level were only available for the period 2013-2040. For the missing years until 2060 population data for the provinces are assumed to be proportional to these population forecasts on the national level in such a way that a certain percentage increase or decrease on the national level between two years is also assumed for each province. For the period 2013-2060 the number of dwellings both on the national and regional level was assumed to be proportional to the population numbers.

Each year a certain number of new dwellings is added to the existing stock of dwellings. We extrapolated the trend of the available data for the number of new dwellings on the national and local level from 1988-2012 and it was determined that a logarithmic extrapolation fitted best. New dwellings were assigned to different dwelling types according to their past shares meaning that we assumed the percentage proportion between e. g. new freestanding and new row houses to remain the same in the future. The total number of demolished dwellings was derived by subtracting the number of new dwellings from the total stock in a respective year. Due to a lack of information, we presumed that only dwellings aged 50 years or older in the considered year are at disposal for demolishing (Frank, 2005; Sartori & Hestnes, 2007; Thormark, 2002; Wan et al., 2011a).

4.2.3 Projection of the future energetic standard of dwellings

The renovation standard of a building was assumed to improve over time. We presumed that in each considered year only those dwellings that are 50 years or older and that are not yet demolished are substantially renovated. This means that the roof, wall, basement and windows are improved. The applied renovation rate per year is 1 % which equals the current annual rate (Buildings Performance Institute of Europe, 2011; Rademaekers et al., 2012) and 3 % which we see as a reasonable, but challenging desirable value. For future new dwellings we used U-values given in the Dutch regulation 'Bouwbesluit' (Rijksoverheid, 2012) and assume a tightening to passive house standards from 2021 on, as required by the European Union (Directive 2010/31/EU of the European parliament and of the council). Regarding energetic improvements of dwellings, we considered those U-values for different dwelling components given in the typology from 2011 onwards and those required in Germany since 2010 (EnEV 2009) starting from 2021 as they are even stricter than those required in the typology (Table 4.3). Thus, if a building is renovated from 2021 onwards, the energetic standard is better than that for dwellings renovated between 2011 and 2020 but worse than that for new dwellings from 2021 onwards.

Table 4.3: U-values [in $W/(m^2K)$] according to regulations for renovation of as well as new dwellings over time by component.

Dwelling component	U-values new dwellings from 2011 on (Bouwbesluit 2012)	U-values new dwellings from 2021 on (EU Directive)	U-values renovated dwellings from 2011 on (typology)	U-values renovated dwellings from 2021 on (German EnEV 2009)
Roof	0.286	0.1	0.36	0.24
Wall	0.286	0.15	0.36	0.24
Basement	0.286	0.12	0.36	0.3
Window	1.1	0.8	1.8	1.3

Under the assumption that all required U-values in the ordinances valid at the respective time are followed, the extent of energetic improvement of dwellings was determined.

4.2.4 Projection of temperatures

We applied data on the mean monthly temperature from the World Climate Research Program Coordinated Regional Downscaling Experiment (EURO-CORDEX) (Giorgi et al., 2009). We selected the downscaling Rossby Centre Regional Atmospheric Model (RCA4) and the global driving model ICHEC-EC-EARTH as this combination allowed us to use results of the two extreme future Representative Concentration Pathways (RCPs) (Moss et al., 2010; Van Vuuren et al., 2011) with a radiative forcing of 2.6 W/m^2 and

8.5 W/m^2 in the year 2100. The climate data has a spatial resolution of about 12.5km. We made use of the delta approach, that means we calculated the temperature differences between 1991 and 2000 and each considered future decade in the projections of the regional climate model. These delta values have then been added to the empirical baseline, which was taken from the gridded observational E-OBS data (resolution 0.22°) provided by the European Climate Assessment & Data (ECA&D) (Haylock et al., 2008). Both data sets have been aggregated to the province level of the Netherlands.

4.2.5 Considered scenarios for the heating energy demand

We combined the population forecasts and assumptions regarding the annual renovation rate into a maximum scenario with a high population, a low renovation rate of only 1 % and outdoor air temperatures according to RCP2.6 (which causes the future heating energy demand to be high) as well as a minimum scenario with a low population, a high renovation rate of 3 % and a temperature according to RCP climate scenario 8.5 (that leads to a comparatively low heating energy demand). For the majority of months, the RCP climate scenario 8.5 projects higher average temperature values for future time periods compared to RCP2.6 but not for all. However, for reason of consistency, we used the RCP8.5 scenario for the minimum and the RCP2.6 for the maximum scenario.

4.3 Results

After a reproduction of the historical heating energy demand, we display per province the simulated future reductions in the heating energy demand as well as the corresponding absolute values for the period 2051-2060. We also show whether the national energy reduction target for 2030 is achievable. Moreover, we calculate how high the annual renovation rates would need to be per province in order to reach this goal. With a sensitivity analysis, we determine the impact of the considered influencing factors on the future heating energy demand.

4.3.1 Reproduction of the historical heating energy demand

We compare the calculated monthly heating energy demand summed over a year with the annual heating energy consumption of Dutch households for room conditioning (Source: Marijke Menkveld, ENC, Personal communication: 17.11.2014) for the period 1995-2012 (Figure 4.2). This past heating energy demand was calculated with the same R script that we used for calculating the future heating energy demand using the building typology, annual data on the total number of dwellings as well as annual data of the outdoor temperature.

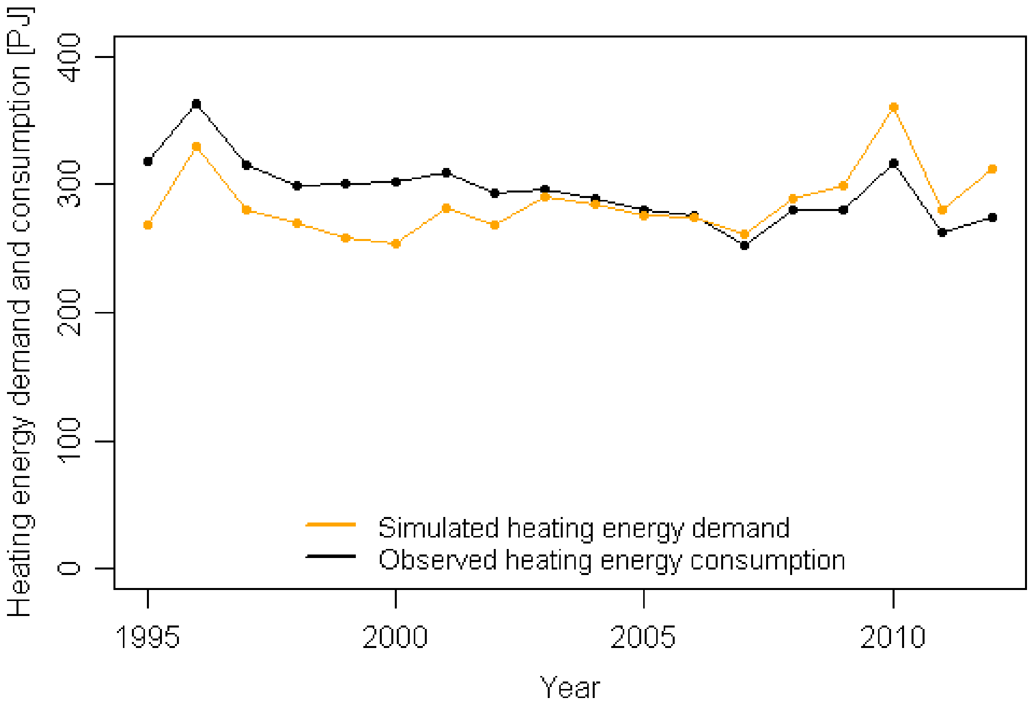

Figure 4.2: Calculated heating energy demand and observed heating energy consumption according to the Dutch Statistical Office (CBS, 2013).

The lower simulated heating energy demand in the first few years can be explained by not having accounted for changes in the renovation status of dwellings before 2012 due to a lack of corresponding information. The building typology provides data on the present state of dwellings in the Netherlands. A backwards calculation of the renovation status and thus a consideration of past renovation measures would have caused the graph of the calculated energy demand to start at a higher point in 1995, as a higher number of dwellings with an inferior energetically standard at that time actually caused more energy consumption than dwellings with an average energetic standard of the 2011 stock.

The deviation between the graphs may be caused by different factors that have not been considered in our calculations:

- Rising energy prices over the considered time period could have caused a decrease in energy consumption over time that we were not able to consider,
- empty dwellings, second residences, and holiday flats that are not constantly inhabited and thus heated may cause the heating energy demand to be lower in reality than what we calculated,
- the specific characteristic of the urban building density can also cause our values to deviate from the observed consumption as we assumed that all dwellings are in buildings that are located in a model surrounding unaffected by other houses, vegetation etc.

Despite the differences, there is a good correlation between the two graphs. Colder years like 1996 and 2010 were characterized by both a higher simulated heating energy demand (orange graph) and a higher observed heating energy consumption (black graph), while warmer years such as 2007 and 2011 had both a lower heating energy demand and consumption.

4.3.2 Estimation of the future energy demand

Based on the assumptions regarding the U-values in Table 4.3, a reduction of the total annual heating energy demand of Dutch dwellings to nearly zero by 2050 is not possible (Figure 4.3). Even increasing the annual renovation rate to more than 3 %, which is very ambitious, would only marginally further reduce the heating energy demand in the middle of the century.

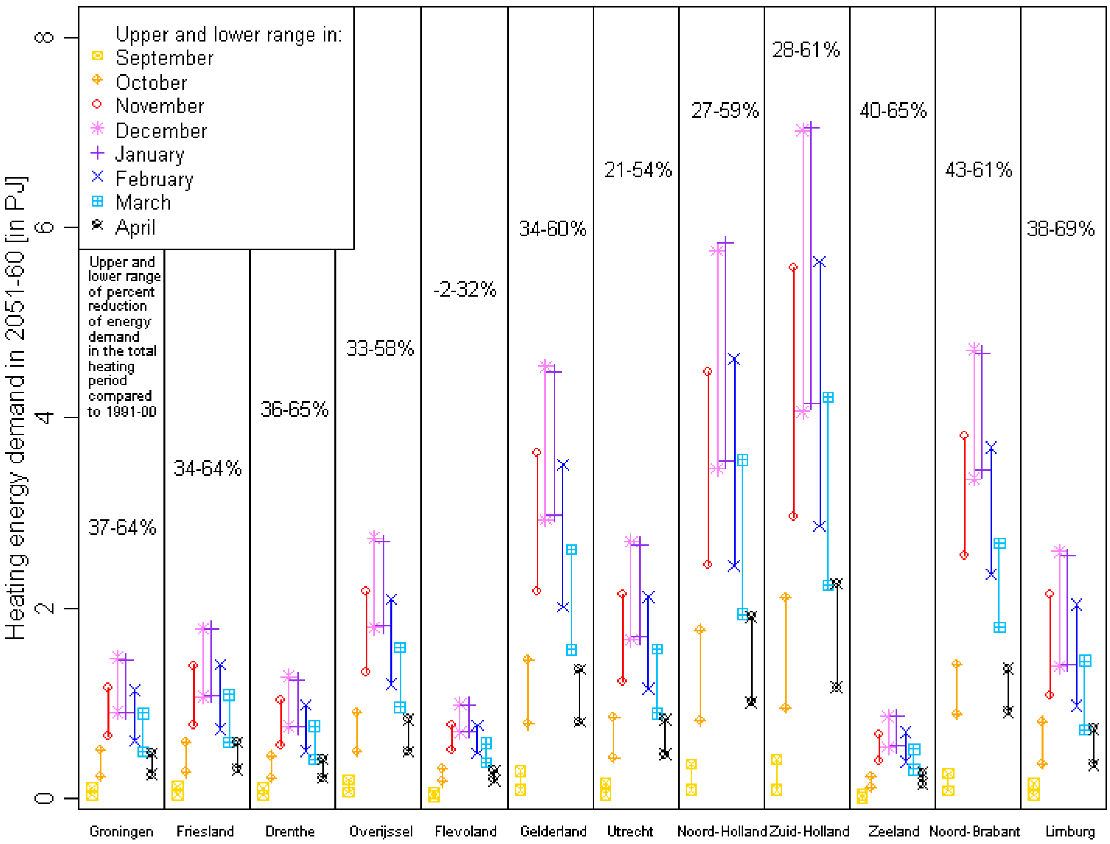

Figure 4.3: Heating energy demand in 2051-2060 for the different provinces and heating months. Note: The upper dot for each province shows the value for the maximum scenario with a high population, a 1 % renovation rate per year and a low temperature increase. Lower dot: Low population, 3 % renovation rate, and high temperature increase. Additionally, we displayed the upper and lower range of the percent reduction of the energy demand in the total heating period compared to 1991-2000.

This is because the renovation standard for dwellings from 2021 onwards is still too poor for a sufficient reduction in the energy demand (as a large number of low-energy houses still demand a large amount of heating energy). However, with some extra effort, especially those provinces with a current low heating energy demand are able to approach the ‘near zero’ mark. These include Zeeland and Flevoland especially, but also Drenthe, Groningen, and Friesland. Due to the already very low heating energy demand in September, it seems possible to achieve the 2050 target in this month in all provinces. Thus, in the future, very little heating will be necessary in the Dutch provinces in September.

In Figure 4.3, we additionally display the upper and lower range of the percentage reduction of the heating energy demand in the total heating period when comparing 2051-2060 with the baseline period 1991-2000. The largest decreases are found for Limburg, Drenthe, and Zeeland with more than 64 % in the minimum scenario. Provinces such as Utrecht, Noord-Holland, and Zuid-Holland are able to reduce their heating energy demand only by less than 30 % in the maximum scenario in the considered period.

For reason of completeness, we also show the results for Flevoland (increase of 2 % to decrease of 32 % in the maximum and minimum scenario) for this part of the analysis as it shows that the province is less important for our analysis as the heating energy demand will anyhow be very low by the middle of the century (3 % of the national heating energy demand in 2051-2060 in the maximum scenario). While for all the other provinces, our assumption regarding a comparable age distribution seems to be valid, there are few old dwellings in Flevoland as it was mainly created by land reclamation in 1986, meaning that our calculated value for 2050 is too high.

As the goal for 2050 (‘near zero’) is quite fuzzy and for the above mentioned reasons not achievable, we take a closer look at the target for 2030 (Table 4.4). We compare the period 1991-2000 (representative baseline for 1990) with 2031-2040 (representative for the 2030 reduction target). In both scenarios, the largest future reductions can be expected in September.

Table 4.4: Heating energy demand reductions in the maximum (left) and minimum (right) scenario for the different provinces when comparing 2031-2040 with the period 1991-2000. Note: The provinces with the lowest reduction per month are marked in red, those with the highest in green. Results for Flevoland are not shown in this table.

	Max. scenario: High popul.,1% renovation/yr, RCP2.6								Min. scenario: Low popul., 3% renovation/yr, RCP8.5							
	J	F	M	A	S	O	N	D	J	F	M	A	S	O	N	D
Groningen	-16	-34	-26	-25	-61	-37	-21	-17	-56	-66	-57	-60	-82	-67	-53	-52
Friesland	-13	-31	-24	-22	-60	-36	-18	-14	-54	-64	-55	-59	-82	-67	-52	-51
Drenthe	-15	-34	-25	-24	-61	-36	-19	-16	-55	-66	-56	-59	-82	-66	-52	-52
Overijssel	-9	-30	-19	-19	-62	-33	-13	-10	-50	-62	-51	-55	-81	-64	-47	-47
Gelderland	-12	-30	-21	-22	-66	-36	-15	-12	-52	-63	-53	-57	-83	-65	-49	-49
Utrecht	4	-17	-8	-7	-61	-25	0	4	-44	-57	-45	-50	-80	-59	-40	-41
Noord-Holland	-4	-23	-16	-15	-62	-32	-10	-5	-49	-60	-51	-55	-83	-64	-47	-46
Zuid-Holland	-7	-25	-17	-16	-66	-33	-9	-6	-51	-61	-52	-56	-84	-65	-47	-48
Zeeland	-21	-34	-29	-27	-74	-43	-22	-19	-57	-65	-57	-62	-86	-70	-54	-54
Noord-Brabant	-10	-27	-19	-18	-66	-33	-11	-9	-51	-62	-52	-56	-83	-64	-48	-49
Limburg	-22	-37	-29	-28	-70	-42	-21	-20	-59	-67	-59	-62	-86	-69	-54	-56
The Netherlands	4	-17	-7	-6	-57	-23	1	1	-55	-65	-56	-60	-84	-68	-52	-53

When comparing the summed heating energy demand between the baseline and 2031-2040 over the eight heating months, in the maximum scenario ('lowest heating energy demand reductions'), the highest reductions will occur in Limburg and Zeeland (-28 %) and Drenthe (-24 %). However, in none of these provinces, the goal of reducing the energy demand by 50 % by 2030 will be reached (Table 4.4). Utrecht will only be able to decrease its heating energy demand by 7 %. The decrease calculated for the whole country will be around 6 %.

In our minimum scenario ('strongest heating energy demand reductions'), the energy demand reductions will be more than 50 % in most provinces and month (Table 4.4, right). Overijssel, Gelderland, Utrecht, Noord-Holland, Zuid-Holland and Noord-Brabant miss the goal in several months. On the national level, the governmental target of reducing the energy demand by at least half would be achievable.

4.3.3 Determination of the necessary annual renovation rates

The required annual renovation rates to reduce the energy demand by half until 2030 can be seen in Figure 4.4 for each province in the maximum scenario.

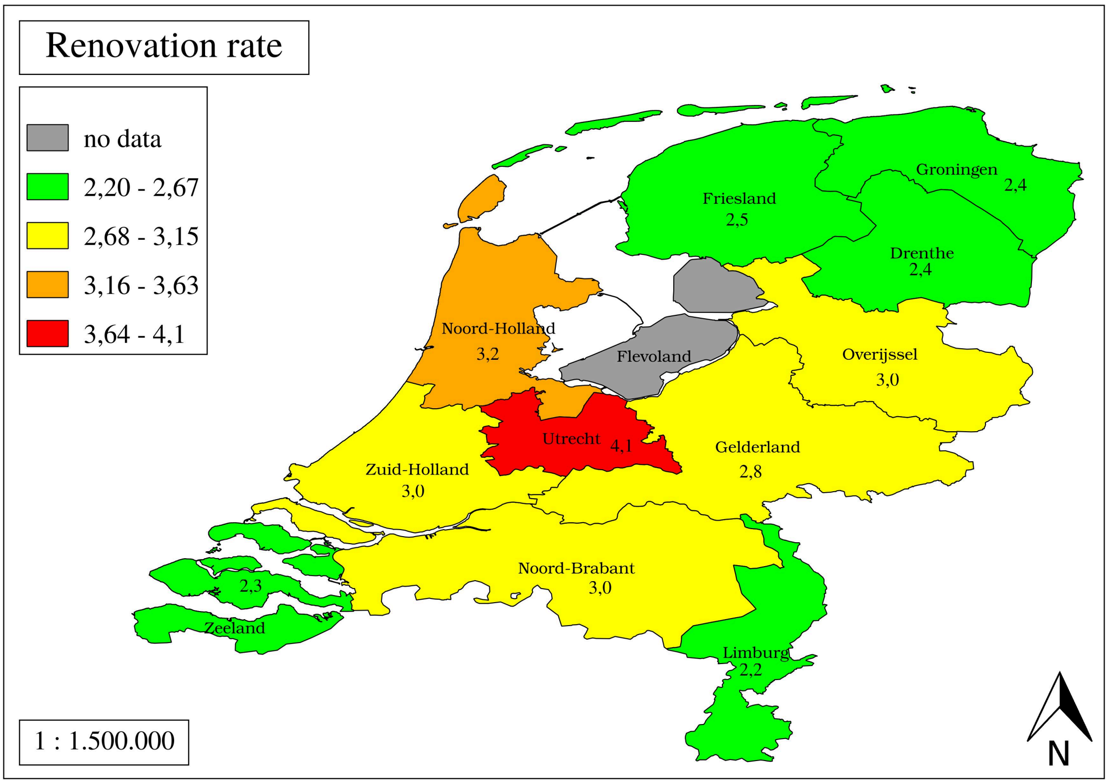

Figure 4.4: Necessary annual renovation rates per province to reduce the energy demand by half given the maximum scenario when comparing the time periods 1991-2000 and 2031-2040. Results for Flevoland are not shown in this map.

The provinces with a high projection for the 2051-2060 population such as Utrecht and Noord-Holland have the highest required renovation rates of 4.1 % and 3.2 % while those with a projected relatively strong population decrease in the national population forecast up to the middle of the century such as Limburg, Zeeland, Drenthe and Groningen have lower rates of 2.2 % to 2.4 %. In general, the values regarding the necessary renovation rate per province may be a bit higher in reality due to the fact that the cooling energy demand is expected to rise in the future and the national reduction targets are meant for both heating and cooling energy use.

4.3.4 Most important influencing factors on the future energy demand

Based on a sensitivity analysis, we determine which of the three influencing factors future population development, projected temperature changes and renovation rates has the largest impact on the future heating energy demand of the housing stock. Per province we vary specific influencing factors while keeping the others constant (Table 4.5). In addition to our extreme scenarios, we consider a scenario with no renovation and one with 2 % renovation per year.

Table 4.5: Sensitivity analysis for the heating energy demand [in PJ] of the different provinces (except Flevoland) in 2051-2060 (average over the heating months). The values show the future heating energy demand for cases where all factors are held constant while one is varied each time, e. g. the climate scenario. Note: The first value in each field shows the result for a high population, the second that for a low population.

Groningen Q_h [PJ]	Climate scenario		Friesland Q_h [PJ]	Climate scenario		Drenthe Q_h [PJ]	Climate scenario	
Annual renovation rate	RCP2.6	RCP8.5	Annual renovation rate	RCP2.6	RCP8.5	Annual renovation rate	RCP2.6	RCP8.5
0%	1.4/1.2	1.2/1.0	0%	1.7/1.4	1.5/1.3	0%	1.2/1.0	1.0/0.9
1%	0.9/0.7	0.8/0.6	1%	1.1/0.9	1.0/0.8	1%	0.8/0.6	0.7/0.6
2%	0.7/0.6	0.6/0.5	2%	0.9/0.7	0.8/0.7	2%	0.6/0.5	0.6/0.5
3%	0.7/0.6	0.6/0.5	3%	0.8/0.7	0.7/0.6	3%	0.6/0.5	0.5/0.4
Overijssel Q_h [PJ]	Climate scenario		Gelderland Q_h [PJ]	Climate scenario		Utrecht Q_h [PJ]	Climate scenario	
Annual renovation rate	RCP2.6	RCP8.5	Annual renovation rate	RCP2.6	RCP8.5	Annual renovation rate	RCP2.6	RCP8.5
0%	2.5/2.1	2.2/1.9	0%	4.1/3.5	3.6/3.1	0%	2.4/2.1	2.1/1.8
1%	1.7/1.4	1.4/1.2	1%	2.7/2.3	2.4/2.0	1%	1.6/1.3	1.4/1.2
2%	1.4/1.2	1.2/1.1	2%	2.3/2.0	2.0/1.7	2%	1.3/1.2	1.2/1.0
3%	1.3/1.2	1.1/1.0	3%	2.1/1.9	1.8/1.7	3%	1.2/1.1	1.1/0.9
Noord-Holland Q_h [PJ]	Climate scenario		Zuid-Holland Q_h [PJ]	Climate scenario		Zeeland Q_h [PJ]	Climate scenario	
Annual renovation rate	RCP2.6	RCP8.5	Annual renovation rate	RCP2.6	RCP8.5	Annual renovation rate	RCP2.6	RCP8.5
0%	5.2/4.5	4.6/4.0	0%	6.3/5.4	5.6/4.8	0%	0.8/0.7	0.7/0.6
1%	3.5/2.9	3.1/2.5	1%	4.3/3.5	3.7/3.0	1%	0.5/0.4	0.5/0.4
2%	2.8/2.4	2.9/2.1	2%	3.3/2.9	2.9/2.5	2%	0.4/0.4	0.4/0.3
3%	2.6/2.2	2.3/2.0	3%	3.0/2.6	2.7/2.3	3%	0.4/0.3	0.3/0.3
Noord-Brabant Q_h [PJ]	Climate scenario		Limburg Q_h [PJ]	Climate scenario				
Annual renovation rate	RCP2.6	RCP8.5	Annual renovation rate	RCP2.6	RCP8.5			
0%	5.2/4.5	4.6/3.9	0%	2.3/2.0	2.0/1.8			
1%	3.5/2.8	3.1/2.5	1%	1.6/1.3	1.4/1.4			
2%	2.7/2.4	2.4/2.1	2%	1.1/1.0	1.0/0.9			
3%	2.5/2.2	2.2/1.9	3%	1.0/0.9	0.9/0.8			

Considering the same renovation rate and the same development of the stock of dwellings (which is strongly dependent on the forecasted population), there are clear differences in the heating energy demand in 2051-2060 between the two considered climate scenarios (at least 10 % difference). In Groningen, for climate scenario RCP2.6 and a 3 % annual renovation rate, the difference between a high and a low future population is e. g. 0.1 PJ in 2051-2060 (0.7 PJ or 0.6 PJ). Exceptions are Friesland, Drenthe, Overijssel, Utrecht, Noord-Holland, Zeeland and Limburg where a lower decrease in the heating energy demand occurs for some scenarios if climate scenario RCP8.5 is considered instead of RCP2.6. In five provinces however, RCP8.5 even shows more than 15 % reductions compared to RCP2.6 for some scenarios.

The number of dwellings also affects the heating energy demand in the period 2051-2060. For almost all scenarios, a low stock of dwellings causes a heating energy demand reduction of more than 10 % compared to a high stock (exceptions with lower reductions in some scenarios can be found for Drenthe, Overijssel, Gelderland, Utrecht, Zeeland, and Limburg). In some scenarios for the provinces Groningen, Friesland, Drenthe, Noord-Brabant, Noord-Holland, and Zeeland, the reduction is even more than 20 %. In Noord-Brabant, for climate scenario RCP2.6 and a renovation rate of 1 %, the heating energy demand is 3.5 PJ for a high population or 2.8 PJ for a low population in 2051-2060.
A large impact can be also seen for an increase of the renovation rate per year to 2 %, which describes a policy option as the current level is about 1 %. This would reduce the heating energy demand in Groningen, Friesland, Drenthe, Gelderland, Zuid-Holland, Noord-Brabant and Limburg by at least 13 %.

Although a 1 % renovation rate and a low population may lead to a similar heating energy demand in 2051-2060 as a 2 % annual renovation rate and a high population for some provinces, striving for a 2 % renovation rate per year is desirable as future changes in the population are difficult to influence. Table 4.5 also clearly shows that the current rate of about 1 % renovation per year causes the heating energy demand in 2051-2060 to be at least 30 % lower in each province (except Zeeland and Limburg) than in the scenarios with no renovation.

4.4 Discussion

Considering future changes in population and temperature, we calculate the heating energy demand of Dutch dwellings up to the middle of the century and determine the annual renovation rates that are necessary in order to reach national targets for this sector. We find that renovation activities have the strongest impact but projected building stock and temperature changes also significantly influence the future heating energy demand.
We approach this topic on both the national and regional as well as an annual and

a monthly scale and find reductions in the heating energy demand of 21-43 % in the maximum scenario and 54-69 % in the minimum scenario (neglecting Flevoland) when comparing 2051-2060 with the period 1991-2000. As far as we know, there is just one study on the energy demand of dwellings in the Netherlands that considers future climatic changes. For three example residential buildings, van der Spoel and van den Ham (2012) studied the pure impact of future temperature changes on the heating and cooling energy demand. As they neglect future renovation measures, they found lower future heating energy demand reductions of 11 %-27 % between 1990 and 2050 and stronger cooling energy demand increases of 43 %-200 %, but from a much lower level compared to the heating energy demand. Other authors analyzed the energy use in the Dutch building sector without taking future climatic changes into consideration. Tambach et al. (2010) examined policy instruments for energy savings in the existing building stock and Noailly and Batrakova (2010) explored the effect of public policies on technological innovations in the housing sector. Both the study of Taleghani et al. (2013) and our study underline that the energy demand of a building is not only depending on its size, but also the energetic standard which is normally correlated to the year of construction.

Our study is aimed at determining the feasibility of national targets regarding energy demand reductions in the building sector. Majcen et al. (2013) found that the theoretical energy demand which is the basis for the efficiency label of a building does not correspond with the actual energy use. While energy-efficient dwellings consume more than predicted, those with a low energy label consume less. This implies that improving a building from a bad to a good energetic standard reduces the energy consumption less than expected which may result in a failure of achieving reduction targets. The difference between the energy demand and the energy consumption that was found by Majcen et al. (2013) is mainly due to social factors such as the heating behaviour of inhabitants. Although, the energy consumption is influenced by these individual aspects, the energy use in Dutch dwellings is strongly influenced by building characteristics. Guerra Santin et al. (2009) showed that the latter have a ten times larger influence on the energy use than the behavior of the occupants. This is in line with our findings regarding the relevance of energetic improvements in the building sector. We show that every Dutch province needs at least to double its annual renovation rate in order to reach the national target of reducing the energy demand of dwellings by half. Overijssel, Noord-Holland, Zuid-Holland, and Noord-Brabant have to triple and Utrecht even has to quadruple this rate to meet the target.

A comparison with Table 4.1 shows that our study allows for a comprehensive analysis of the future heating energy demand of residential buildings under climate change. Less than half of the listed publications consider more than one of these factors: comprehensive stock of buildings, population changes, or future renovation measures. Moreover, only one of the listed publications presents future results for the energy use on a monthly basis and none provides recommendations regarding the amount of necessary renovation measures in order to reach national targets. Our study fills this gap and thus forms a sound and reliable basis of argumentation for decision makers.

Comparing our results regarding the heating energy demand development and sensitivity of the Dutch residential building sector with that of studies for other countries is difficult due to differences in the modeling approaches, the considered scenarios as well as future changes in population and climate. However, reductions that are similar to ours have been calculated by Aguiar et al. (2002) who discovered heating energy demand decreases of 34-60 % for residential buildings in Portugal between 1961-1990 and 2070-2099 and Frank (2005) who calculated reductions of 33-44 % for Switzerland in 2050-2100 compared to the same reference period. Taking different energy efficiency measures such as wall or roof insulation into account, Gaterell and McEvoy (2005) calculated heating energy demand reductions in UK houses of 9-39 % in the low emission scenario up to 2050 and 17-53 % in the high emission scenario, which is also close to our results. The aforementioned publications are all based on very detailed and data demanding models (MD), but do not consider population changes or a comprehensive stock of buildings. Strong reductions in warmer regions that are similar to our results should not be misinterpreted. On the one hand, the authors often only analyse example buildings instead of a comprehensive building stock or do not consider future population changes (Table 4.1), on the other hand, heating often only plays a minor role in the considered countries such as in Hong Kong (Lam et al., 2010) and Australia (Wang et al., 2010). Chow and Levermore (2010) conducted a study for different office buildings in three cities in the UK up to the 2080s and underlined that the focus should be on renovating existing houses as the rate of new buildings per year is too low for a sufficient reduction in energy demand for room conditioning. The large importance of renovation measures was also shown in our study and that of Olonscheck et al. (2011) who also used simplified, intermediate complexity models (MI).

We used an U-value of 0.286 for roof, wall and basement as we consider the values for new buildings from 2011 onwards and neglect another tightening of the U-values to 0.222 between 2011 and 2021. Such a consideration would have made the calculation effort very large. However, in order to check, whether using an U-value of 0.222 instead of 0.286 has a significant impact on the result, we calculated the heating energy demand using an U-value of 0.222 for all new dwellings erected between 2011 and 2021 (when the better U-values are anyhow assumed). The difference to our original result was in all scenarios and for all provinces neglectable (less than 1 %).

Some aspects had to be neglected in our study. We assume a constant desired indoor temperature although in reality not all dwellings are heated uniformly to this temperature as physical characteristics, personal attitudes, and lifestyles also play a role regarding how much and how strongly people warm their dwellings. As Chappells and Shove (2005) point to the fact that the comfort zone of people could extend in the future due to familiarization with greater variety which may reduce the energy demand for heating and cooling. Moreover, a dwelling typology is only a simplified representation of the Dutch building stock. Especially, passive houses and plus energy houses that will gain in importance in the future were not considered due to a lack of adequate trend data. While Frank (2005) found that the heating season will be 53 days shorter, we do not study changes in the length of the heating period but only look at changes in the amount of heating energy that is required per month. However, we could show that by the middle of the century, heating will play a small role for Dutch residential buildings in September.

Hekkenberg et al. (2009a) found an increasingly positive trend in the electricity demand for the summer months which could be an indication for future summer electricity demand peaks in the Netherlands. Thus, although we do not focus on the future developments in the cooling energy demand as it does not play a significant role in most middle European countries at the moment (Collins et al., 2010; Olonscheck et al., 2011), it is important to keep in mind that this may change in the coming decades due to more frequent and longer lasting heat waves. Klein et al. (2013) already showed that the electricity sector of the Netherlands is quite susceptible to climatic changes which is partly caused by the projected rise in the share of air conditioners. However, as our method is based on monthly values regarding the future energy demand, the threshold for cooling of 24 °C will not be exceeded until 2060. Thus, for future studies, it would be necessary to focus on daily outdoor temperature values in order to be able to adequately consider times with a cooling energy demand. A follow-up study aims to calculate future cooling energy demand changes of the housing stock in the Netherlands in order to find out whether the country as a whole and its provinces are going to benefit from projected temperature increases or not. For the present study, such an analysis would exceed the scope substantially.

4.5 Conclusion and outlook

Retrofitting buildings is a win-win option as it not only helps to mitigate climate change and to lower the dependency on fossil fuels, but it also converts the building stock into one that is better equipped for extreme temperatures that may occur more frequently with climate change. Whether such a transformation to a low energy demand of the stock of residential buildings is possible, mainly depends on future climatic and demographic changes as well as renovation activities. Our method allows for the consideration of these factors and provides data on the past heating energy demand that correlate quite well with the observed heating energy consumption. Thus, the method is likely also suitable for computing the future heating energy demand of residential buildings. We show that renovation measures have a strong impact on the future heating energy demand. In the majority of provinces a doubling of the current annual rate of 1 % would lead to at least 13 % less heating energy demand at the middle of the century. However, both the future dwelling stock and the projected temperatures also play a crucial role, but are difficult to influence locally. The presented information on the required annual renovation rates per province which range from 2.2 % to 4.1 % is robust and supports policy makers in taking the necessary steps on a regional level. Our approach constitutes an important step towards a better understanding of the relation between future temperature changes and the heating energy demand of the residential building sector. Given appropriate input data, the method can be applied for other spatial and temporal scales - something which is left for future work.

5
Discussion

Chapters 2 to 4 of this thesis dealt with the impact of climate change on the energy sector. The first objective was to find out how climate change will affect the electricity sector susceptibility of European countries. Despite the huge importance of such a ranking for political decision makers and energy suppliers who are responsible for guaranteeing energy security, comprehensive analyses on these aspects have been missing. This was probably due to the extensive effort to collect the required data related to the European electricity sector.

The second objective of this thesis was to determine the future residential energy demand for room conditioning under climate change in two of these European countries, namely: Germany and the Netherlands. Although such analyses have a very high political relevance as retrofitting buildings is seen as an effective measure to reduce a country's energy demand and to meet given energy and climate targets, corresponding studies have been largely missing so far. One reason could be that there have been no building typologies for most countries until recently. Another reason might be the huge effort to assemble the mathematical equations from different industrial standards in such a way that a consideration of different future changes was possible.

5.1 Discussion of the overall research questions

In the following sections, the four overall research questions are addressed by summarizing and discussing the main findings from the Chapters 2 to 4. An overview regarding the discussion of the overall research questions RQ1 and RQ2, targeting the first objective, and RQ3 and RQ4, targeting the second objective of this thesis is provided in Figure 5.1 and 5.2, respectively.

5.1.1 Research Question 1 (RQ1): Does the geographical location of a country allow conclusions on its electricity sector susceptibility to climate change and how sensitive is a ranking of countries to the choice of influencing factors?

Climate change affects the energy sector. The degree of impact depends on different factors and differs from one country to another. There was a need for an index that considers the electricity sector susceptibility of different countries to climate change. This has been developed in Chapter 2. First, relevant influencing factors have been identified for which suitable data was available for the 21 European countries studied. A correlation analysis was applied to discover and eliminate redundant factors (Section 2.2.2 and Table 2.1). Ultimately, it was possible to generate a final relative susceptibility index based on 14 influencing factors (Figure 2.1).

5.1.1.1 Correlation between location and electricity sector susceptibility

The analysis in Chapter 2 reveals that in Europe there is no correlation between the location of a country in a geographic coordinate system and its final ranking position in the electricity sector susceptibility index (Figure 2.7). Thus, a general conclusion that the electricity sector of countries in Southern Europe is more susceptible than that of Northern countries is not possible. While Greece and Portugal are situated in the same climatic region (Köppen, 1923), their position in the susceptibility ranking is very different. The same holds true for the neighboring countries Slovakia and Czech Republic, which is particularly surprising as the two countries were united until 1992. Our analysis underlines the fact that there are country-specific characteristics, which need to be considered when studying the electricity sector susceptibility of European countries.

5.1.1.2 Sensitivity of the ranking to the choice of influencing factors

In order to determine the influencing factors with the largest impact on the final result, sensitivity analyses have been conducted. This was done with regard to the ranking of countries according to their electricity sector susceptibility (Chapter 2) and to find the most relevant factors for the future energy demand for space conditioning of residential buildings in Germany (Chapter 3) and the Netherlands (Chapter 4). The final electricity sector susceptibility ranking is most sensitive to the projected temperature increase in summer (factor 4.2) and the current share of electricity production in thermoelectric power plants (factor 3.1) (Section 2.3.3). Omitting one of these factors has the strongest impact on the final ranking. In contrast, excluding the factors representing the slope between mean temperature and production and consumption respectively on the cooling side (factors 1.3 and 1.4) has little affect on the final ranking. This low sensitivity is due to the fact that only five countries reach the cooling threshold (see Section 2.4.1.3 for details).

Would the omission of one factor lead to a clearer North-South or East-West pattern with regard to the electricity sector susceptibility of the European countries? Having a closer look at the sensitivity analysis, this has to be negated (Figure 8.9 in the appendix). Finland, Sweden and Norway hardly change their ranking position if an influencing factor is omitted. Finland and Norway will always be at least 10 ranks away from each other. The same is true for Portugal and Greece which display a difference of more than 14 ranks – regardless which influencing factor is neglected. Luxembourg would always be the country with the highest susceptibility independent of the influencing factor omitted.

Nevertheless, the exclusion of the Summer Production and Consumption Correlation factor (2.1) would shift the ranking position of Slovakia a considerable six places which would make the country far less susceptible. This reflects the extremely poor correlation between electricity production and consumption in the country before 2004 (Figure 8.8 in the appendix). A similar picture emerges for Denmark, albeit in the other direction. The omission of the Winter Production and Consumption Discrepancy factor (2.4) would substantially increase the susceptibility of the country by five positions. One reason for the quite low susceptibility of Denmark is the large surplus of electricity production in winter. The majority of this electricity comes from wind turbines (Roselund & Bernhardt, 2015).

5.1.2 Research Question 2 (RQ2): Which influencing factors explain the ranking positions of the most and least susceptible countries?

The analysis in Chapter 2 ranks countries based on the susceptibility of their electricity sectors to climate change for the first time and enables the identification of the main influencing factors for a low or high susceptibility. This is the basis for developing adequate measures to reduce the susceptibility of a country's electricity sector to climate change. For the four most and least susceptible countries, an overview of their position in the ranking of 21 countries is provided for each of the 14 considered influencing factors (Table 5.1). For each influencing factor where a most (least) susceptible country occupies one of the last (top) three ranks, the ranking position is marked in red.

5.1.2.1 Factors for the poor rank of the four most susceptible countries

We identified that Luxembourg, Greece, Slovakia and Italy are the countries with the highest electricity sector susceptibility to climate change (Table 2.2 and Figure 2.7). This is in accordance with existing studies (Gnansounou, 2008; Scheepers et al., 2007; Sovacool & Brown, 2009). One reason for the poor ranking positions of Luxembourg and Italy in the analysis in Chapter 2 was the fact that the countries display a large discrepancy between electricity production and consumption both in summer and winter (Figure 2.3, left). They are therefore very dependent on electricity imports. Luxembourg also ranks high with regard to its vulnerability of imported oil products (Jewell, 2011). Both Luxembourg and Italy are very susceptible because monthly electricity consumption and mean temperature are unrelated below the heating threshold. Thus, rising future temperatures will reduce heating electricity consumption only slightly. Greece and Italy are highly susceptible because electricity consumption rises strongly with mean temperature above the cooling threshold (Figure 2.2, left) – more strongly than in other countries considered in this thesis.

Table 5.1: Susceptibility ranking position regarding each of the 21 influencing factors for the four countries that perform best and the four that perform poorest. Those factors that mainly explain the electricity sector susceptibility of the eight countries are marked in red. 1=lowest susceptibility, 21=highest susceptibility. Note: Due to missing air conditioner data for Norway and Switzerland, there are only 19 ranking positions for the influencing factors 5.1 and 5.2.

Influencing factor	1.1 Heating: Production & Mean temperature slope	1.2 Heating: Consumption & Mean temperature slope	1.3 Cooling: Production & Mean temperature slope	1.4 Cooling: Consumption & Mean temperature slope	2.1 Summer: Production & Consumption Correlation	2.2 Winter: Production & Consumption Correlation	2.3 Summer: Production & Consumption Discrepancy	2.4 Winter: Production & Consumption Discrepancy	3.1 Thermal Production Percent (2011)	3.2 Thermal Production Change (2000-2011)	4.1 Winter: Projected Temperature Increase	4.2 Summer: Projected Temperature Increase	5.1 Air Conditioner Projection (2030)	5.2 Air Conditioner Percent Difference (2005-2030)
Most susceptible countries														
Luxembourg	15	21	7	6	17	13	21	21	6	21	13	12	11	10
Greece	10	13	21	21	4	8	14	12	14	7	16	17	18	1
Slovakia	11	12	2	1	21	21	5	4	13	14	15	5	17	7
Italy	19	20	19	17	1	4	16	20	9	9	14	15	19	8
Least susceptible countries														
Norway	5	3	5	4	13	14	4	8	1	17	3	3	/	/
Czech Republic	13	8	14	13	11	11	1	2	18	11	12	6	3	2
Portugal	1	1	18	18	8	10	15	13	5	2	11	20	6	5
Denmark	2	9	12	11	18	17	17	1	8	1	4	8	13	13

Assuming future changes in climate only, Eskeland and Mideksa (2010) found the combined heating and cooling energy demand to decrease in most European countries until 2100, whereas they estimated increases for Italy and Greece. For the period until 2100, Mirasgedis et al. (2007) estimated climate related changes of the electricity demand in Greece of at least 10 % for each month between June and September. Slovakia is highly susceptible due to the quite weak correlation between electricity production and consumption. Both Greece and Slovakia are also highly vulnerable due to their strong import dependence from only a small number of oil and gas suppliers (Cohen et al., 2011; Gupta, 2008; Le Coq & Paltseva, 2009).

One influencing factor for determining the susceptibility of a country to climate change was the share of electricity produced in thermoelectric power plants, as different studies have shown that these plants can be affected during heat waves and droughts (Flörke et al., 2011b; Förster & Lilliestam, 2009; Rübbelke & Vögele, 2011b). Both Greece and Luxembourg produce the majority of their electricity using thermoelectric power plants. Luxembourg also saw the strongest increase in thermal electricity production of all countries between 2000 and 2011 (Figure 2.4, right). Finally, the poor position in the susceptibility ranking of Greece, Italy and Slovakia can also be explained by strong future increases in mean summer temperature (Figure 2.5, left, Fidje and Martinsen (2007); Jacob et al. (2014); Kjellström et al. (2011); Nikulin et al. (2011)) and the use of air conditioners which is anticipated to be more than 46 % in 2030 (Figure 2.6, left).

5.1.2.2 Factors for the good rank of the four least susceptible countries

The electricity sectors of Norway, the Czech Republic, Portugal and Denmark were found to be least susceptible to climate change (Table 2.2 and Figure 2.7). While Norway is the 3rd least vulnerable country in the analysis of Gnansounou (2008), the other three countries are located in the middle and upper middle range of the energy vulnerability index. Norway produces almost all of its electricity by means of hydropower. As it therefore has hardly any thermoelectric power plants, it is assumed to have a very low susceptibility (Chapter 2). Gnansounou (2008) failed to shed light on the reasons for the good ranking position of Norway. Both Denmark and Portugal saw a decrease in their thermal electricity production of more than 14 % between 2000 and 2011. In 2014, the share of renewable energies in the electricity production of both countries was about 60 % (Roselund & Bernhardt, 2015) which supports the low susceptibility ranking positions. In the energy security performance change ranking of Sovacool and Brown (2009), Norway gets a position in the lower middle range as it showed a similar development of the indicators described above for Greece. However, the natural gas import dependency and the energy intensity decreased more than in Greece.

The analysis in Chapter 2 shows that the Czech Republic produces more electricity than it consumes (Figure 2.3, right) which also explains its low susceptibility in the final index. Norway has a production surplus in summer (ENTSO-E, 2015) and Denmark produces more electricity than it consumes in winter. Denmark also has a good ranking position as it is almost independent of oil and gas imports (Cohen et al., 2011; Le Coq & Paltseva, 2009; Röller et al., 2007; Scheepers et al., 2007). Both Norway and the Czech Republic will see an increase of the future temperature particularly in the winter period (Figure 2.5, right). Therefore, both countries have a low susceptibility for this influencing factor, as the heating electricity demand in winter is likely to decrease with rising temperatures. Especially Norway will benefit from this development because of the strong correlation between monthly electricity consumption and mean temperature below the heating threshold. Future increasing temperatures will thus cause the electricity consumption to decrease more significantly than in other countries.

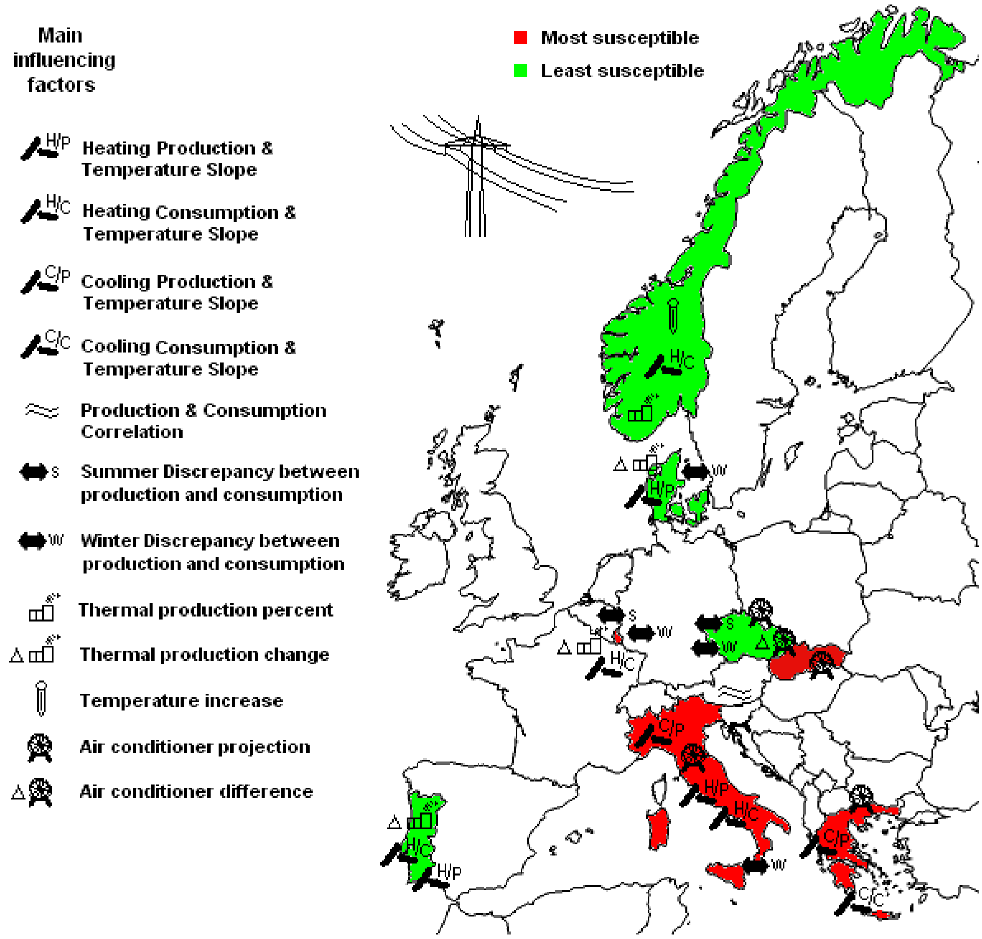

Figure 5.1: Summary figure of the European electricity sector susceptibility analysis. The four most (red) and least (green) susceptible countries are marked and the most important influencing factors for their susceptibility are displayed. Note: The legend shows only 12 instead of the 14 influencing factors as both Slovakia and Norway have each the same ranking position for two of the factors (see Table 5.1)

The good ranking position of Norway is partly due to missing air conditioner data which necessitated the exclusion of this dimension for calculating the country's index (Section 2.4.1.1). However, Norway is still far from reaching and surpassing the cooling threshold which is in line with the low susceptibility. This is emphasized by Seljom et al. (2011) who found that the cooling energy demand in the residential sector of Norway may still only be 2 % of the heating energy demand in 2050. The Czech Republic is projected to only have a low share of air conditioners of less than 5 % in 2030 (Figure 2.6, left, Hitchin et al. (2013)) which explains its good final ranking position. If a country only has a low share of air conditioners which is also projected to only slightly increase in the future, it will also only see a small increase in its future space cooling energy demand in residential buildings. This was confirmed by the analysis for Germany in Chapter 3 (Figure 3.4). Figure 5.1 provides an overview on the main influencing factors that determine the susceptibility of the four most and least susceptible European countries as described in Section 5.1.2.

5.1.3 Research Question 3 (RQ3): How will the energy demand for space conditioning of residential buildings change until the middle of the 21st century and will this be enough to achieve the national energy and climate targets?

Within this thesis, a comprehensive retrofitting algorithm for considering dynamic changes in the insulation quality of the residential building stock is exemplarily applied to two countries. For both analyses, plausible assumptions regarding the development of the considered influencing factors are combined in a way that allows to display a range of the future energy demand for space conditioning of buildings. While the focus of the analysis for Germany was on both the heating and cooling energy demand as well as the resulting GHG emissions, the analysis for the Netherlands was aimed at having a closer look at the regional level and considering a finer temporal resolution.

5.1.3.1 Decreases in the heating energy demand

Numerous studies on the impact of climate change on the building sector have projected a decreasing heating energy demand in the future (Dolinar et al., 2010; Lam et al., 2010; Zhou et al., 2013). For Germany, the presented thesis found a corresponding reduction of 55-81 % between 2010 and 2060 (Section 3.3.1). The heating energy demand of residential buildings is estimated to decrease by more than 30-60 % in the majority of the Dutch provinces between 1991-2000 and 2051-2060 (Section 4.3.2). However, due to province specific characteristics, there are huge differences in the future heating energy demand reduction. While the province of Limburg is projected to have a 38-69 % lower demand by the middle of this century, the province of Utrecht is expected to see a decrease of just 21-54 %. Looking at the future monthly heating energy demand, it is apparent that there will be very little heating necessary in the Dutch provinces in September. This is due to the already low current heating energy demand in this month but also to the future temperature increase which is projected to be stronger than in most other months. Thus, heating energy savings in September will be 61-95 % depending on the province and the climate scenario.

The estimated reductions regarding the future residential heating energy demand are stronger than in most existing studies. One exception is the analysis of Scott et al. (1994) that found heating demand decreases of 68-83 % depending on the considered U.S. city. The authors assumed a temperature rise of 3.9 °C and an advanced building envelope with advanced insulation. Other studies found reductions of up to 60 % (Section 3.4; Section 4.4). However, a comparison with existing analyses is not always appropriate because the considered influencing factors differ. Most studies neglect future population changes or only look at example buildings rather than at a comprehensive national building stock (Table 4.1). Moreover, they often focus on countries with warmer climates where heating requirements are very small. Lam et al. (2010) estimated a future reduction in the heating energy demand of office buildings in Hong Kong of about 45 %, but emphasized that the absolute decrease would be small due to the low starting values. The differences in the future heating energy demand reductions between Germany and the Netherlands are mainly attributed to the differing future population forecasts. In the considered period, the German population is projected to decrease by 6-24 %, whereas the Dutch population projection ranges from a decrease of 4 % to an increase of up to 36 %. The stronger reduction in the German population will be mainly responsible for the stronger future heating energy demand reduction compared to that of the Netherlands.

5.1.3.2 Increases in the cooling energy demand

While it is reasonable to assume that all occupied residential buildings in Germany have a heating system, the share of air conditioners is much lower and is projected to only slightly increase in the coming decades (Adnot et al., 2008; Hitchin et al., 2013). However, this share is decisive for the future cooling energy demand. Assuming a share of 13 % for Germany by the middle of the century, which is the current share of air conditioners in Italy, whose climate is projected for Germany in the future (Kopf et al., 2008), the future cooling energy demand would strongly increase. However, it would still be only a very small fraction of the heating energy demand in 2060. Even with a 100 % share of air conditioners, the future cooling energy demand would be only less than 5 % of the heating energy demand at that time (Section 3.3.1). For the UK housing stock, Collins et al. (2010) calculated strong increases in the space cooling energy demand, but underline that the heating energy demand will still be higher than the demand for cooling until 2080. The same was found by Dirks et al. (2015) for the Eastern part of the U.S. until the end of this century compared to 2004. The strong increase in the future demand for cooling, which is estimated in the presented thesis, is in accordance with existing studies (Frank, 2005; Isaac & van Vuuren, 2009). However, due to the focus of some studies on cooling-dominated regions, the absolute reduction in heating will often be offset by the increase in the cooling energy demand, leading to an increase in the total energy demand for space conditioning (Aguiar et al., 2002; Lam et al., 2010).

5.1.3.3 Feasibility of national energy and climate targets

The analyses for both Germany and the Netherlands show that the national targets for the middle of this century are not very feasible even if the annual retrofitting rate would be tripled compared to now (Figure 3.3; Figure 4.3). The German government aims to achieve an almost climate neutral residential building stock by 2050 (FG, 2010). The presented thesis estimated reductions in the GHG emissions of 60-78 % between 2010 and 2050 which would still mean 61-139 Mt CO_2 eq. by 2050 as opposed to zero (Figure 3.7). That would still be the amount of GHG emitted by Ireland (lower value) or Belgium (upper value) in 2013 (European Commission, 2015). The Dutch government plans for an energy neutral residential building stock to be in place in 2050 (SER, 2013). In 2050, the Dutch heating energy demand alone would still be 103-177 PJ (Figure 4.3). In addition, the national target is meant for both heating and cooling and the cooling energy demand will probably rise with future temperature increases.

5.1.4 Research Question 4 (RQ4): What are the dominant factors shaping the future energy demand for space conditioning?

The analysis of the future residential building energy demand for room conditioning presented here considers the three important influencing factors: climate change, population and retrofitting. To find out the impact of each factor on the energy demand in 2051-2060, a sensitivity analysis was conducted. This was done by varying one specific influencing factor while keeping the others constant. Assuming the extreme scenarios regarding the future development of climate, population and retrofitting measures, retrofitting of buildings has the largest impact on the future heating energy demand in Germany and the Dutch provinces. The second-most important influencing factor in Germany and almost all provinces of the Netherlands are future population changes. In the Dutch provinces of Gelderland and Limburg, future temperature and population changes are equally important but are less decisive for the future heating energy demand than retrofitting measures. This underlines the large importance of retrofitting measures for reducing the future heating energy demand of residential buildings. Regarding the future cooling energy demand of German residential buildings in 2051-2060 assuming a theoretical air conditioner market penetration of 100 %, future population changes will have the strongest effect on the demand for cooling. Retrofitting measures are second-most important.

The only two studies on the impact of climate change on the energy demand of buildings that also consider future population changes and retrofitting measures did not test which of the three influencing factors is most decisive for the future energy demand (Belzer et al., 1996; Yu et al., 2014). Zhou et al. (2013), who considered future climate and population change in China and the U.S., found a considerably higher impact of temperature changes than of population developments on the future energy demand for space conditioning. They explain this finding by the small range in future population scenarios. Frank (2005) and Gaterell and McEvoy (2005) estimated the future heating and cooling energy demand for Switzerland and the UK and underline that retrofitting measures have a stronger impact than future temperature changes. The opposite was found for Hong Kong by Wan et al. (2011a). Isaac and van Vuuren (2009) modeled the global future heating and cooling energy demand and showed that population changes are more decisive than climate changes. The different results found in these studies can not only be explained by differences in the considered sectors and regions, but also by the usage of varying modeling approaches (Table 4.1).

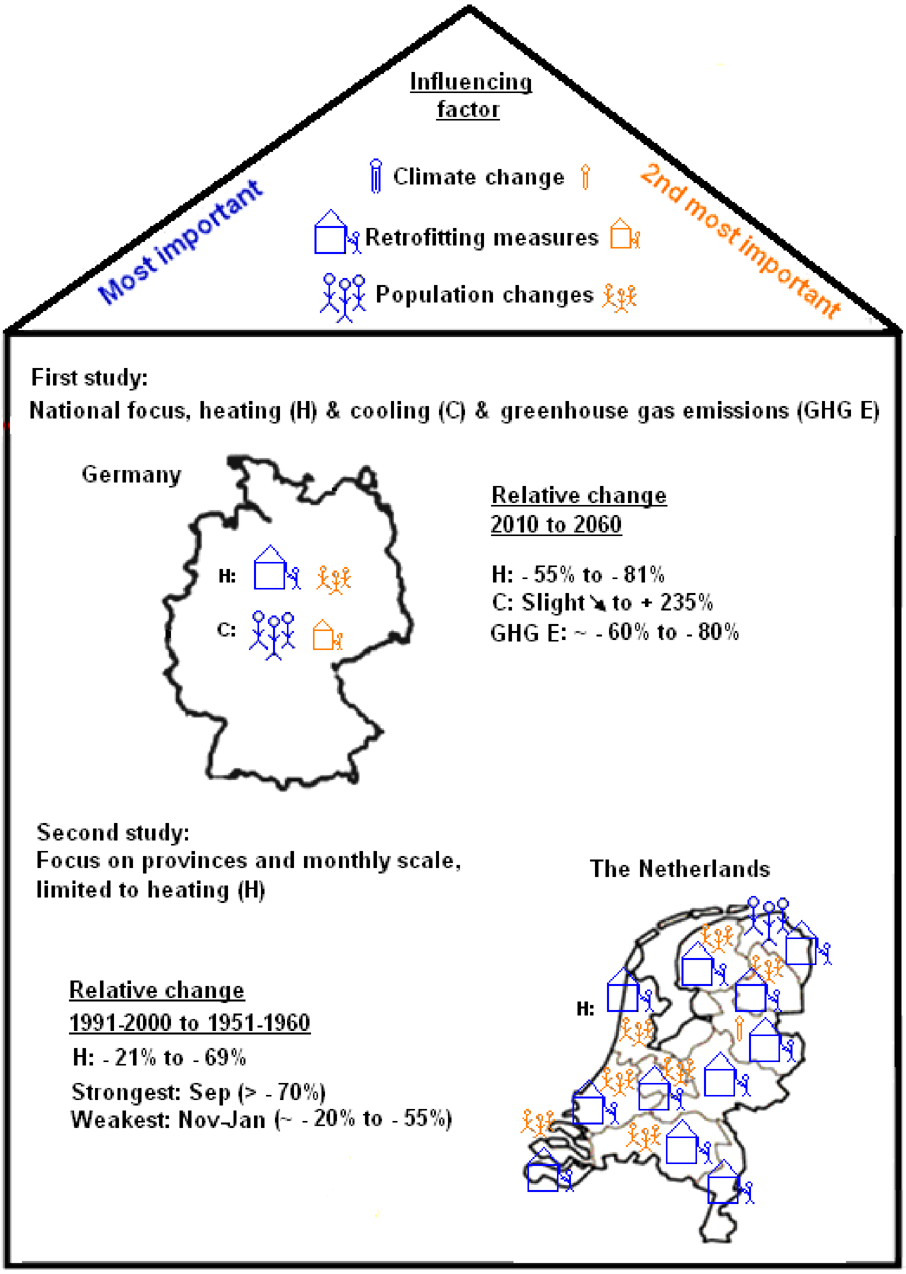

Figure 5.2: Summary figure of the building energy demand analyses. The results regarding the most (blue) and second-most (orange) important influencing factor (sensitivity analysis) are valid for a comparison of the building energy demand values between the considered extreme range scenarios regarding population, climate and retrofitting for the period 2051-2060. If only the most important influencing factor is displayed for a Dutch province (like in Gelderland and Limburg), the other two factors have the same second-most impact (and are therefore not displayed). If two factors with the same size are displayed (like in Groningen), they are equally important factors. The results for the Netherlands concern only the heating energy demand.

Figure 5.2 provides an overview on the most and second-most important influencing factor for the future heating energy demand in the Dutch provinces as well as the future heating and cooling energy demand in Germany. Moreover, it provides information on the relative changes of these demands between the past and the future.

5.2 Additional drivers of the electricity sector susceptibility and building energy demand

In addition to the considered influencing factors, there are further factors that may affect the susceptibility of the electricity sector and the energy demand for space conditioning of residential buildings. Some of these factors have been already discussed (Section 2.4, Sections 3.4 and 4.4).

Another factor that affects the electricity sector susceptibility to climate change is the type of cooling system. Within this thesis, countries with a high share of fossil fuels used for electricity production are considered more susceptible due to possible cooling water problems caused by increased water temperatures or decreased discharge. However, the degree to which thermoelectric power plants are susceptible to climate change also depends on the availability of cold ocean water and the type of cooling system. A power plant with a cooling tower is less susceptible to a lack of adequate cooling water than one with once-through cooling that requires much more water (Förster & Lilliestam, 2009; Koch & Vögele, 2009). Thus, a country with thermal power plants that mainly have cooling towers may be less susceptible than identified in this thesis. The same is true if most thermoelectric power plants within a country are located at the coast, such as in Sweden or Finland. However, data on these aspects are scarce and a detailed and comprehensive analysis of the thousands of thermoelectric power plants located in the 21 considered countries would have gone far beyond the scope of this thesis.

Within this thesis, renewable energies are assumed to lower the susceptibility of a country's electricity sector. However, a high share of renewable energies other than hydropower does not necessarily mean a low susceptibility. In contrast, certain forms of renewable energies may be even more susceptible than thermoelectric power plants to climatic changes such as increases in the frequency and intensity of extreme weather events (Mideksa & Kallbekken, 2010). As wind turbines could be damaged during heavy storms (Arent et al., 2014; Pryor & Barthelmie, 2010), a country with a high number of wind turbines may be especially susceptible. However, a simultaneous failure of a large number of wind turbines, which each only having a small power output, is extremely unlikely. Moreover, wind speed projections are still associated with large uncertainties (Bett et al., 2013; Kjellström et al., 2011; Nolan et al., 2012). Gradual changes in temperature and solar radiation may affect power output of photovoltaic systems, but impacts in European countries may be positive (Crook et al., 2011; Wild et al., 2015) or negative (Fidje & Martinsen, 2007; Smith et al., 2015). The problem is that there is still a lot of uncertainty regarding the impact of climate change on different forms of renewable energy generation (Mideksa & Kallbekken, 2010) and consistent quantitative information about these impacts is missing (Kovats et al., 2014).

Finally, the analysis neglects impacts on the physical transport infrastructure which may be increasingly affected by e. g. future extreme weather events (Mideksa & Kallbekken, 2010; Rothstein & Parey, 2011; Schaeffer et al., 2012; The World Bank, 2008b). However, it is out of the scope of this research to find suitable quantitative data to reflect these complex impacts.

Regarding the future heating and cooling energy demand of buildings, future political decisions both on a national and EU-level can have a large effect. National electricity saving programs, incentives or requirements may decrease the space conditioning demand of buildings (Hitchin et al., 2015). However, such aspects have not been integrated into this thesis as they are hard to foresee. Moreover, demographic projections for the middle of this century are associated with large uncertainties, especially because of uncertain future fertility rates and migration developments (Lee, 2011; Raftery et al., 2014). Considering the recent developments, this becomes particularly clear: while the German population is still projected to substantially decrease in the future (United Nations, 2015), increasing streams of refugees may lead to a much higher number of inhabitants by the middle of the century. This could lead to a higher energy demand than that calculated within this thesis as the German government determined lower energy standards for reception facilities and shared accommodations for refugees to faster provide new apartments for them (FG, 2015). The actual future energy demand may also be higher because of a projected increase of the number of households both in Germany and the Netherlands (CBS, 2015; DESTATIS, 2015) and thus the energy demand for space conditioning.

Socio-cultural factors such as lifestyle changes may be important for the actual energy consumption but are hard to quantify and generalize. Therefore, we only calculated the theoretical energy demand that is independent of such factors. Nevertheless, our model performed well in comparison with historical data on the heating energy consumption of German and Dutch households which shows a good correlation with the heating energy demand estimated within this thesis.

A lack of proper and consistent quantitative data to adequately depict the aforementioned aspects has hindered a consideration of these aspects within this thesis. These should be considered as soon as suitable data is available.

6 Conclusions and Outlook

This thesis for the first time compares countries' electricity sector susceptibility to climate change quantitatively. An influencing factor-wise ranking of the 21 European countries allows the identification of where measures could be best applied to reduce the electricity sector susceptibility. The analysis reveals that the most susceptible countries could promote and invest in passive cooling systems, like sun protection devices or light building paints, in order to reduce the growth in the future number of air conditioners. Another option is investing in renewable energies with the aim of avoiding cooling water deficiencies in thermal power plants during hot and dry periods. This also lowers the dependency on electricity imports.

The thesis is also the first analysis on the combined effect of climate change, population development and retrofitting measures on the future energy demand of residential buildings in Germany and the Netherlands. To the best of the authors knowledge, there is no study yet that considers dynamic changes in the insulation quality of the total residential building stock over time. The annual retrofitting rate is thereby seen as an important adjusting screw for testing the feasibility of national energy and climate targets in the building sector. The findings indicate that Germany and the Netherlands are going to benefit from a decreased total energy demand for room conditioning caused by the projected temperature increases. However, these decreases will be by far not sufficient to reach the given future national energy and climate targets of the two countries up to the middle of this century. To do so, the annual retrofitting rate would need to be at least tripled compared to now. This underlines the huge importance of retrofitting measures.

The study on the electricity sector susceptibility should be extended in the future: over time, the data availability in other European countries will probably improve further which may allow for the consideration of additional countries in the future. Moreover, given appropriate data on the monthly electricity production and consumption, the share of thermal in the total electricity production as well as the share of air conditioners, the method should be applied to examine the electricity sector susceptibility of African, Asian or South American countries. Such analyses are still lacking. The results could be compared with those obtained for the European countries within this thesis. Finally, it may be possible to consider some additional influencing factors that are discussed in Chapter 5.

Regarding the impact of climate change on the future building energy demand, a follow-up study is aimed to extend the analysis to up to 30 European countries. The novelty will be the use of hourly temperature data in order to better account for peak electricity demands and the focus will be on both the heating and cooling energy demand. An extension to commercial buildings is considered. This European study will not only allow for the examination of the impact of climate change on the building energy demand, but also allow for the determination of the contribution that each country can make to reduce greenhouse gas emissions and to mitigate climate change. This thesis lays the methodological foundation for this challenge.

Especially in light of the recent political decisions taken at the COP21, countries should think about how their energy system can be transformed in order to be able to efficiently cope with climate change and to reduce GHG emissions. This thesis shows that the energy sector of countries can benefit from climate change, e. g. due to the decreasing energy demand in the building sector. However, it also emphasizes that additional efforts like intensifying retrofitting measures or increasing the share of renewable energies could amplify these benefits or prevent disadvantages caused by climate change impacts. It thus demonstrates future options for both mitigation of and adaptation to climate change in the energy sector.

7
References

Adnot, J., Grignon-Masse, L., Legendre, S., Marchio, D., Lebrun, J., Andre, P., ... Karatasou, S. (2008). *Preparatory Study on the environmental Performance of residential Room Conditioning Appliances (Airco and Ventilation) - Draft Report of Task 2.* ARMINES, Université de Liège, Universiy of Porto, Austrian Energy Agency, BRE, IASA.

Aebischer, B., Catenazzi, G., & Jakob, M. (2007). *Impact of Climate Change on thermal Comfort, Heating and Cooling Energy Demand in Europe. Proceedings eceee 2007 Summer Study "Saving Energy - Just do it!". 4.-9.Juni 2007. La Colle sur Loupe, France.*

AgentschapNL. (2011). *Voorbeeldwoningen 2011 – EPA Detailgegevens per Woningtype, Subtype en Bouwperiode.*

Aguiar, R., Oliveira, M., & Goncalves, H. (2002). Climate Change Impacts on the thermal Performance of Portuguese Buildings, Results of the SIAM Study. *Building Service Engineering Research and Technology*, *23*, 223-231.

Alcamo, J., Moreno, J. M., Nováky, B., Bindi, M., Corobov, R., Devoy, R., ... Shvidenko, A. (2007). *Europe.* In: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. Cambridge, UK, 541–580.

Altvater, S., de Block, D., Bouwma, I., Dworak, T., Frelih-Larsen, A., Görlach, B., ... Tröltzsch, J. (2012). *Adaptation Measures in the EU: Policies, Costs, and economic Assessment.*

Amato, A. D., Ruth, M., Kirshen, P., & Horwitz, J. (2005). Regional Energy Demand Responses to Climate Change: Methodology and Applications to the Commonwealth of Massachusetts. *Climatic Change*, *71*, 175-201.

Arent, D., Tol, R., Faust, E., Hella, J., Kumar, S., Strzepek, K., ... Yan, D. (2014). *Key economic Sectors and Services.* In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B. and Barros, V.R. and Dokken, D.J. and Mach, K.J. and

Mastrandrea, M.D. and Bilir, T.E. and Chatterjee, M. and Ebi, K.L. and Estrada, Y.O. and Genova, R.C. and Girma, B. and Kissel, E.S. and Levy, A.N. and MacCracken, S. and Mastrandrea, P.R. and White, L.L. (eds.)]. Cambridge University Press, Cambridge, UK and New York, USA, 659-708.

Arnell, N., Tompkins, E., Adger, N., & Delaney, K. (2005). *Vulnerability to abrupt Climate Change in Europe. Tyndall Centre for Climate Change Research.* Technical Report, 34.

Auffhammer, M., & Mansur, E. (2014). Measuring climatic Impacts on Energy Consumption: A Review of the empirical Literature. *Energy Economics*, *46*, 522–530.

Barben, R. (2010). *Vulnerability Assessment of electric Power Supply under extreme Weather Conditions.* Doctoral Thesis. Ecolé Polytechnique Fédérale de Lausanne. Switzerland. 9th December 2010.

Beer, M. (2011). *Personal communication via email.* Forschungsstelle für Energiewirtschaft e. V., München, received at 23.05.2011.

Beer, M., Corradini, R., Fieger, C., Gobmaier, T., Köll, L., Podhajsky, R., ... Karl, H.-D. (2009). *Energiezukunft 2050 - Endbericht der Forschungsstelle für Energiewirtschaft e.V. (Ffe) in Zusammenarbeit mit dem ifo Institut für Wirtschaftsforschung.* FfE.

Belzer, D., Scott, J., & Sands, R. (1996). Climate Change Impacts on U.S. commercial Building Energy Consumption: An Analysis using Sample Survey Data. *Energy Sources*, *18(2)*, 177–201.

Benestad, R. (2008). *Heating Degree Days, Cooling Degree Days and Precipitation in Europe - Analysis for the CELECT-Project.* Norwegian Meteorological Institute.

Bertoldi, P., & Atanasiu, B. (2009). *Electricity Consumption and Efficiency Trends in European Union.* European Commission, Joint Research Centre, Institute for Energy. Luxemburg.

Bett, P., Thornton, H., & Clark, R. (2013). European Wind Variability over 140 yr. *Advances in Science and Research*, *10*, 51–58.

Blanco, G., Gerlagh, R., Suh, S., Barrett, J., de Coninck, H. C., Diaz Morejon, C. F., ... Zhou, P. (2014). *Drivers, Trends and Mitigation.* In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O. and Pichs-Madruga, R. and Sokona, Y. and Farahani, E. and Kadner, S. and Seyboth, K. and Adler, A. and Baum, I. and Brunner, S. and Eickemeier, P. and Kriemann, B. and Savolainen, J. and Schlömer, S. and von Stechow, C. and Zwickel T. and Minx, J.C. (eds.)]. Cambridge University Press, Cambridge, UK and NY, USA.

Boermans, T., & Petersdorff, C. (2007). *U-Values for better Performance of Buildings.* Report established by ECOFYS for EURIMA, Ecofys GmbH, Köln.

BP. (2015). *BP Statistical Review of World Energy.* 64th edition, June 2015.

Breidthardt, A. (2011). *German Government wants nuclear Exit by 2022 at latest.* Berlin. Retrieved from http://uk.reuters.com/article/2011/05/30/us-germany-nuclear-idUKTRE74Q2P120110530 (Retrieved: 23/8/2012)

Buchert, M. (2009). *Klimaschutzmaßnahmen im Bauen und Wohnen. In: Grothmann, T., Krömker, D., Homburg, A., Siebenhüner, B. (Hrsg.), KyotoPlus-Navigator Praxisleitfaden zur Förderung von Klimaschutz und Anpassung an den Klimawandel - Erfolgsfaktoren, Instrumente, Strategie.*

Buildings Performance Institute of Europe. (2011). *Europe's Buildings under the Microscope. A Country–by–Country Review of the Energy Performance of Buildings.*

Cartalis, C., Synodinou, A., Proedrou, M., Tsangrassoulis, A., & Santamouris, M. (2001). Modifications in Energy Demand in urban Areas as a Result of Climate Changes: An Assessment for the southeast Mediterranean Region. *Energy Conversion and Management*, *42(14)*, 1647-1656.

CBS. (2013). *Statline. Tabellen per Thema.* Centraal Bureau voor de Statistiek. Retrieved from http://statline.cbs.nl/Statweb/dome/?TH=81942&PA=80868NED&LA=nl (Retrieved: 4/5/2015)

CBS. (2014). *Energieverbruik per Sector, 1990-2013 (Indicator 0052, Versie 19, 29 September 2014).* CBS in Samenwerking met PBL en Wageningen UR, Den Haag; Planbureau voor de Leefomgeving, Den Haag/Bilthoven en Wageningen UR, Wageningen. Retrieved from http://www.compendiumvoordeleefomgeving.nl/indicatoren/nl0052-Energieverbruik-per-sector.html?i=6-40 (Retrieved: 4/3/2016)

CBS. (2015). *Huishoudens, Grootte, Positie in het Huishouden, 1 Januari 1995-2013.* Centraal Bureau voor de Statistiek. 16.02.2015. Retrieved from http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=37312&D1=a&D2=0,5,10,15-18&HDR=G1&STB=T&VW=T (Retrieved: 13/5/2015)

Chappells, H., & Shove, E. (2005). Debating the Future of Comfort: Environmental Sustainability, Energy Consumption and the indoor Environment. *Building Research and Information*, *33(1)*, 32-40.

Chaturvedia, V., Eoma, J., Clarkea, L., & Shuklab, P. (2012). Long term Building Energy Demand for India: Disaggregating End Use Energy Services in an integrated Assessment Modeling Framework. *Energy Policy*, *64*, 226–242.

Chow, D., & Levermore, G. (2010). The Effects of future Climate Change on Heating and Cooling Demands in Office Buildings in the UK. *Building Services Engineering Research & Technology*, *31*(1), 307–323.

Christenson, M., Manz, H., & Gyalistras, D. (2006). Climate Warming Impact on Degree-Days and Building Energy Demand in Switzerland. *Energy Conversion and Management*, *47(6)*, 671-686.

Climate Interactive. (2015). *Climate Scoreboard.* Retrieved from http://www.climateinteractive.org/tools/scoreboard/ (Retrieved: 25/1/2016)

Cohen, G., Joutz, F., & Loungani, P. (2011). *Measuring Energy Security: Trends in the Diversification of Oil and Natural Gas Supplies.* IMF Working Paper. WP/11/39.

Collins, L., Natarajan, S., & Levermore, G. (2010). Climate Change and future Energy Consumption in UK Housing Stock 2010. *Building Service Engineering Research and Technology*, *31(1)*, 75– 90.

Costa, L., & Kropp, J. P. (2012). Linking Components of Vulnerability in theoretic Frameworks and Case Studies. *Sustainability Science*, *8*, 1–9.

Crook, J., Jones, L., Forster, P., & Crook, R. (2011). Climate Change Impacts on future Photovoltaic and concentrated Solar Power Energy Output. *Energy & Environmental Science*, *4(9)*, 3101-3109.

DESTATIS. (2009). *Bevölkerung Deutschlands bis 2060 - Ergebnisse der 12. koordinierten Bevölkerungsvorausberechnung.* Federal Statistical Office.

DESTATIS. (2010). *Lange Reihen zur Fortschreibung des Wohngebäude- und Wohnungsbestandes in Deutschland von 1950 - 1998.* Federal Statistical Office.

DESTATIS. (2011). *Weniger Kohlendioxid-Emissionen privater Haushalte.* Retrieved from http://www.destatis.de/DE/Publikationen/STATmagazin/Umwelt/2011_01/2011_01CO2.html (Retrieved: 6/11/2011)

DESTATIS. (2015). *Haushalte nach Haushaltsgrößen, Deutschland, 1961-2014.* Statistisches Bundesamt. Retrieved from http://www.destatis.de/DE/ZahlenFakten/Indikatoren/LangeReihen/Bevoelkerung/lrbev05.html;jsessionid=2231E538CFABB6E7EC1FC36BF5057163.cae3 (Retrieved: 12/12/2015)

Diefenbach, N., & Born, R. (2007). *Deutsche Gebäudetypologie. Häufigkeit von Gebäudetypen unterschiedlichen Baualters.* Institut Wohnen und Umwelt GmbH.

Diefenbach, N., Enseling, A., Loga, T., Hertle, H., Jahn, D., & Duscha, M. (2005). *Beiträge der EnEV und des KfW-CO_2-Gebäudesanierungsprogramms zum Nationalen Klimaschutzprogramm, Endbericht im Auftrag des Umweltbundesamtes.* Institut Wohnen und Umwelt GmbH.

Diekmann, J., Hopf, R., Ziesing, H.-J., Kleemann, M., Krey, V., Markewitz, P., ... Harthan, R. (2005). *Klimaschutz in Deutschland bis 2030 - Endbericht zum Forschungsvorhaben, Politikszenarien III, Studie im Auftrag des Umweltbundesamtes.* Deutsches Institut für Wirtschaftsforschung (DIW), Forschungszentrum Jülich, Fraunhofer-Institut für System- und Innovationsforschung (ISI) und Öko-Institut.

DIN. (2003). *Wärmeschutz und Energie-Einsparung in Gebäuden. Teil 6: Berechnung des Jahresheizwärme- und des Jahresheizenergiebedarfs, DIN 4108-6* (Vol. DIN V 4108-6). Deutsches Institut für Normung e. V.

DIN. (2007). *Berechnung des Nutz-, End- und Primärenergiebedarfs für Heizung, Kühlung, Lüftung, Trinkwarmwasser und Beleuchtung (Energiebilanz) von Gebäuden, DIN 18599-2.* Deutsches Institut für Normung e. V.

Dirks, J., Gorrissen, W., Hathaway, J., Skorski, D., Scott, M., Pulsipher, T., ... Rice, J.

(2015). Impacts of Climate Change on Energy Consumption and Peak Demand in Buildings: A detailed regional Approach. *Energy*, *79*, 20-32.

Dolinar, M., Vidrih, B., Kajfez-Bogataj, L., & Medved, S. (2010). Predicted Changes in Energy Demands for Heating and Cooling due to Climate Change. *Physics and Chemistry of the Earth*, *35*, 100–106.

Dougherty, C. (2007). *Germany finds solution to its withering Coal Mines.* 14.06.2007. Retrieved from http://www.nytimes.com/2007/06/14/world/europe/14iht-coal.4.6143627.html?_r=1 (Retrieved: 23/8/2012)

EIA. (2010). *International Energy Outlook 2010. U.S.* Energy Information Administration.

Engle, R., Mustafa, C., & Rice, J. (1992). Modelling and Forecasting daily Series of Electricity Demand. *Journal of Forecasting*, *11*, 241–251.

ENTSO-E. (2015). *Scenario Outlook & Adequacy Forecast 2015.* Belgium.

Eskeland, G. S., & Mideksa, T. K. (2009). *Climate Change and residential Electricity Demand in Europe.* SSRN Electronic Journal 06/2009.

Eskeland, G. S., & Mideksa, T. K. (2010). Electricity Demand in a changing Climate. *Mitigation and Adaptation Strategies for Global Change*, *15*(8), 877–897.

ESRI. (2011). *ArcGIS Desktop.* Redlands: Environmental Systems Research Institute.

EU. (2009). *EC Energy Performance of Building Directive, No.: 351/2009.*

European Climate Assessment and Dataset. (2012). *E-OBS Gridded Dataset.* Retrieved from http://eca.knmi.nl/download/ensembles/download.php#datafiles (Retrieved: 25/6/2012)

European Commission. (2007). *Luxembourg - Energy Mix Fact Sheet.*

European Commission. (2009). *Economic Crisis in Europe : Causes, Consequences and Responses.* Economic and Financial Affairs. Luxembourg.

European Commission. (2015). *Emission Database for global Atmospheric Research. CO_2 Time Series 1970-2013 Dataset.* Retrieved from http://edgar.jrc.ec.europa.eu/overview.php?v=CO2ts1990-2013 (Retrieved: 12/1/2016)

European Parliament and Council. (2001). *Directive 2000/84/EC of the European Parliament and of the Council of 19 January 2001 on Summer-time Arrangements.*

EUROSTAT. (2006). *GEOSTAT 1km^2 Population Grid Dataset.* European Commission. Retrieved from http://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/population-distribution-demography (Retrieved: 2/7/2012)

EUROSTAT. (2012). *Energy Statistics Database.* European Commission. Retrieved from http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/database (Retrieved: 12/4/2012)

EWEA. (2012). *EU met its 2010 renewable Electricity Target - ambitious 2030 Target needed.* Retrieved from http://www.ewea.org/news/detail/2012/01/12/eu-met-its-2010-renewable-electricity-target-ambitious-2030-target-needed/

(Retrieved: 4/9/2012)

FG. (2007). *Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagentechnik bei Gebäuden - Energieeinsparverordnung, Bundesgesetzblatt Jahrgang 2007, Teil 1, Nr. 34 vom 24. Juli.* Federal Government.

FG. (2010). *Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung. 28. September 2010.* Federal Government.

FG. (2015). *EnEV. Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagentechnik bei Gebäuden. Energieeinsparverordnung vom 24. Juli 2007 (BGBI.I S. 1519), die zuletzt durch Artikel 3 der Verordnung vom 24.Oktober 2015 (BGBI.I S. 1789) geändert worden ist.* Federal Government.

Fidje, A., & Martinsen, T. (2007). *Solar Energy.* In: Jes, F. (Ed.), Impacts of Climate Change on renewable Energy Sources, their Role in the Nordic Energy System.

Flörke, M., Bärlund, I., & Kynast, E. (2011a). Will Climate Change affect the Electricity Production Sector? A European Study. *Journal of Water and Climate Change*, *3*(1), 44.

Flörke, M., Teichert, E., & Bärlund, I. (2011b). Future Changes of Freshwater Needs in European Power Plants. *Management of Environmental Quality*, *22(1)*, 89-104.

FMENCNS. (2005). *Kleine Kraft-Wärme-Kopplung für den Klimaschutz.* Federal Ministry for the Environment. Nature Conservation & Nuclear Safety.

FMET. (2009). *Energie in Deutschland - Trends und Hintergründe zur Energieversorgung in Deutschland.* Federal Ministry of Economics & Technology.

FMTBUD. (2009). *Wohnen und Bauen in Zahlen 2008/2009.* Federal Ministry of Transport, Building & Urban Development.

Förster, H., & Lilliestam, J. (2009). Modeling thermoelectric Power Generation in View of Climate Change. *Regional Environmental Change*, *10*, 327–338.

Fraiman, R., Justel, A., & Svarc, M. (2008). Selection of Variables for Cluster Analysis and Classification Rules. *Journal of the American Statistical Association*, *103(483)*, 1294–1303.

Franco, G., & Sanstad, A. (2008). Climate Change and Electricity Demand in California. *Climatic Change*, *87*, 139–151.

Frank, T. (2005). Climate Change Impacts on Building Heating and Cooling Energy Demand in Switzerland. *Energy and Buildings*, *37*, 1175–1185.

Frieler, K., Meinshausen, M., Golly, A., Mengel, M., Lebek, K., Donner, S., & Hoegh-Guldberg, O. (2013). Limiting Global Warming to 2°C is unlikely to save most Coral Reefs. *Nature Climate Change*, *3*, 165-170.

Gallego, J., & Peedell, S. (2001). *Using CORINE Land Cover to map Population Density. Towards agrienvironmental Indicators.* EEA. Topic report 6/2001, Chapter 6.

Gaterell, M., & McEvoy, M. (2005). The Impact of Climate Change uncertainties on the Performance of Energy Efficiency Measures applied to Dwellings. *Energy and Buildings*, *37*, 982–995.

Gertis, K., & Steimle, F. (1989). *Impact of Climate Change on Energy Consumption for Heating and Air Conditioning.* Report to the Federal Minister for Economics, Summary.

Giorgi, F., Jones, C., & Asrar, G. (2009). Addressing Climate Information needs at the regional Level: the CORDEX Framework. *WMO Bull*, *58(3)*, 175–183.

GKSS. (2010). *Climate limited-area Modelling Community. GKSS Research Centre.* Retrieved from http://clm.gkss.de/ (Retrieved: 23/9/2011)

Gnansounou, E. (2008). Assessing the Energy Vulnerability: Case of industrialised Countries. *Energy Policy*, *36*(10), 3734–3744.

Guardian. (2015). *G7 Leaders agree to phase out Fossil Fuel Use by the End of Century.* Retrieved from http://www.theguardian.com/world/2015/jun/08/g7-leaders-agree-phase-out-fossil-fuel-use-end-of-century (Retrieved: 5/1/2016.)

Guerra Santin, O., Itard, L., & Visscher, H. (2009). The Effect of Occupancy and Building Characteristics on Energy Use for Space and Water Heating in Dutch residential Stock. *Energy and Buildings*, *41*, 1223–1232.

Gupta, E. (2008). Oil Vulnerability Index of oil-importing Countries. *Energy Policy*, *36*, 1195–1211.

Hadley, S., Erickson III, D., Hernandez, J., Broniak, C., & Blasing, T. (2006). Responses of Energy Use to Climate Change: A Climate Modeling Study. *Geophysical Research Letters*, *33, L17703*, 1-4.

Hansen, J., Kharecha, P., Sato, M., Masson-Delmotte, V., Ackerman, F., Beerling, D., ... Zachos, J. (2013). Assessing dangerous Climate Change: Required Reduction of Carbon Emissions to protect young People, future Generations and Nature. *PLoS ONE*, *8(12)*, e81648.

Hansen, J., Nazarenko, L., Ruedy, R., Sato, M., Willis, J., Del Genio, A., ... Tausnev, N. (2005). Earth's Energy Imbalance: Confirmation and Implications. *Science*, *308*, 1431-1435.

Hare, W., Cramer, W., Schaeffer, M., Battaglini, A., & Jaeger, C. (2011). Climate Hotspots: Key vulnerable Regions, Climate Change and Limits to Warming. *Regional Environmental Change*, *11*, 1–13.

Haylock, M., Hofstra, N., Klein Tank, A., Klok, E., Jones, P., & New, M. (2008). A European daily high-resolution gridded Data Set of Surface Temperature and Precipitation for 1950 – 2006. *Journal of Geophysical Research*, *113*, 1–12.

Hekkenberg, M., Benders, R., Moll, H., & Schoot Uiterkamp, A. (2009a). Indications for a changing Electricity Demand Pattern: The Temperature Dependence of Electricity Demand in the Netherlands. *Energy Policy*, *37*, 1542–1551.

Hekkenberg, M., Moll, H., & Schoot Uiterkamp, A. (2009b). Dynamic Temperature Dependence Patterns in future Energy Demand Models in the Context of Climate Change. *Energy*, *34*, 1797–1806.

Hitchin, R., Pout, C., & Butler, D. (2015). Realisable 10-year Reductions in European

Energy Consumption for Airconditioning. *Energy and Buildings*, *86*, 478–491.

Hitchin, R., Pout, C., & Riviere, P. (2013). Assessing the Market for Air Conditioning Systems in European Buildings. *Energy and Buildings*, *58*, 355–362.

Hoffmann, B., Häfele, S., & Karl, U. (2013). Analysis of Performance Losses of thermal Power Plants in Germany. A System Dynamics Model Approach using Data from regional Climate Modelling. *Energy*, *49*, 193–203.

Howden, S., & Crimp, S. (2001). Effect of Climate and Climate Change on Electricity Demand in Australia. *CSIRO Sustainable Ecosystems*.

Huber, C., & Gutschi, C. (2010). *Pump-Storage Hydro Power Plants in the European Electricity Market.* Institute for Electricity and Energy Innovations, Graz University of Technology. Graz.

IEA. (2007). *Energy Policies of IEA Countries: Switzerland 2007 Review.* International Energy Agency. Paris.

IEA. (2009a). *Energy Policies of IEA Countries: Luxembourg 2008 Review.* International Energy Agency. Paris.

IEA. (2009b). *Energy Policies of IEA Countries: Spain 2009 Review.* International Energy Agency. Paris.

IEA. (2010a). *Energy Policies of IEA Countries: France 2009 Review.* International Energy Agency. Paris.

IEA. (2010b). *Energy Policies of IEA Countries: The Czech Republic 2010 Review.* International Energy Agency. Paris.

IEA. (2012). *Monthly Electricity Statistics Archives.* International Energy Agency. Paris: International Energy Agency. Retrieved from http://www.iea.org/stats/surveys/elec_archives.asp (Retrieved: 12/4/2012)

IEA. (2013a). *CO_2 Emissions from Fuel Combustion. 2013 Edition.* International Energy Agency. Retrieved from http://www.oecd-ilibrary.org/energy/co2-emissions-from-fuel-combustion-2013_co2_fuel-2013-en (Retrieved: 4/2/2013)

IEA. (2013b). *IEA Online Data Services.* International Energy Agency. Retrieved from http://data.iea.org/ieastore/statslisting.asp (Retrieved: 18/11/2013)

IPCC. (2013). *Summary for Policymakers.* In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F. and Qin, D. and Plattner, G.-K. and Tignor, M. and Allen, S.K. and Boschung, J. and Nauels, A. and Xia, Y. and Bex, V. and Midgley, P.M. (eds.)]. Cambridge University Press, Cambridge, UK and New York, USA.

Isaac, M., & van Vuuren, D. (2009). *Modeling global residential Sector Energy Demand for Heating and Air Conditioning in the Context of Climate Change* (Vol. 37(2)). Intergovenmental Panel on Climate Change.

IWU. (2007). *Deutsche Gebäudetypologie, Systematik und Datensätze.* Institut Wohnen und Umwelt GmbH.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O., Bouwer, L., ... Yiou, P. (2014). EURO-CORDEX: New high-resolution Climate Change Projections for European Impact Research. *Regional Environmental Change*, *14*, 563–578.

Jenkins, D., Liu, Y., & Peacock, A. (2008). Climatic and internal Factors affecting future UK Office Heating and Cooling Energy Consumptions. *Energy Buildings*, *40*, 874–81.

Jewell, J. (2011). *The IEA Model of Short-Term Energy Security (MOSES): Primary Energy Sources and secondary Fuels. OECD publishing, Paris, France, 48 pp.* Retrieved from http://www.iea.org/publications/freepublications/publication/moses_paper.pdf (Retrieved: 29/9/2012)

Jochem, E., Jaeger, C., Battaglini, A., Bradke, H., Cremer, C., Eichhammer, W., ... Wietschel, M. (2008). *Investitionen für ein klimafreundliches Deutschland, Studie im Auftrag des Bundesministeriums für Umwelt, Naturschutz und Reaktorsicherheit.* BSR-Sustainability, European Climate Forum (ECF), Fraunhofer-Institut für System- und Innovationsforschung (ISI), Öko-Zentrum NRW, Potsdam-Institut für Klimafolgenforschung (PIK).

Jungmann, U., & Lambrecht, K. (2008). *Energieausweis für Gebäude - nach Energieeinsparverordnung (EnEV 2007). Informationsbroschüre des Bundesministeriums für Verkehr, Bau und Stadtentwicklung. Econsult.*

Kellogg, R., & Wolff, H. (2007). *Does Extending Daylight Saving Time Save Energy? Evidence from an Australian Experiment.* Institute for the Study of Labor (IZA). Bonn.

Kjellström, E., Nikulin, G., Hansson, U., Strandberg, G., & Ullerstig, A. (2011). 21st Century Changes in the European Climate: Uncertainties derived from an Ensemble of regional Climate Model Simulations. *Tellus A, Series A*, *63A(1)*, 24–40.

Kleemann, M., Heckler, R., Kolb, G., & Hille, M. (2000). *Die Entwicklung des Energiebedarfs zur Wärmebereitstellung in Gebäuden - Szenarionanalysen mit dem IKARUS-Raumwärmemodell.* Bremer Energie Institut.

Klein, D., Olonscheck, M., Walther, C., & Kropp, J. (2013). Susceptibility of the European Electricity Sector to Climate Change. *Energy*, *59*, 183–193.

Klinckenberg, F., McAndrew, L., & Pirie, M. F. (2013). *Renovation Roadmaps for Buildings.* A report by the Policy Partners for Eurima.

Koch, H., & Vögele, S. (2009). Dynamic Modeling of Water Demand, Water Availability and Adaptation Strategies for Power Plants to global Change. *Ecological Economics*, *68(7)*, 203–2039.

Kopf, S., Ha-Duong, M., & Hallegatte, S. (2008). Using Maps of City Analogues to display and interpret Climate Change Scenarios and their Uncertainty. *Natural Hazards and Earth System Sciences*, *8*, 905–918.

Köppen, W. (1923). *Die Klimate der Erde.* De Gruyter.

Koroneos, C., & Kottas, G. (2007). Energy Consumption Modeling Analysis and environmental Impact Assessment of Model House in Thessaloniki (Greece). *Building and Environment*, *42*(1), 122–138.

Kotchen, M. J., & Grant, L. E. (2008). *Does Daylight Saving Time save Energy? Evidence from a natural Experiment in Indiana.* Cambridge. (Working Paper)

Kott, K., & Behrends, S. (2009). *Ausstattung mit Gebrauchsgütern und Wohnsituation privater Haushalte in Deutschland - Ergebnisse der Einkommens- und Verbrauchsstichprobe.* Statistisches Bundesamt.

Kovats, R., Valentini, R., Bouwer, L., Georgopoulou, E., Jacob, D., Martin, E., ... Soussana, J.-F. (2014). *Europe.* In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R. and Field, C.B. and Dokken, D.J. and Mastrandrea, M.D. and Mach, K.J. and Bilir, T.E. and Chatterjee, M. and Ebi, K.L. and Estrada, Y.O. and Genova, R.C. and Girma, B. and Kissel, E.S. and Levy, A.N. and MacCracken, S. and Mastrandrea, P.R. and White, L.L. (eds.)]. Cambridge University Press, Cambridge, UK and New York, USA, 1267-1326.

Lam, J. C., Wan, K. K., Lam, T. N., & Wong, S. (2010). An Analysis of future Building Energy Use in subtropical Hong Kong. *Energy*, *35(3)*, 1482–1490.

Laustsen, J. (2008). *Energy Efficiency Requirements in Building Codes, Energy Efficiency Policies for new Buildings.* International Energy Agency (IEA).

Lautenschlager, M., Keuler, K., Wunram, C., Keup-Thiel, E., Schubert, M., Will, A., ... Boehm, U. (2009). *Climate Simulation with CLM, Scenario A1B run no.1, Data Stream 3: European region MPI-M/MaD. World Data Center for Climate.* Retrieved from http://cera-www.dkrz.de/WDCC/ui/Compact.jsp?acronym=CLM_A1B_1_D3 (Retrieved: 17/8/2012)

Le Coq, C., & Paltseva, E. (2009). Measuring the Security of external Energy Supply in the European Union. *Energy Policy*, *37*, 4474–4481.

Lee, R. (2011). The Outlook for Population Growth. *Science*, *333(6042)*, 569–573.

Li, D., Yang, L., & Lam, J. (2012). Impact of Climate Change on Energy Use in the Built Environment in different Climate Zones - A Review. *Energy*, *42*, 103–112.

Linnerud, K., Mideksa, T., & Eskeland, G. (2011). The Impact of Climate Change on Nuclear Power Supply. *The Energy Journal*, *32 (1)*, 149-168.

Loga, T., Diefenbach, N., Enseling, A., Hakce, U., Born, R., Knissel, J., & Hinz, E. (2007). *Querschnittsbericht Energieeffizienz im Wohngebäudebestand - Techniken, Potenziale, Kosten und Wirtschaftlichkeit. Eine Studie im Auftrag des Verbandes der Südwestdeutschen Wohnungswirtschaft e.V.* Institut Wohnen und Umwelt GmbH.

Loveland, J. E., & Brown, G. Z. (1990). *Impacts of Climate Change on the Energy Performance of Buildings in the United States.* OTA/UW/UO, Contract J3-4825.0.

Washington, D.C., Office of Technology Assessment, US Congress.

Lucon, O., Ürge-Vorsatz, D., Zain Ahmed, A., Akbari, H., Bertoldi, P., Cabeza, L. F., ... Vilarino, M. (2014). *Buildings. In: Climate Change 2014: Mitigation of Climate Change.* Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O. and Pichs-Madruga, R. and Sokona, Y. and Farahani, E. and Kadner, S. and Seyboth, K. and Adler, A. and Baum, I. and Brunner, S. and Eickemeier, P. and Kriemann, B. and Savolainen, J. and Schlomer, S. and von Stechow, C. and Zwickel, T. and Minx, J.C. (eds.)]. Cambridge University Press, Cambridge, UK and New York, USA.

Majcen, D., Itard, H., & Visscher, H. (2013). Theoretical vs. actual Energy Consumption of labelled Dwellings in the Netherlands: Discrepancies and Policy Implications. *Energy Policy*, *54*, 125–136.

Matzarakis, A., & Thomsen, F. (2009). *Heating and Cooling Degree Days as an Indicator of Climate Change in Freiburg.* University of Freiburg. Freiburg.

McGlade, C., & Ekins, E. (2015). The geographical Distribution of Fossil Fuels unused when limiting Global Warming to 2 °C. *Nature*, *517*, 187–190.

McGregor, G. R., Ferro, C. A. T., & Stephenson, D. B. (2005). Projected Changes in Extreme Weather and Climate Events in Europe. In W. Kirch, B. Menne, & R. Bertollini (Eds.), *Extreme Weather Events and public Health Responses* (pp. 13–23). Springer.

Memmler, M., Mohrbach, E., Schneider, S., Dreher, M., & Herbener, R. (2009). *Emissionsbilanz erneuerbarer Energieträger - Durch Einsatz erneuerbarer Energien vermiedene Emissionen im Jahr 2007.* Umweltbundesamt.

Mequignona, M., Haddoub, H., Thellierc, F., & Bonhommed, M. (2013). Greenhouse Gases and Building Lifetimes. *Building and Environment*, *68*, 77–86.

Met Office. (2015). *Global Climate in Context as the World approaches 1°C above pre-industrial for the first Time.* Research News, 11/11/2015. Retrieved from http://www.metoffice.gov.uk/research/news/2015/global-average-temperature-2015 (Retrieved: 3/2/2016)

Michaelowa, A., Connor, H., & Williamson, L. E. (2010). Use of Indicators to improve Communication on Energy Systems Vulnerability, Resilience and Adaptation to Climate Change. In A. Troccoli (Ed.), *Management of Weather and Climate Risk in the Energy Industry* (pp. 69–87). Springer.

Mideksa, T., & Kallbekken, S. (2010). The Impact of Climate Change on the Electricity Market: A Review. *Energy Policy*, *38(7)*, 3579-3585.

Mimler, S., Müller, U., Greis, S., & Rothstein, B. (2009). Impacts of Climate Change on Electricity Generation and Consumption. In *Interdisciplinary Aspects of Climate Change* (pp. 11–37). Frankfurt: Peter Land Scientific Publishers.

Mirasgedis, S., Sarafidis, Y., Georgopoulou, E., Kotroni, V., Lagouvardos, K., & Lalas, D. (2007). Modelling Framework for estimating Impacts of Climate Change on

Electricity Demand at regional Level: Case of Greece. *Energy Conversion and Management*, *48(5)*, 1737-1750.

Mitchell, T., Hulme, M., & New, M. (2002). *Climate Data for political Areas* (Vol. Area 34). Tyndall Centre.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Van Vuuren, D. P., ... Wilbanks, T. J. (2010). The next Generation of Scenarios for Climate Change Research and Assessment. *Nature*, *463(7282)*, 747–756.

Naish, C., McCubbin, I., Edberg, O., & Harfoot, M. (2008). *Outlook of Energy Storage Technologies.* European Parliament. Brussels.

Nardo, M., Saisana, M., Saltelli, A., Tarantola, S., Hoffman, A., & Giovannini, E. (2005). *Handbook on Constructing Composite Indicators: Methodology and User's Guide.* (OECD)

Nejat, P., Jomehzadeh, F., Taheri, M., Ghari, M., & Zaimi Abd. Majid, M. (2015). A global Review of Energy Consumption, CO_2 Emissions and Policy in the residential Sector (with an Overview of the Top Ten CO_2 emitting Countries). *Renewable and Sustainable Energy Reviews*, *43*, 843–862.

Nikulin, G., Kjellström, E., Hansson, U., Jones, C., & Strandberg, G. (2011). Evaluation and future Projections of Temperature, Precipitation and Wind Extremes over Europe in an Ensemble of regional Climate Simulations. *Tellus*, *63A*, 41–55.

NOAA. (2015). *Trends in atmospheric Carbon Dioxide.* Retrieved from http://www.esrl.noaa.gov/gmd/ccgg/trends/ (Retrieved: 14/1/2016)

Noailly, J., & Batrakova, S. (2010). Stimulating energy-efficient Innovations in the Dutch Building Sector: Empirical Evidence from Patent Counts and Policy Lessons. *Energy Policy*, *38*, 7803–7817.

Nolan, P., Lynch, P., Mcgrath, R., Semmler, T., & Wang, S. (2012). Simulating Climate Change and its Effect on the the Wind Energy Resource of Ireland. *Wind Energy*, *15*, 593-608.

OECD. (2007). *OECD Rural Policy Reviews: Germany.* Organisation for Economic Co-operation & Development. Retrieved from http://www.oecd.org/document/59/0,3343,en_33873108_33873402_38899515_1_1_1_1,00.html.chapter_1 (Retrieved: 23/11/2011)

Olonscheck, M., Holsten, A., & Kropp, J. P. (2011). Heating and Cooling Energy Demand and related Emissions of the German residential Building Stock under Climate Change. *Energy Policy*, *39*, 4795–4806.

Oppenheimer, M., Campos, M., Warren, R., Birkmann, J., Luber, G., ONeill, B., & Takahashi, K. (2014). *Emergent Risks and Key Vulnerabilities.* In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B. and Barros, V.R. and Dokken, D.J. and Mach, K.J. and Mastrandrea, M.D. and Bilir, T.E. and Chatterjee, M.

and Ebi, K.L. and Estrada, Y.O. and Genova, R.C. and Girma, B. and Kissel, E.S. and Levy, A.N. and MacCracken, S. and Mastrandrea, P.R. and White, L.L. (eds.)]. Cambridge University Press, Cambridge, UK and New York, USA, 1039-1099.

Orlowsky, B., Gerstengarbe, F.-W., & Werner, P. (2008). A resampling Scheme for regional Climate Simulations and its Performance compared to a dynamical RCM. *Theoretical and Applied Climatology*, *92*, 209-223.

Paul, F., Kääb, A., & Haeberli, W. (2007). Recent Glacier Changes in the Alps observed by Satellite: Consequences for future Monitoring Strategies. *Global and Planetary Change*, *56*(1-2), 111–122.

PBL. (2014). *Trends in global CO_2 Emissions. 2014 Report. Background Studies.* PBL Netherlands Environmental Assessment Agency and Institute for Environment and Sustainability (IES) of the European Commissions Joint Research Centre (JRC).

Petermann, T., Bradke, H., Lüllmann, A., Poetzsch, M., & Riehm, U. (2010). *Gefährdung und Verletzbarkeit moderner Gesellschaften – am Beispiel eines grossräumigen Ausfalls der Stromversorgung.* Endbericht zum TA-Projekt. Büro für Technikfolgenabschätzung beim Deutschen Bundestag.

Pilli-Sihvola, K., Aatola, P., Ollikainen, M., & H., T. (2010). Climate and Electricity Consumption – Witnessing increasing or decreasing Use and Costs? *Energy Policy*, *38*, 2409-2419.

Prek, M., & Butala, V. (2010). *Base Temperature and Cooling Degree Days.* University of Ljubljana.

Prettenthaler, F., & Gobiet, A. (2008). *Studien zum Klimawandel in Österreich.* (Vol. 2). Joanneum Research Forschungsgesellschaft mbH.

Pryor, S., & Barthelmie, R. (2010). Climate Change Impacts on Wind Energy: A Review. *Renewable and Sustainable Energy Reviews*, *14*, 430-437.

Psiloglou, B., Giannakopoulos, C., Majithia, S., & Petrakis, M. (2009). Factors affecting Electricity Demand in Athens, Greece and London, UK: A comparative Assessment. *Energy*, *34*(11), 1855–1863.

Rademaekers, K., Boonekamp, P., Harmsen, R., Boeve, S., & Sijm, J. (2012). *The Energy Efficiency Investment Potential for the Building Environment. Two Approaches. EROFYS, 1-24.*

Raftery, A., Alkema, L., & Gerland, P. (2014). Bayesian population projections for the United Nations. *Statistical Sciences*, *29(1)*, 58–68.

RDCT. (2013). *R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. R Development Core Team.* Retrieved from http://www.R-project.org (Retrieved: 14/12/2013)

Rebetez, M., Dupont, O., & Giroud, M. (2008). An Analysis of the July 2006 Heatwave Extent in Europe compared to the Record Year of 2003. *Theoretical and Applied Climatology*, *95*(1-2), 1–7.

Rijksoverheid. (2012). *Bouwbesluit 2012.* Retrieved from http://vrom.bouwbesluit

.com/Inhoud/docs/wet/bb2012 (Retrieved: 23/2/2013)

Roberts, S. (2008). Altering existing Buildings in the UK. *Energy Policy*, *36(12)*, 4482-4486.

Rocha, M., Hare, N., Schaeffer, M., Jeffery, L., Höhne, N., Fekete, H., ... Blok, K. (2015). *G20 - all INDCs in, but large Gap remains. Climate Action Tracker Update.*

Röller, L., Delgado, J., & Friederiszick, H. (2007). *Energy: Choices for Europe, Bruegel Blueprint Series.*

Roselund, C., & Bernhardt, J. (2015). *Lessons learned along Europes Road to Renewables.* Institute of Electrical and Electronics Engineers (IEEE). 4.05.2015. Retrieved from http://spectrum.ieee.org/energy/renewables/lessons-learned-along-europes-road-to-renewables (Retrieved: 6/7/2015)

Rothstein, B., & Parey, S. (2011). *Impacts of and Adaptation to Climate Change in the Electricity Sector in Germany and France.* In: Ford, JD., Ford, LB. (Hrsg): Climate Change Adaptation in developed Nations. From Theory to Practice. Springer. Netherlands. 231-242.

Roupas, C., Flamos, A., & Psarras, J. (2009). Measurement of EU27 oil vulnerability. *International Journal of Energy Sector Management*, *3(2)*, 203–218.

Rübbelke, D., & Vögele, S. (2011a). *Distributional Consequences of Climate Change Impacts on the Power Sector: Who gains and who loses ?* (No. 349). Centre for European Policy Studies. Brussels.

Rübbelke, D., & Vögele, S. (2011b). Impacts of Climate Change on European critical Infrastructures: The Case of the Power Sector. *Environmental Science & Policy*, *14*(1), 53–63.

Rypdal, M., & Rypdal, K. (2014). Long-memory Effects in linear Response Models of Earths Temperature and Implications for future Global Warming. *Journal of Climate*, *27*, 5241-5258.

Sailor, D. J. (2001). Relating residential and commercial Sector Electricity Loads to Climate - Evaluating State Level Sensitivities and Vulnerabilities. *Energy*, *26(7)*, 645-657.

Sailor, D. J., & Muiqoz, J. R. (1997). Sensitivity of Electricity and Natural Gas Consumption to Climate in the U.S.A. - Methodology and Results for eight States. *Energy*, *22*(10), 987–998.

Sailor, D. J., & Pavlova, A. A. (2003). Air Conditioning Market Saturation and long-term Response of residential Cooling Energy Demand to Climate Change. *Energy*, *28(9)*, 941-951.

Sartori, I., & Hestnes, A. (2007). Energy Use in the Life Cycle of conventional and low-energy Buildings: A Review Article. *Energy and Buildings*, *39 (3)*, 249–257.

Schaeffer, R., Szklo, A. S., Pereira de Lucena, A. F., Moreira Cesar Borba, B. S., Pupo Nogueira, L. P., Fleming, F. P., ... Boulahya, M. S. (2012). Energy sector vulnerability to climate change: A Review. *Energy*, *38(1)*, 1–12.

Scheepers, M., Seebregts, A., de Jong, J., & Maters, H. (2007). *EU Standards for Energy Security of Supply. Updates on the Crisis Capability Index and the Supply/Demand Index. Quantification for EU-27.* Energy Research Centre of the Netherlands.

Scott, M., Dirks, J., & Cort, K. (2007). The Value of Energy Efficiency Programs for US residential and commercial Buildings in a warmer World. *Mitigation and Adaptation Strategies for Global Change*, *13*, 307-339.

Scott, M., Wrench, L., & Hadley, D. (1994). Effects of Climate Change on commercial Building Energy Demand. *Energy sources*, *16(3)*, 317–332.

Seljom, P., Rosenberg, E., Fidje, A., Haugen, J., Meir, M., Rekstad, J., & Jarlset, T. (2011). Modelling the Effects of Climate Change on the Energy System - A Case Study of Norway. *Energy Policy*, *39(11)*, 7310-7321.

Semadeni, M. (2003). *Energy Storage as an essential Part of sustainable Energy Systems - A Review on applied Energy Storage Technologies* (Tech. Rep. No. 24). Zürich: Centre for Energy Policy and Economics.

SER. (2013). *Energieakkoord voor duurzame Groei. Sociaal-economische Raad* (Vol. 32).

Shove, E. (2003). *Comfort, Cleanliness and Convenience: the social Organization of Normality.* Berg Publishers, Oxford and New York.

Smith, C., Crook, R., & Forster, P. (2015). *Changes in Solar PV Output due to Water Vapour Loading in a future Climate Scenario.* In: EU PVSEC Proceedings. 31st European Photovoltaic Solar Energy Conference 2015, 14-18 Sep 2015, Hamburg.

Sovacool, B. (2013). An international Assessment of Energy Security Performance. *Ecological Economics*, *88*, 148–158.

Sovacool, B., & Brown, M. (2009). *Competing Dimensions of Energy Security: An international Perspective.* Working Paper 45. Georgia Institute of Technology.

Sovacool, B., Mukherjee, I., Drupady, I., & D'Agostino, A. (2011). Evaluating Energy Security Performance from 1990 to 2010 for eighteen Countries. *Energy*, *36(10)*, 5846–5853.

Szalay, A. (2007). What is missing from the Concept of the new European Building Directive? *Building and Environment*, *42(4)*, 1761–1769.

Taleghani, M., Tenpierik, M., Dobbelsteen, A., & De Dear, R. (2013). Energy Use Impact of and thermal Comfort in different urban Block Types in the Netherlands. *Energy and Buildings*, *67*, 166–175.

Tambach, M., Hasselaar, E., & Itard, L. (2010). Assessment of current Dutch Energy Transition Policy Instruments for the existing Housing Stock. *Energy Policy*, *38 (2)*, 981–996.

The World Bank. (2008a). *Europe and Central Asia Region - How Resilient is the Energy Sector to Climate Change?* Background Paper. Retrieved from http://siteresources.worldbank.org/INTECA/Resources/AdaptationandEnergy11032009.pdf (Retrieved: 23/7/2012)

The World Bank. (2008b). *Europe and Central Asia Region - How Resilient is the Energy*

Sector to Climate Change? Background Paper.

The World Bank. (2011). *The World Development Indicators (WDI): Population, total.* The World Bank. Retrieved from http://data.worldbank.org/indicator/SP.POP.TOTL

The World Bank. (2013). *Turn Down the Heat: Climate Extremes, regional Impacts, and the Case for Resilience.* A report for the World Bank by the Potsdam Institute for Climate Impact Research and Climate Analytics. Washington, DC: World Bank. License: Creative Commons Attribution – Non Commercial – NoDerivatives3.0 – Unported license (CC BY-NC-ND 3.0).

Thormark, C. (2002). A low Energy Building in a Life Cycle – its embodied Energy, Energy Need for Operation and Recycling Potential. *Building and Environment*, *37*, 429–435.

Turner, B. L., Kasperson, R. E., Matson, P., McCarthy, J. J., Corell, R. W., Christensen, L., . . . Schiller, A. (2003). A Framework for Vulnerability Analysis in Sustainability Science. *Proceedings of the National Academy of Sciences of the United States of America*, *100(14)*, 8074–8079.

Umweltbundesamt. (2015). *Energieverbrauch nach Energieträgern und Sektoren.* Mitteilung vom 29.06.2015. Retrieved from http://www.umweltbundesamt.de/daten/energiebereitstellung-verbrauch/energieverbrauch-nach-energietraegern-sektoren (Retrieved: 28/11/2015)

UNFCCC. (2015a). *Adoption of the Paris Agreement. Proposal by the President. Draft Decision -/CP.21. Conference of the Parties. Twenty-first Session. 12 December 2015.* United Nations Framework Convention on Climate Change.

UNFCCC. (2015b). *Report on the structured Expert Dialogue on the 2013-2015 Review. Note by the Co-facilitators of the structured Expert Dialogue. FCCC/SB/2015/INF.1.* United Nations Framework Convention on Climate Change.

United Nations. (2015). *World Population Prospects: The 2015 Revision, Key Findings and advanced Tables. Working Paper No. ESA/P/WP.241.* Department of Economic and Social Affairs, Population Division.

Valor, E., Meneu, V., & Caselles, V. (2001). Daily Air Temperature and Electricity Load in Spain. *Journal of Applied Meteorology*, *40*, 1413–1421.

van der Spoel, W., & van den Ham, E. (2012). *Pilot Effect Klimaatverandering op Energiegebruik en Besparingsconcepten bij Woningen. 2012.* TU Delft.

van Vliet, M. T. H., Yearsley, J. R., Ludwig, F., Vögele, S., Lettenmaier, D. P., & Kabat, P. (2012). Vulnerability of US and European Electricity Supply to Climate Change. *Nature Climate Change*, *2(7)*, 1–6.

Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., . . . Rose, S. K. (2011). The Representative Concentration Pathways: An Overview. *Climatic Change*, *109(1-2)*, 5–31.

VROM. (2009). *Innovatieagenda Energie gebouwde Omgeving. Ministerie van Volkshuisvesting, ruimtelijke Ordening en Milieubeheer.*

Wan, K., Li, D., & Lam, J. (2011a). Assessment of Climate Change Impact on Building Energy Use and Mitigation Measures in subtropical Climates. *Energy*, *36*, 1404–1414.

Wan, K., Li, D., Liu, D., & Lam, J. (2011b). Future Trends of Building Heating and Cooling Loads and Energy Consumption in Different Climates. *Building and Environment*, *46(1)*, 223–234.

Wang, X., Chen, D., & Ren, Z. (2010). Assessment of Climate Change Impact on residential Building Heating and Cooling Energy Requirement in Australia. *Building and Environment*, *45(7)*, 1663–1682.

Werner, P., & Gerstengarbe, F.-W. (1997). Proposal for the Development of Climate Scenarios. *Climate Research*, *8(3)*, 171-180.

White, P., Pelling, M., Sen, K., Seddon, D., Russell, S., & Few, R. (2005). *Disaster Risk Reduction : A Development Concern. A scoping Study on links between Disaster Risk Reduction, Poverty and Development.* Department for International Development.

Wilbanks, T. J., Bhatt, V., Bilello, D. E., Bull, S. R., Ekmann, J., Horak, W. C., ... Scott, M. J. (2008). *Effects of Climate Change on Energy Production and Use in the United States.* U.S. Climate Change Science Program.

Wild, M., Folini, D., Henschel, F., Fischer, N., & Müller, B. (2015). Projections of long-term Changes in Solar Radiation based on CMIP5 Climate Models and their Influence on Energy Yields of Photovoltaic Systems. *Solar Energy*, *116*, 12-24.

World Business Council for Sustainable Development. (2009). *Energy Efficiency in Buildings: Transforming the Market.* Background Report. Retrieved from http://www.greenbiz.com/sites/default/files/document/transformingthemarket.pdf (Retrieved: 11/2/2012)

Yang, L., Yan, H., & Lam, J. (2014). Thermal Comfort and Building Energy Consumption Implications – A Review. *Applied Energy*, *115*, 164–173.

Yu, S., Eom, J., Zhou, Y., Evans, M., & Clarke, L. (2014). Scenarios of Building Energy Demand for China with a detailed regional Representation. *Energy*, *67*, 284–297.

Zhou, Y., Eom, J., & Clarke, L. (2013). The Effect of global Climate Change, Population Distribution, and Climate Mitigation on Building Energy Use in the U.S. and China. *Climatic Change*, *119*, 979–992.

Zmeureanu, R., & Renaud, G. (2008). Estimation of Potential Impact of Climate Change on the Heating Energy Use of existing Houses. *Energy Policy*, *36*, 303–310.

8

Appendix

8.1 Supplementary material for Chapter 2

8.1.1 Principal component analysis (PCA) results

Table 8.1: PCA results: Importance of components.

	Comp. 1	Comp. 2	Comp. 3	Comp. 4	Comp. 5
Standard deviation	1.864	1.709	1.457	1.293	1.008
Proportion of Variance	0.248	0.209	0.152	0.119	0.0725
Cumulative Proportion	0.248	0.457	0.608	0.728	0.800

Table 8.2: PCA results: Factor loadings.

Influencing Factor	Comp. 1	Comp. 2	Com. 3	Comp. 4	Comp. 5
1.1 Production and Mean Temperature Slope (Heating)	-0.016	-0.432	-0.027	0.421	-0.072
1.2 Consumption and Mean Temperature Slope (Heating)	0.024	-0.446	-0.101	0.309	0.293
1.3 Production and Mean Temperature Slope (Cooling)	0.460	-0.103	0.114	-0.132	0.062
1.4 Consumption and Mean Temperature Slope (Cooling)	0.465	-0.110	0.118	-0.129	0.038
2.1 Production and Consumption Correlation (Summer)	-0.317	-0.160	0.381	-0.250	0.310
2.2 Production and Consumption Correlation (Winter)	-0.290	-0.222	0.399	-0.255	0.091
2.3 Production and Consumption Discrepancy (Summer)	0.051	-0.244	-0.451	-0.296	0.298
2.4 Production and Consumption Discrepancy (Winter)	0.056	-0.347	-0.457	-0.203	-0.134
3.1 Thermal Production Percent (2011)	0.089	0.061	0.060	0.532	0.499
3.2 Thermal Production Change (2000-2011)	-0.185	-0.424	-0.042	0.005	-0.269
4.1 Projected Temperature Increase (Winter)	0.322	0.188	-0.142	-0.114	-0.021
4.2 Projected Temperature Increase (Summer)	0.180	-0.285	0.322	-0.006	-0.440
5.1 Air Conditioner Projection (2030)	0.287	-0.181	0.199	-0.309	0.388
5.2 Air Conditioner Percent Difference (2005-2030)	-0.348	0.065	-0.278	-0.213	0.164

8.1.2 Actual and ranked index tables

Table 8.3: Group 1: Production and consumption and mean temperature slope values (Actual values). Source: adapted from European Climate Assessment and Dataset (2012) and IEA (2012).

Influencing Factor 1.1		Influencing Factor 1.2		Influencing Factor 1.3		Influencing Factor 1.4	
Country	Production (Heating)	Country	Consumption (Heating)	Country	Production (Cooling)	Country	Consumption (Cooling)
CH	0.0031	LU	-0.0014	GR	0.0514	GR	0.0525
AT	-0.0050	IT	-0.0041	ES	0.0154	ES	0.0155
IT	-0.0077	HU	-0.0063	IT	0.0101	HU	0.0131
BE	-0.0096	DE	-0.0082	PT	0.0027	PT	0.0089
PL	-0.0103	NL	-0.0095	AT	0.0000	IT	0.0079
DE	-0.0105	PL	-0.0099	BE	0.0000	AT	0.0000
LU	-0.0108	BE	-0.0103	CH	0.0000	BE	0.0000
NL	-0.0108	AT	-0.0115	CZ	0.0000	CH	0.0000
CZ	-0.0114	GR	-0.0119	DE	0.0000	CZ	0.0000
HU	-0.0126	SK	-0.0126	DK	0.0000	DE	0.0000
SK	-0.0132	CH	-0.0138	FI	0.0000	DK	0.0000
GR	-0.0155	FI	-0.0140	FR	0.0000	FI	0.0000
ES	-0.0166	DK	-0.0154	GB	0.0000	FR	0.0000
SE	-0.0166	CZ	-0.0158	IE	0.0000	GB	0.0000
FI	-0.0167	ES	-0.0174	LU	0.0000	IE	0.0000
IE	-0.0187	IE	-0.0182	NL	0.0000	LU	0.0000
NO	-0.0254	SE	-0.0234	NO	0.0000	NL	0.0000
GB	-0.0274	GB	-0.0261	PL	0.0000	NO	0.0000
FR	-0.0277	NO	-0.027	SE	0.0000	PL	0.0000
DK	-0.0373	FR	-0.0344	SK	0.0000	SE	0.0000
PT	-0.0434	PT	-0.0369	HU	-0.0042	SK	0.0000

Table 8.4: Group 1: Production and consumption and mean temperature slope values (Ranked index values). Source: adapted from European Climate Assessment and Dataset (2012) and IEA (2012).

Influencing Factor 1.1		Influencing Factor 1.2		Influencing Factor 1.3		Influencing Factor 1.4	
Country	Production (Heating)	Country	Consumption (Heating)	Country	Production (Cooling)	Country	Consumption (Cooling)
CH	0.073	LU	-0.038	GR	1.000	GR	1.000
AT	-0.116	IT	-0.11	ES	0.300	ES	0.295
IT	-0.178	HU	-0.169	IT	0.197	HU	0.249
BE	-0.221	DE	-0.221	PT	0.053	PT	0.169
PL	-0.238	NL	-0.257	AT	0.000	IT	0.150
DE	-0.242	PL	-0.268	BE	0.000	AT	0.000
LU	-0.248	BE	-0.278	CH	0.000	BE	0.000
NL	-0.25	AT	-0.31	CZ	0.000	CH	0.000
CZ	-0.263	GR	-0.323	DE	0.000	CZ	0.000
HU	-0.291	SK	-0.342	DK	0.000	DE	0.000
SK	-0.305	CH	-0.374	FI	0.000	DK	0.000
GR	-0.358	FI	-0.378	FR	0.000	FI	0.000
SE	-0.382	DK	-0.418	GB	0.000	FR	0.000
ES	-0.383	CZ	-0.427	IE	0.000	GB	0.000
FI	-0.386	ES	-0.472	LU	0.000	IE	0.000
IE	-0.432	IE	-0.493	NL	0.000	LU	0.000
NO	-0.585	SE	-0.635	NO	0.000	NL	0.000
GB	-0.632	GB	-0.706	PL	0.000	NO	0.000
FR	-0.64	NO	-0.732	SE	0.000	PL	0.000
DK	-0.861	FR	-0.932	SK	0.000	SE	0.000
PT	-1.000	PT	-1.000	HU	-0.081	SK	0.000

Table 8.5: Group 2: Production and consumption summer and winter correlation and discrepancy (Actual values). Source: adapted from IEA (2012).

Influencing Factor 2.1		Influencing Factor 2.2		Influencing Factor 2.3		Influencing Factor 2.4	
Country	Correlation (Summer)	Country	Correlation (Winter)	Country	Discrepancy (Summer)	Country	Discrepancy (Winter)
SK	-0.301	SK	0.181	LU	0.431	LU	0.480
CH	0.183	CH	0.337	FI	0.826	IT	0.861
SE	0.370	AT	0.477	HU	0.827	AT	0.876
DK	0.391	SE	0.569	NL	0.837	NL	0.889
LU	0.499	DK	0.593	DK	0.841	FI	0.889
NL	0.525	HU	0.694	IT	0.875	CH	0.903
FR	0.554	BE	0.704	PT	0.898	HU	0.912
FI	0.563	NO	0.708	GR	0.910	BE	0.921
NO	0.573	LU	0.733	IE	0.960	PT	0.948
HU	0.639	FI	0.746	BE	0.969	GR	0.970
CZ	0.677	CZ	0.756	GB	0.972	SE	0.972
BE	0.682	PT	0.802	DE	0.979	IE	0.975
AT	0.703	NL	0.825	ES	1.008	GB	0.986
PT	0.811	GR	0.856	SE	1.020	NO	1.006
DE	0.906	FR	0.860	AT	1.028	ES	1.006
IE	0.913	DE	0.867	PL	1.035	DE	1.040
PL	0.940	PL	0.901	SK	1.079	PL	1.053
GR	0.941	IT	0.925	NO	1.107	SK	1.073
GB	0.965	GB	0.964	FR	1.168	FR	1.086
ES	0.973	IE	0.976	CH	1.190	CZ	1.181
IT	0.978	ES	0.992	CZ	1.255	DK	1.191

Table 8.6: Group 2: Production and consumption summer and winter correlation and discrepancy (Ranked index values). Source: adapted from IEA (2012).

Influencing Factor 2.1		Influencing Factor 2.2		Influencing Factor 2.3		Influencing Factor 2.4	
Country	Correlation (Summer)	Country	Correlation (Winter)	Country	Discrepancy (Summer)	Country	Discrepancy (Winter)
SK	0.307	SK	-0.182	LU	1.000	LU	1.000
CH	-0.187	CH	-0.339	FI	0.306	IT	0.267
SE	-0.378	AT	-0.480	HU	0.304	AT	0.240
DK	-0.400	SE	-0.573	NL	0.286	NL	0.214
LU	-0.510	DK	-0.598	DK	0.279	FI	0.214
NL	-0.537	HU	-0.699	IT	0.220	CH	0.187
FR	-0.567	BE	-0.710	PT	0.180	HU	0.170
FI	-0.576	NO	-0.713	GR	0.158	BE	0.153
NO	-0.586	LU	-0.739	IE	0.071	PT	0.099
HU	-0.653	FI	-0.751	BE	0.054	GR	0.057
CZ	-0.692	CZ	-0.762	GB	0.050	SE	0.055
BE	-0.697	PT	-0.809	DE	0.037	IE	0.048
AT	-0.718	NL	-0.831	ES	-0.031	GB	0.027
PT	-0.829	GR	-0.863	SE	-0.078	NO	-0.030
DE	-0.926	FR	-0.867	AT	-0.109	ES	-0.032
IE	-0.934	DE	-0.874	PL	-0.139	DE	-0.209
PL	-0.961	PL	-0.908	SK	-0.312	PL	-0.279
GR	-0.962	IT	-0.932	NO	-0.421	SK	-0.382
GB	-0.986	GB	-0.971	FR	-0.659	FR	-0.449
ES	-0.994	IE	-0.984	CH	-0.745	CZ	-0.949
IT	-1.000	ES	-1.000	CZ	-1.000	DK	-1.000

Table 8.7: Group 3: Thermal electricity production (Actual values). Source: adapted from IEA (2012).

Influencing Factor 3.1		Influencing Factor 3.2	
Country	Thermal Production Percent (2011)	Country	Thermal Production Percent Difference (2000-2011)
HU	0.975	LU	0.435
PL	0.963	AT	0.151
NL	0.951	SE	0.047
CZ	0.935	CH	0.039
GB	0.932	NO	0.035
BE	0.912	FI	0.030
FR	0.883	FR	0.021
GR	0.860	SK	0.020
SK	0.851	PL	-0.007
DE	0.828	HU	-0.020
FI	0.814	CZ	-0.031
IE	0.812	NL	-0.035
IT	0.751	IT	-0.036
DK	0.707	GB	-0.044
ES	0.704	GR	-0.049
LU	0.673	BE	-0.067
PT	0.577	DE	-0.107
SE	0.494	ES	-0.127
CH	0.461	IE	-0.137
AT	0.440	PT	-0.143
NO	0.039	DK	-0.168

Table 8.8: Group 3: Thermal electricity production share (Ranked index values). Source: adapted from IEA (2012).

Influencing Factor 3.1		Influencing Factor 3.2	
Country	Thermal Production Percent (2011)	Country	Thermal Production Percent Difference (2000-2011)
HU	1.000	LU	1.000
PL	0.987	AT	0.347
NL	0.975	SE	0.108
CZ	0.958	CH	0.090
GB	0.956	NO	0.080
BE	0.935	FI	0.069
FR	0.905	FR	0.049
GR	0.881	SK	0.045
SK	0.872	PL	-0.039
DE	0.849	HU	-0.116
FI	0.835	CZ	-0.186
IE	0.833	NL	-0.209
IT	0.770	IT	-0.214
DK	0.724	GB	-0.263
ES	0.722	GR	-0.294
LU	0.690	BE	-0.399
PT	0.592	DE	-0.634
SE	0.506	ES	-0.755
CH	0.473	IE	-0.815
AT	0.451	PT	-0.848
NO	0.040	DK	-1.000

Table 8.9: Group 4: Scenario A2 temperature increase 1961-90 to 2070-99 (°C) (Actual values). Source: adapted from Mitchell et al. (2002).

Influencing Factor 4.1		Influencing Factor 4.2	
Country	Winter Increase	Country	Summer Increase
FI	7.081	ES	4.976
SE	5.761	HU	4.740
NO	5.093	CH	4.737
PL	5.089	AT	4.522
SK	4.698	FR	4.491
CZ	4.469	GR	4.406
HU	4.453	SK	4.402
DK	4.278	IT	4.309
AT	4.153	LU	4.189
DE	4.103	CZ	4.108
CH	3.743	PT	4.056
LU	3.733	BE	3.946
NL	3.674	PL	3.939
BE	3.626	DE	3.886
IT	3.369	FI	3.796
FR	3.307	NL	3.531
GR	3.120	SE	3.530
ES	3.057	DK	3.399
GB	2.981	NO	3.264
PT	2.757	GB	3.088
IE	2.579	IE	2.702

Table 8.10: Group 4: Scenario A2 temperature increase 1961-90 to 2070-99 (Ranked index values). Source: adapted from Mitchell et al. (2002).

Influencing Factor 4.1		Influencing Factor 4.2	
Country	Winter Increase	Country	Summer Increase
IE	-0.364	ES	1.000
PT	-0.389	HU	0.953
GB	-0.421	CH	0.952
ES	-0.432	AT	0.909
GR	-0.441	FR	0.903
FR	-0.467	GR	0.885
IT	-0.476	SK	0.885
BE	-0.512	IT	0.866
NL	-0.519	LU	0.842
LU	-0.527	CZ	0.826
CH	-0.529	PT	0.815
DE	-0.580	BE	0.793
AT	-0.587	PL	0.792
DK	-0.604	DE	0.781
HU	-0.629	FI	0.763
CZ	-0.631	NL	0.710
SK	-0.663	SE	0.710
PL	-0.719	DK	0.683
NO	-0.719	NO	0.656
SE	-0.814	GB	0.621
FI	-1.000	IE	0.543

Table 8.11: Group 5: Air conditioner prevalence (per capita) (Actual values). Note: No data was available for CH or NO. Source: adapted from Adnot et al. (2008).

Influencing Factor 5.1		Influencing Factor 5.2	
Country	Projection (2030)	Country	Percentage Difference (2005-2030)
IT	0.521	FI	3.651
GR	0.491	SE	3.316
SK	0.469	GB	3.189
ES	0.420	AT	3.145
FR	0.250	NL	3.082
NL	0.246	FR	3.061
DK	0.242	DK	3.040
BE	0.227	IE	2.948
LU	0.211	BE	2.766
GB	0.186	LU	2.242
FI	0.166	HU	2.062
HU	0.162	IT	1.956
SE	0.154	SK	1.645
PT	0.146	PL	1.635
IE	0.143	PT	1.501
AT	0.088	ES	1.491
CZ	0.044	DE	1.368
DE	0.042	CZ	1.128
PL	0.015	GR	0.790
CH	-	CH	-
NO	-	NO	-

Table 8.12: Group 5: Air conditioner prevalence (Ranked index values). Note: No data was available for CH or NO. Source: adapted from Adnot et al. (2008).

Influencing Factor 5.1		Influencing Factor 5.2	
Country	Projection (2030)	Country	Percentage Difference (2005-2030)
IT	1.000	FI	1.000
GR	0.942	SE	0.908
SK	0.901	GB	0.874
ES	0.806	AT	0.862
FR	0.480	NL	0.844
NL	0.472	FR	0.838
DK	0.464	DK	0.833
BE	0.435	IE	0.808
LU	0.404	BE	0.758
GB	0.358	LU	0.614
FI	0.319	HU	0.565
HU	0.310	IT	0.536
SE	0.296	SK	0.451
PT	0.279	PL	0.448
IE	0.274	PT	0.411
AT	0.169	ES	0.408
CZ	0.084	DE	0.375
DE	0.080	CZ	0.309
PL	0.029	GR	0.216
CH	-	CH	-
NO	-	NO	-

8.1.3 Additional results figures

8.1.3.1 Electricity production and consumption by mean temperature

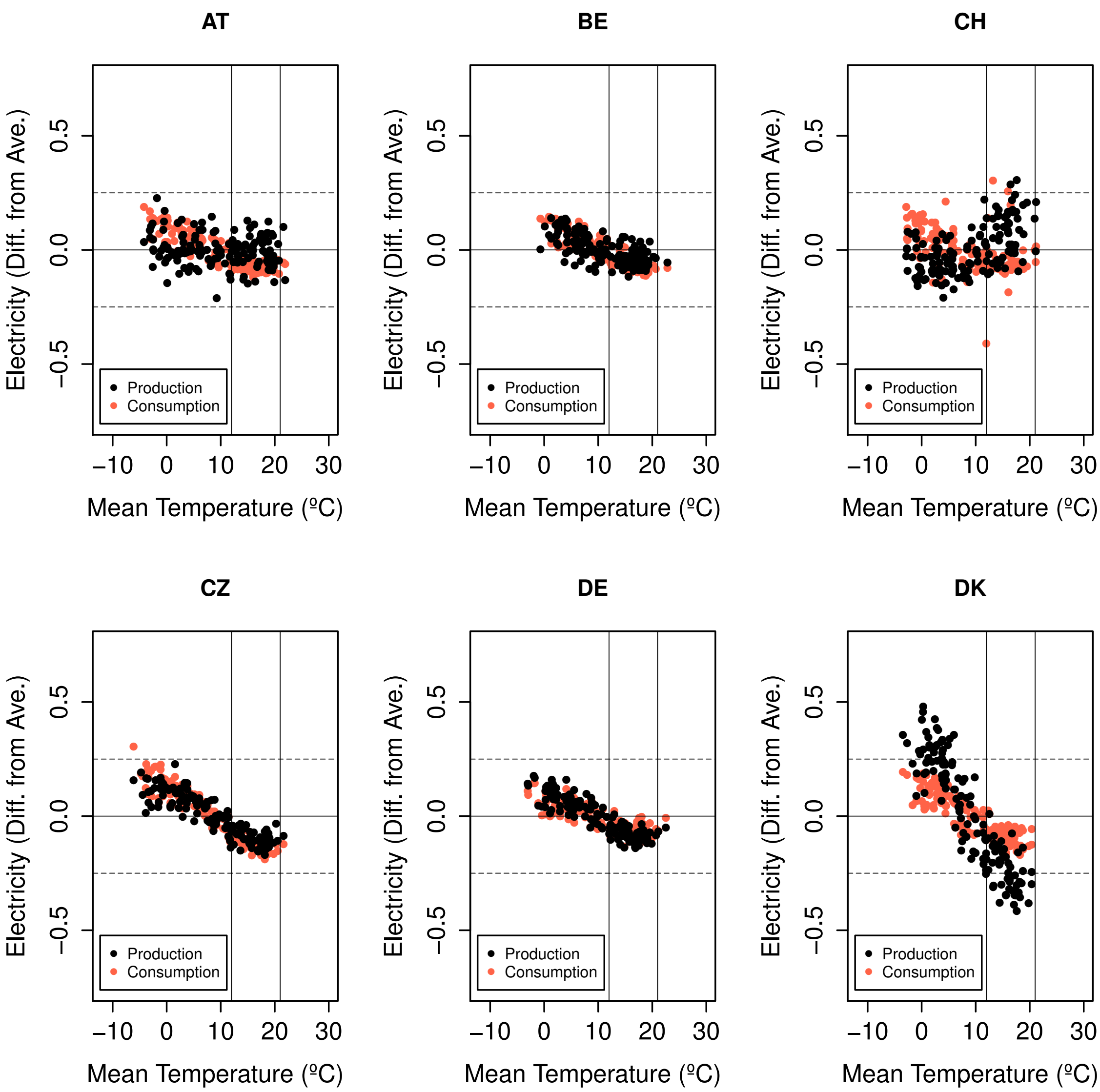

Figure 8.1: Mean temperature vs. the percent difference of electricity consumption from the annual average, including the heating threshold of 12 °C and above the cooling threshold of 21 °C (1/4). Source: adapted from European Climate Assessment and Dataset (2012) and IEA (2012).

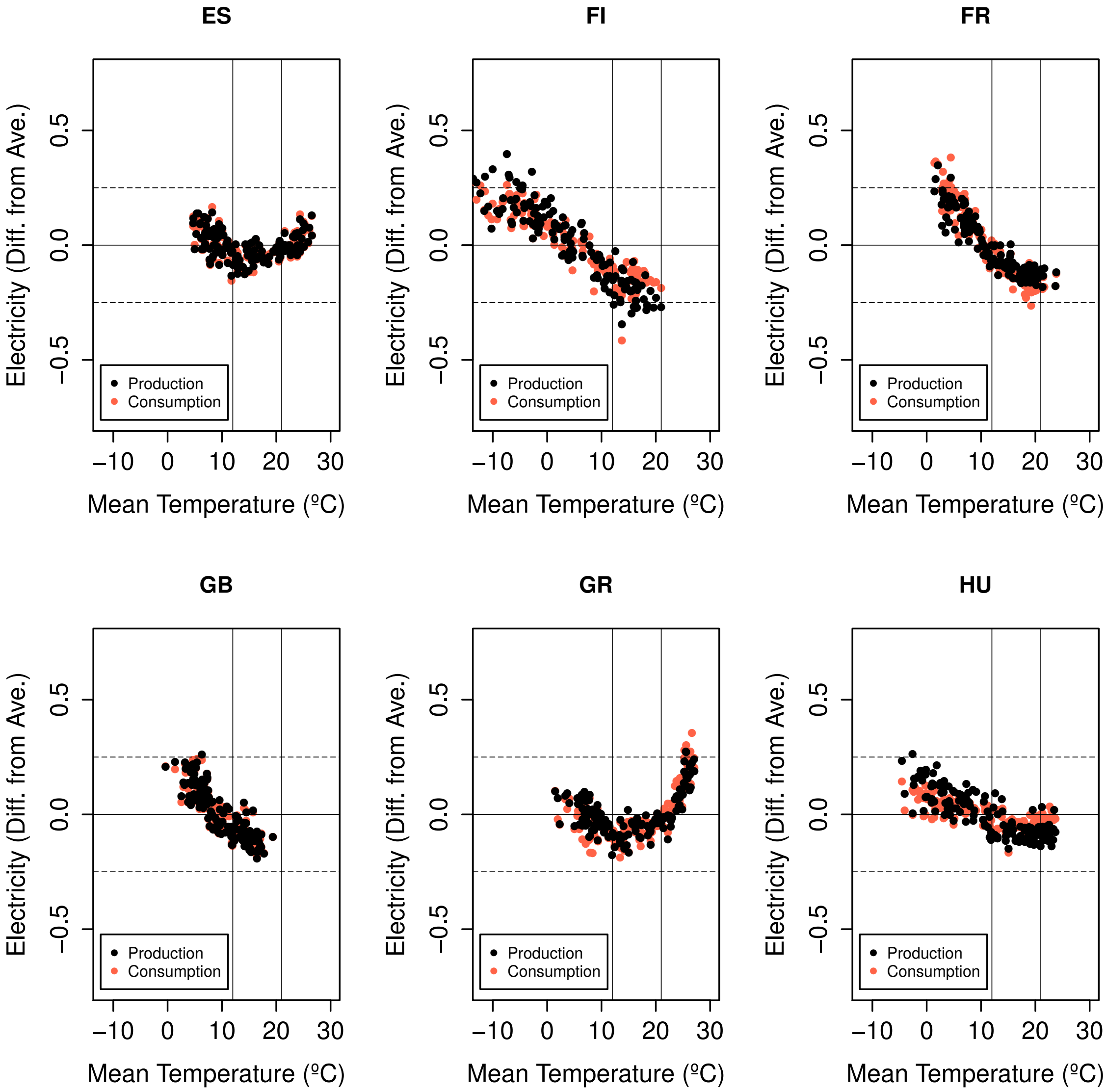

Figure 8.2: Mean temperature vs. the percent difference of electricity consumption from the annual average, including the heating threshold of 12 °C and above the cooling threshold of 21 °C (2/4). Source: adapted from European Climate Assessment and Dataset (2012) and IEA (2012).

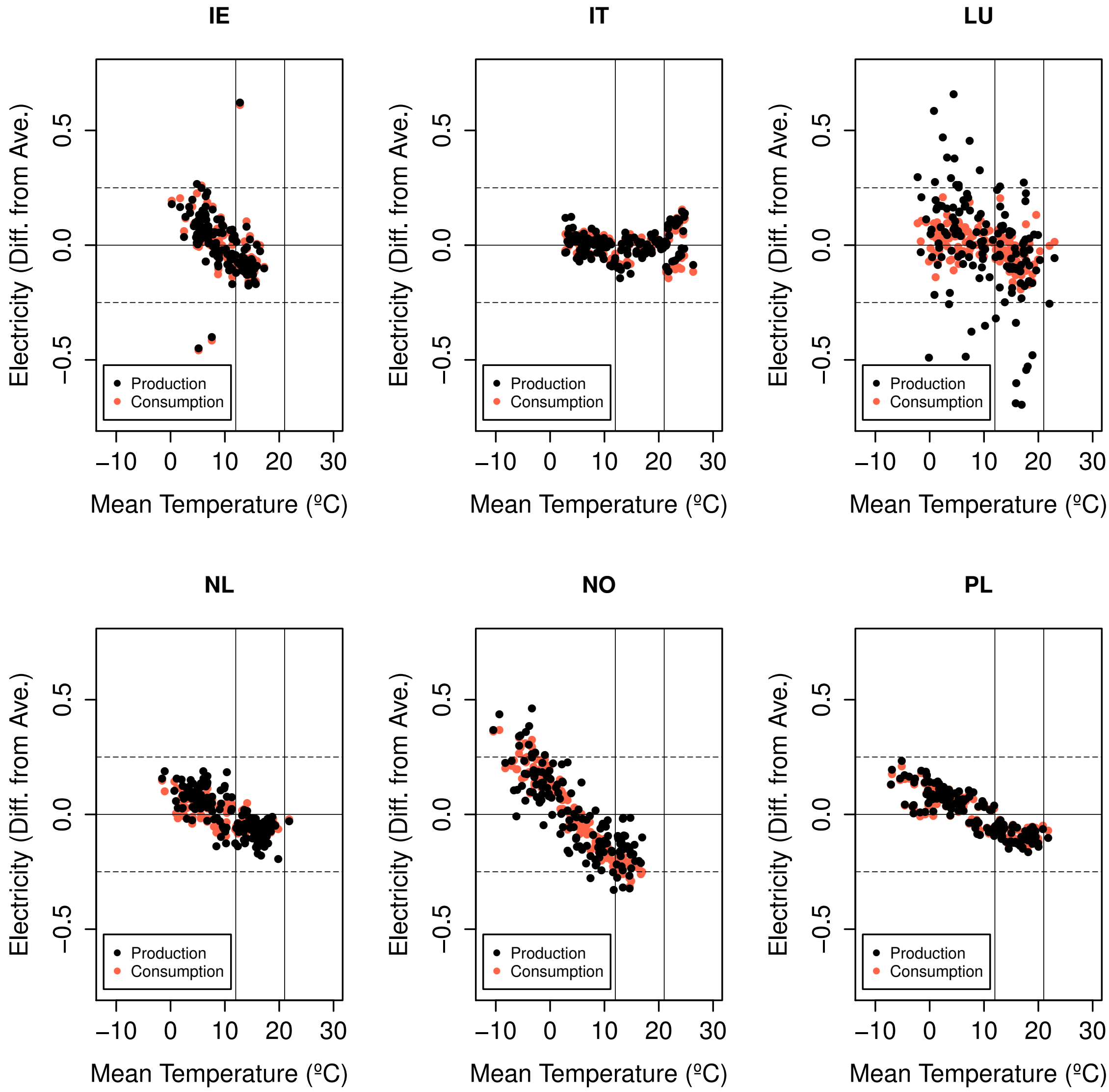

Figure 8.3: Mean temperature vs. the percent difference of electricity consumption from the annual average, including the heating threshold of 12 °C and above the cooling threshold of 21 °C (3/4). Source: adapted from European Climate Assessment and Dataset (2012) and IEA (2012).

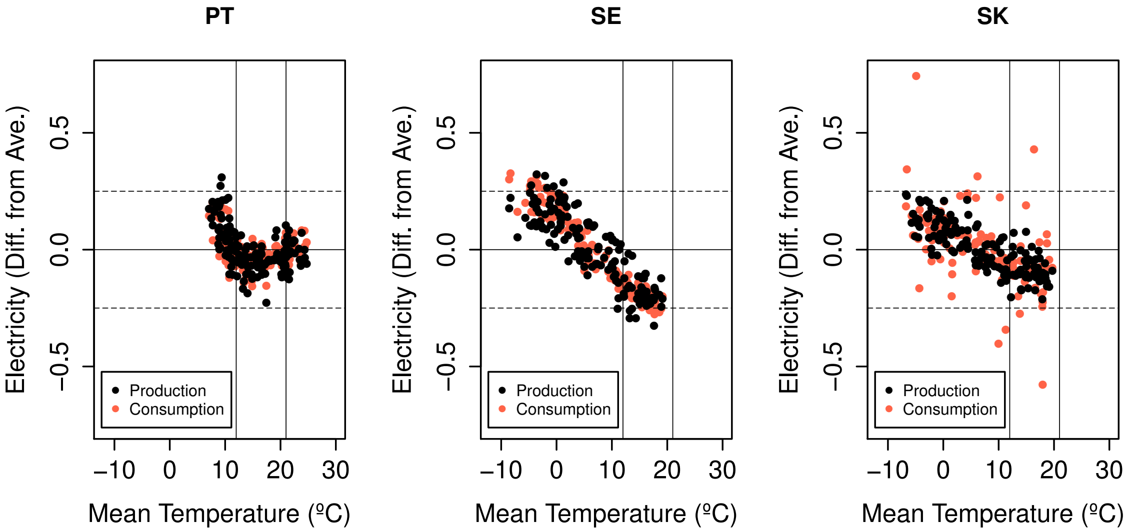

Figure 8.4: Mean temperature vs. the percent difference of electricity consumption from the annual average, including the heating threshold of 12 °C and above the cooling threshold of 21 °C (4/4). Source: adapted from European Climate Assessment and Dataset (2012) and IEA (2012).

8.1.3.2 Monthly electricity production, consumption, imports and exports over time (2000-2011)

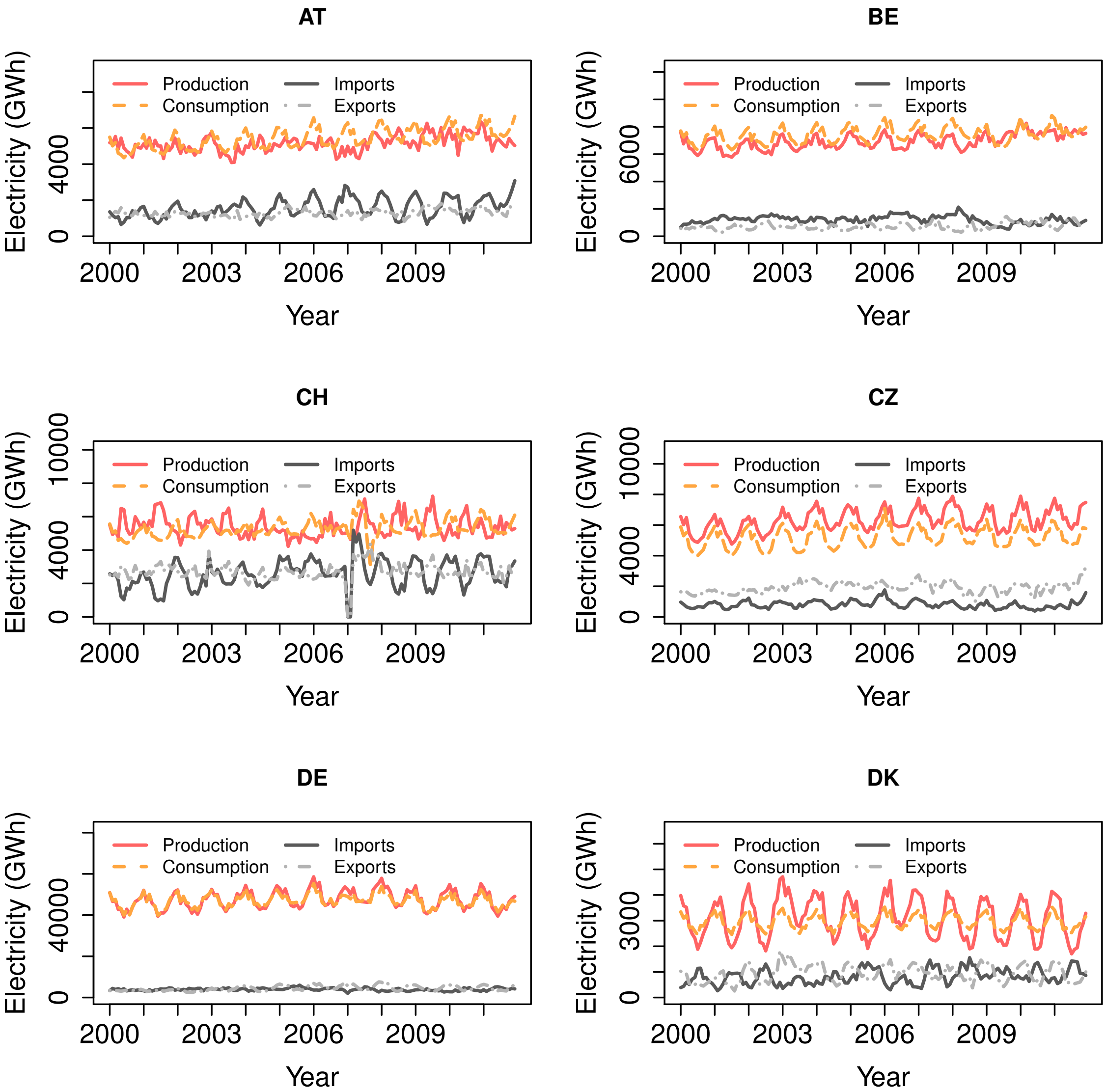

Figure 8.5: Monthly electricity production and consumption over time (2000-2011) (1/4). Source: adapted from IEA (2012).

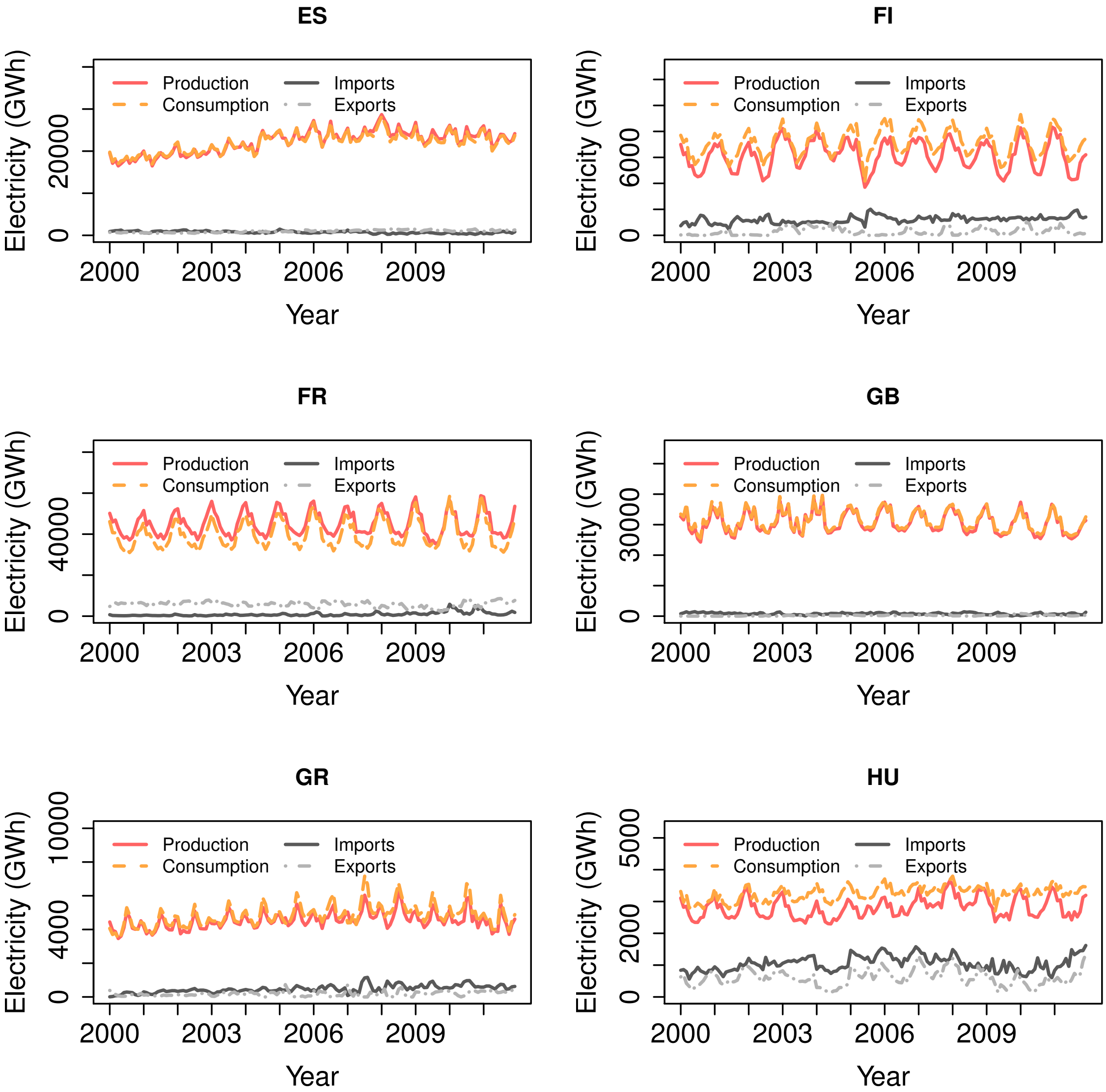

Figure 8.6: Monthly electricity production and consumption over time (2000-2011) (2/4). Source: adapted from IEA (2012).

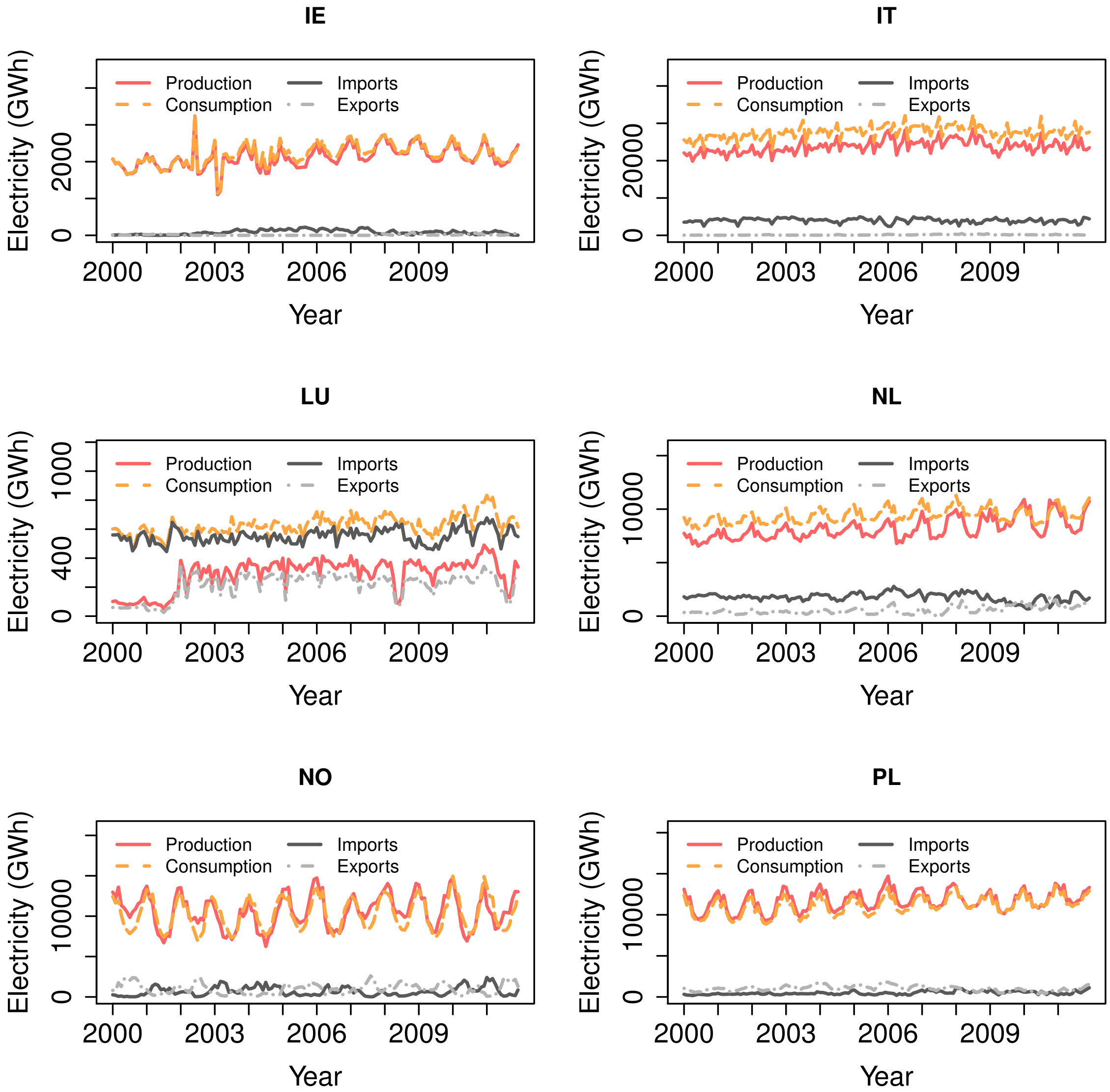

Figure 8.7: Monthly electricity production and consumption over time (2000-2011) (3/4). Source: adapted from IEA (2012).

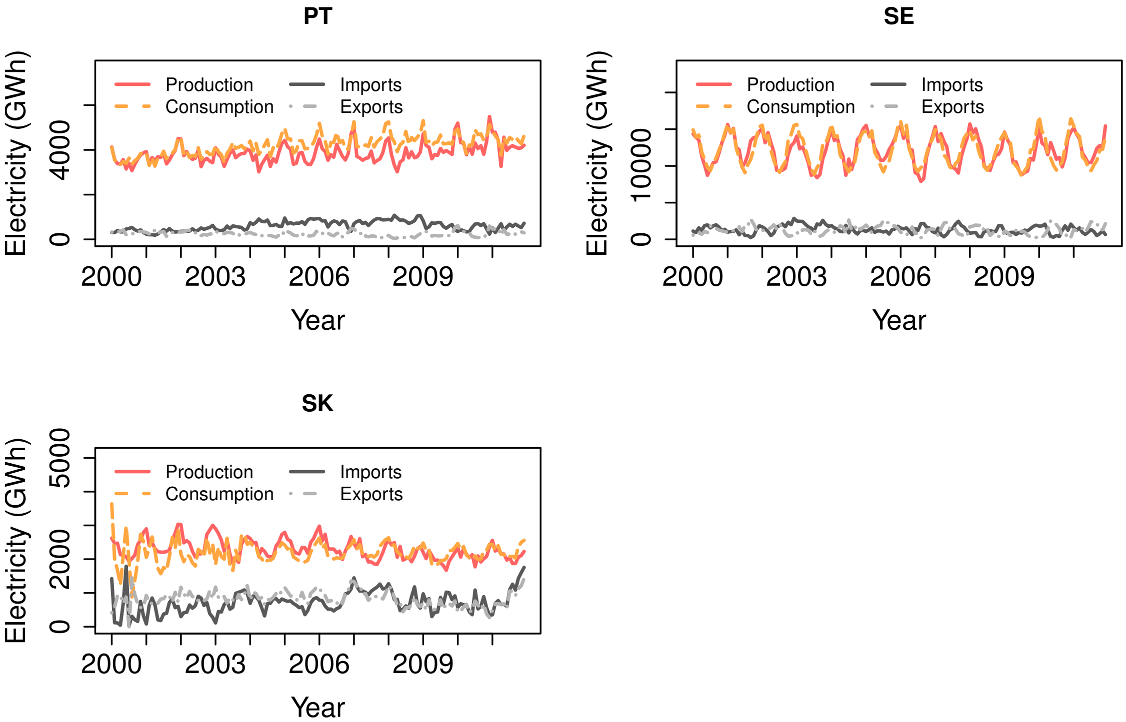

Figure 8.8: Monthly electricity production and consumption over time (2000-2011) (4/4). Source: adapted from IEA (2012).

8.1.3.3 Sensitivity analysis of influencing factors

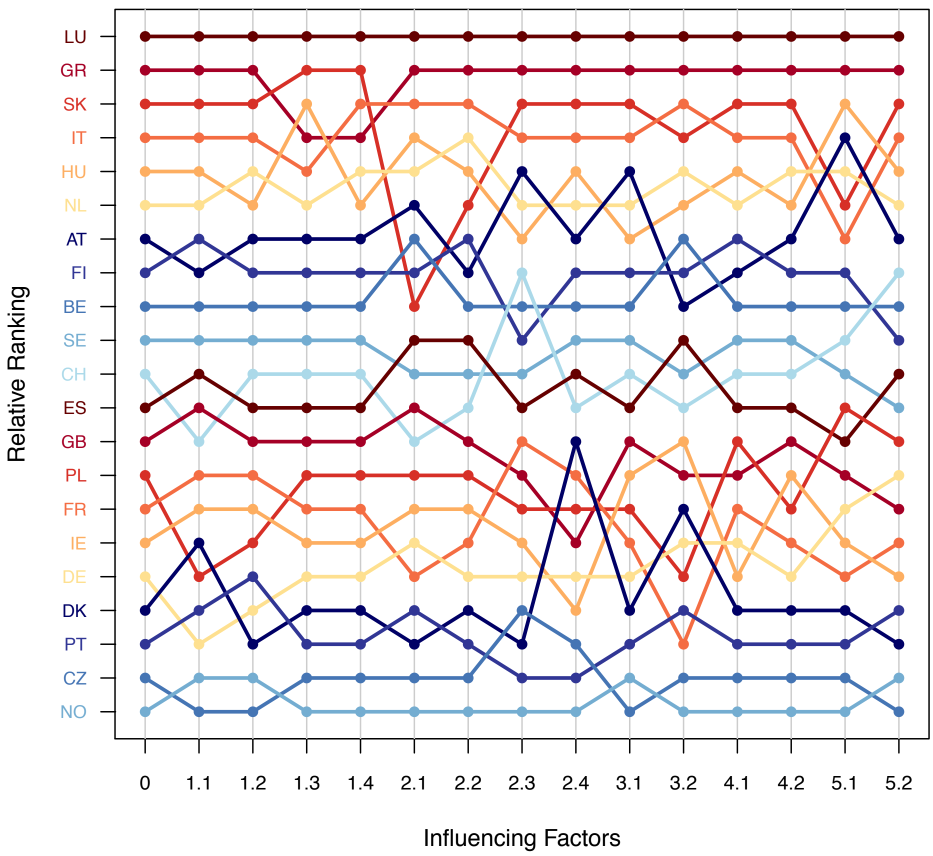

Figure 8.9: Sensitivity analysis of influencing factors on the final index ranking chart. Note: Influencing factor 0 represents the original index ranking.

8.2 Supplementary material for Chapter 4

8.2.1 Dwelling structure in the Netherlands

Table 8.13: Applied data on the type of dwellings as well as the total number in 2012 and in 2050 according to the three population forecasts per province.

Province	% dwellings in freestanding houses	% dwellings in semi-detached houses	% dwellings in row houses	% dwellings in huge houses	Total number of dwellings in 2012	Total number of dwellings in the lower 95% forecast intervall	Total number of dwellings in the population forecast	Total number of dwellings in the upper 95% forecast intervall
Groningen	24.4	15.2	29.0	31.4	267,466	257,660	268,227	280,880
Friesland	31.7	20.6	29.7	18.0	289,381	283,971	295,618	309,563
Drenthe	29.7	22.7	28.6	19.0	214,890	200,105	208,312	218,138
Overijssel	19.6	19.6	38.7	22.1	485,392	486,281	506,225	530,104
Flevoland	8.9	10.9	61.1	19.1	159,496	197,951	206,070	215,791
Gelderland	18.7	16.6	39.7	25.0	859,853	839,090	873,504	914,708
Utrecht	7.0	10.2	46.9	36.0	534,595	578,665	602,398	630,814
Noord-Holland	8.1	7.2	37.8	46,9	1,262,792	1,330,932	1,385,518	1,450,875
Zuid-Holland	5.3	4.5	40.8	49.3	1,618,648	1,700,469	1,770,211	1,853,713
Zeeland	23.4	14.7	43.6	18.3	180,369	169,346	176,291	184,607
Noord-Brabant	17.9	15.9	42.7	23.5	1,062,387	1,071,441	1,115,384	1,167,998
Limburg	19.5	21.8	30.3	28.4	514,029	464,334	483,378	506,179

Table 8.14: Applied data on the age of dwellings (valid both for the whole country and each province)

Period of erection	% dwellings in freestanding houses	% dwellings in semi-detached houses	% dwellings in row houses	% dwellings in huge houses
Before 1946	/	/	18.4	12.0
1946-1964	45.8	34.4	16.8	30.5
1965-1974	12.7	17.2	21.5	20.1
1975-1991	23.2	27.1	30.9	21.7
1992-2005	18.3	21.3	12.4	15.7
Sum	100	100	100	100

8.2.2 Additional equations for the calculation of the heating energy demand

The time and temperature weighted air volume supply and return flow $q_{ve,mn}$ was calculated according to NEN 8088 by:

$$q_{ve,mn} = q_{ve,sys} + 0.48 \cdot q_{ve,spec,spui} \cdot A_g + q_{ve,verbr} + q_{ve,inf} \tag{8.1}$$

where

$q_{ve,sys}$ = Time weighted air volume flow as consequence of the ventilation system $[dm^3/s]$,

$q_{ve,spec,spui}$ = Specific intensive ventilation = 0.125 for a system with natural supply and return, mechanically = 0.147 $[dm^3/(s \cdot m^2)]$,

A_g = Base area $[m^2]$,

$q_{ve,verbr}$ = Time weighted air volume flow necessary for open ovens $[dm^3/s]$,

$q_{ve,inf}$ = Time weighted air volume flow as consequence of infiltration $[dm^3/s]$.

The time weighted air volume flow as consequence of the ventilation system $q_{ve,sys}$ was calculated by:

$$q_{ve,sys} = 0.48 \cdot f_{kan} \cdot f_{sys} \cdot q_{vr,spec,functieg} \cdot A_g \tag{8.2}$$

where

f_{kan} = Correction factor for air leak losses from air supply channels = 1.2 for a mechanical system, natural = 1 [-],

f_{sys} = Air volume flow factor related to the ventilation system [-], in case of a system with natural supply $= 1.24 \cdot (1 - T_{sysC}) + 3T_{sysC}$, in case of a system with mechanical supply $= 3 \cdot (1 - T_{sysC}) + T_{sysC}$,

T_{sysC} = Temperature weighted time fraction of the maximum usage of the installed ventilation capacity (depending on the considered month: J:0.01, F:0.11, M:0.08, A:0.3, M:0.73, J:0.88, J:1, A:0.93, S:0.89, O:0.56, N:0.17, D:0.03) [-],

$q_{vr,spec,functieg}$ = Specific ventilation capacity related to the utilitarian purpose = 0.72 $[dm^3/(s \cdot m^2)]$.

The time weighted combustion air supply capacity necessary for open ovens $q_{ve,verbr}$ was calculated by:

$$q_{ve,verbr} = 0.2 \cdot f_{tst} \cdot q_{ve,spec,verbr} \cdot B_i \tag{8.3}$$

where

f_{tst} = Correction factor for the degree in which the air volume supply flow neccessary for open ovens has to be considered = 0 for a natural supply system, otherwise = 1 [-],

$q_{ve,spec,verbr}$ = Specific air volume flow necessary for open ovens $[dm^3/s \cdot kW]$,

B_i = Nominal stress of the open oven [kW].

Values for $q_{ve,spec,verbr}$ and B_i are given for different types of heating in NEN 8088. Due to a lack of information on the share of each type of heating, we averaged values for $q_{ve,spec,verbr}$ as well as B_i over all types obtaining values of 1.4 and 17.15.
The time weighted air volume supply flow as consequence of infiltration $q_{ve,inf}$ was calculated by:

$$q_{ve,inf} = \cdot f_{inf} \cdot f_{type} \cdot f_{jaar} \cdot q_{v10,spec,reken} \cdot A_g \tag{8.4}$$

where

f_{inf}= Correction factor for infiltration caused by the ventilation system = 0.08 for a natural supply system, otherwise = 0.115 [-],

f_{type} = Correction factor for infiltration depending on the dwelling type = 1.4 in case of dwellings in freestanding, semi-detached and row houses, otherwise = 1.8 [-],

f_{jaar} = Construction year correction factor for infiltration depending on the dwelling type and the year of construction, 4 in case of dwellings erected before 1975, 3.2 for dwellings erected after 1974 [-],

$q_{v10,spec,reken}$ = Value for the specific air volume flow caused by infiltration = 0.8 in case of dwellings in freestanding, semi-detached and row houses, otherwise = 0.5 $[dm^3/(s * m^2)]$.

Due to a lack of information, we averaged values for stone, concrete and timber frame and types of dwellings (e. g. flat and pitched roof).

The correction factor for levelling the temperature in a dwelling $f_{int,set,H,adj}$ was calculated by:

$$f_{int,set,H,adj} = \frac{(0.3 \cdot H_{e,spec}) + H_{int,spec}}{(0.5 \cdot H_{e,spec}) + H_{int,spec}} \tag{8.5}$$

where

$H_{e,spec}$ = Specific heat transfer coefficient for transmission and ventilation $[W * m^2/K]$,

$H_{int,spec}$ = Internal heat transfer coefficient = 2.0 $[W/m^2 \cdot K]$.

The specific heat transfer coefficient for transmission and ventilation $H_{e,spec}$ was calculated by:

$$H_{e,spec} = \frac{(H_{tr,adj} + H_{ve,adj})}{A_g} \tag{8.6}$$

The reduction factor for night setback of the temperature $a_{H,red,night}$ was calculated as follows:

As:

$$\frac{t_{H,hr,low}}{\tau_H} > \frac{1}{3}: \qquad a_{H,red,night} = \frac{47}{72} \tag{8.7}$$

where

$t_{H,hr,low}$ = Number of hours per day with reduced indoor temperature or room thermostat switched off = 10,

τ_H = Time constant for heating.

The time constant for heating τ_H was calculated by:

$$\tau_H = \frac{C_m/3600}{H_{tr,adj} + H_{ve,adj}} \tag{8.8}$$

where

C_m = Effective internal heat capacity = $D_m \cdot A_g$,

D_m = Specific internal heat capacity = 400 $[kJ/m^2 \cdot K]$.

Heat flow caused by incoming sun rays $\phi_{sol,k}$ was calculated by:

$$\phi_{sol,k} = A_{sol,k} \cdot I_{sol,k} - 0.5 \cdot R_{se} \cdot U_c \cdot A_T \cdot h_r \cdot \Delta\theta_{er} \tag{8.9}$$

where
$A_{sol,k}$ = Effective collector surface of construction k $[m^2]$,
$I_{sol,k}$ = Mean amount of energy of incoming sun rays given a slope of 60 and averaged over all orientations (depending on the considered month: J:30.06, F:46.39, M:67.23, A:132.91, M:157.98, J:167.38, J:147.65, A:142.49, S:97.125, O:67.26, N:33.41, D:24.19)$[W/m^2]$,
R_{se} = Heat transfer resistor of the outside of the non-transparent construction = 0.04 $[m^2 * K/W]$,
U_c = Heat transfer coefficient of the non-transparent construction $[W/m^2 * K]$,
A_T = Total surface of the non-transparent construction $[m^2]$,
h_r = Heat transfer coefficient caused by radiation outside the construction = 4,5 $[W/m^2 * K]$,
$\Delta\theta_{er}$ = Time weighted difference between the temperature of the external air and the apparent sky temperature = 11 [°C].

The effective collector surface of transparent constructions $A_{sol,trans}$ was calculated by:

$$A_{sol,trans} = 0.4725 \cdot A_{w,p} \tag{8.10}$$

where

$A_{w,p}$ = Total surface of the glazing $[m^2]$.

The effective collector surface of non-transparent constructions $A_{sol,ntrans}$ was calculated by:

$$A_{sol,ntrans} = 0.8 \cdot R_{se} \cdot U_c \cdot A_T \tag{8.11}$$

Declaration of Authorship

I, Mady Olonscheck, declare that this dissertation titled, 'Climate change impacts on electricity and residential energy demand' and the work presented in it are my own. I confirm that I did not use any other than the declared sources, references and tools. All passages included from other works, whether verbatim or in content, have been indicated as such. No part of this dissertation has been submitted for any other degree, neither in Germany nor in another country.

Mady Olonscheck

Potsdam, May 2016

This publication was printed on 100% recycled paper.