Springer Climate

Karl W. Steininger · Martin König
Birgit Bednar-Friedl · Lukas Kranzl
Wolfgang Loibl · Franz Prettenthaler
Editors

Economic Evaluation of Climate Change Impacts

Development of a Cross-Sectoral Framework and Results for Austria

EXTRA MATERIALS
extras.springer.com

Springer

Springer Climate

Karl W. Steininger · Martin König · Birgit Bednar-Friedl · Lukas Kranzl · Wolfgang Loibl
Franz Prettenthaler *Editors*

Economic Evaluation of Climate Change Impacts

Development of a Cross-Sectoral Framework and Results for Austria

This volume deals with the multifaceted and interdependent impacts of climate change on society from the perspective of a broad set of disciplines. The main objective of the book is to assess public and private cost of climate change as far as quantifyable, while taking into account the high degree of uncertainty. It offers new insights for the economic assessment of a broad range of climate change impact chains at a national scale. The framework presented in the book allows consistent evaluation including mutual interdependencies and macroeconomic feedback. This book develops a toolbox that can be used across the many areas of climate impact and applies it to one particular country: Austria.

"This study is a landmark, setting a new standard for the assessment of the impacts of climate change. It stands out for the comprehensiveness of its coverage of potential impacts across different sectors of the economy and its methodological innovations, including tracing climate impacts to economic endpoints."
Michael Hanemann, Professor of Economics, Arizona State University and Professor of the Graduate School, University of California, Berkeley

"This volume develops a consistent, bottom-up approach for a robust evaluation across the whole range of impact fields, acknowledging their macroeconomic feedbacks and budgetary implications."
Thomas Sterner, Professor of Economics, University of Gothenburg

"The lasting value of this book will come from the methodology with its frameworks, consistent toolbox and comprehensive integration, as well as the lessons learnt and shared, exemplified through application in Austria."
Roger Street, Director of UK Climate Impacts Programme, University of Oxford

Environment

ISBN 978-3-319-12456-8

9 783319 124568

EXTRA MATERIALS
extras.springer.com

Springer Climate is an interdisciplinary book series dedicated to all climate research. This includes climatology, climate change impacts, climate change management, climate change policy, regional climate, climate monitoring and modelling, palaeoclimatology etc. The series hosts high quality research monographs and edited volumes on Climate, and is crucial reading material for researchers and students in the field, but also policy makers, and industries dealing with climatic issues. Springer Climate books are all peer-reviewed by specialists (see Editorial Advisory board). If you wish to submit a book project to this series, please contact your publisher (elodie.tronche@springer.com).

More information about this series at
http://www.springer.com/series/11741

Karl W. Steininger • Martin König •
Birgit Bednar-Friedl • Lukas Kranzl •
Wolfgang Loibl • Franz Prettenthaler
Editors

Economic Evaluation of Climate Change Impacts

Development of a Cross-Sectoral Framework and Results for Austria

Springer

Editors
Karl W. Steininger
University of Graz
Graz, Austria

Martin König
Environment Agency Austria
Vienna, Austria

Birgit Bednar-Friedl
University of Graz
Graz, Austria

Lukas Kranzl
Vienna University of Technology
Vienna, Austria

Wolfgang Loibl
Austrian Institute of Technology
Vienna, Austria

Franz Prettenthaler
Institute for Economic and Innovation Research
Graz, Austria

Additional material to this book can be downloaded from http://extras.springer.com

ISSN 2352-0698 ISSN 2352-0701 (electronic)
ISBN 978-3-319-12456-8 ISBN 978-3-319-12457-5 (eBook)
DOI 10.1007/978-3-319-12457-5
Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014959279

The results reported in this book have been acquired in a project financially supported by the Austrian Climate and Energy Fund (COIN project, carried out within the Austrian Climate Research Programme, ACRP).

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

Preface

Our current actions determi
tions. Beyond climate cha
action and potential impact
priate response may entail
clear need for adequate inf
Climate change impacts
high degree of uncertainty.
broad set of disciplines and
In this volume, we show h
climate change impacts can
generation of information re
of climate change. A tool bo
climate impact is developed
Climate scenario analy
associated with climate ch
values are surrounded by a
consider the potential range
lower damage values). Ide
clarify that several different
socio-economic developme
of greenhouse gas emission
determine how resilient so
(and whether they will be i
sures in response). For exam
infrastructure in flood pron
increase the urban heat isla
people's homes are equippe
expected future ageing), wh
transport, production proce
crucial in determining a so

Chapter 14
Electricity

Lukas Kranzl, Gerhard Totschnig, Andreas Müller, Gabriel Bachner, and Birgit Bednar-Friedl

Abstract This chapter investigates the impact of climate change on the electricity sector. We quantified two main impact chains: (1) impact of climate change on electricity supply, in particular on hydropower and (2) impact of climate change on electricity demand, in particular for heating and cooling. The combined effects of these two impact chains were investigated using the optimization model HiREPS. This takes the hourly resolution of the electricity system into account and considers, in particular, the interaction of the Austrian and German electricity markets. The results show that by 2050 there is a robust shift in the generation of hydroelectric power from summer to winter periods and a slight overall reduction in hydropower generation. The absolute increase in electricity demand is moderate. However, the electricity peak for cooling approximately reaches the level of the overall electricity load in 2010. These two effects—decreasing hydropower supply and increasing cooling electricity peak load (cf. Chap. 13)—lead to moderate sectoral climate change costs in 2050 compared to the baseline scenario without climate change. Regarding macroeconomic effects coming from climate change impacts on the electricity sector we see negative impacts on welfare as well as GDP. However, significant uncertainties remain and the effect of extreme events and natural hazards on electricity supply and transmission infrastructure also needs further examination. The costs of a potential increase in black out risk may be orders of magnitude higher than the costs indicated in our mid-range scenario.

L. Kranzl (✉) • G. Totschnig • A. Müller
Institute of Energy Systems and Electrical Drives, Vienna University of Technology, Vienna, Austria
e-mail: kranzl@eeg.tuwien.ac.at; totschnig@eeg.tuwien.ac.at; mueller@eeg.tuwien.ac.at

G. Bachner
Wegener Center for Climate and Global Change, University of Graz, Graz, Austria
e-mail: gabriel.bachner@uni-graz.at

B. Bednar-Friedl
Wegener Center for Climate and Global Change, University of Graz, Graz, Austria

Department of Economics, University of Graz, Graz, Austria
e-mail: birgit.friedl@uni-graz.at

K.W. Steininger et al. (eds.), *Economic Evaluation of Climate Change Impacts*, Springer Climate, DOI 10.1007/978-3-319-12457-5_14

14.1 Introduction

As the highest emission of greenhouse gases occurs in the energy sector it is clearly one of the key drivers of climate change. At the same time, however, climate change itself has an effect on energy provision and consumption: e.g. the demand for cooling energy increases, the demand for heating energy decreases, hydropower generation is affected by changes in levels of precipitation and evaporation, power plants may be affected by rising sea level, decreasing cooling water supply (quantity and temperature) and the risk of damage to energy grid infrastructure as a result of an increase in natural hazards is also likely to increase [on a global scale, these aspects are discussed in detail in Arent and Tol (2014)].

The energy sector has been subject to radical change in the last few years and decades (see e.g. Haas et al. 2008; Grübler et al. 2011). In the future, the sector clearly will have a major impact on global sustainability indicators and the level of greenhouse gas emissions. The objective of this chapter is to assess the cost of climate change in the electricity sector. Despite of the fact that the costs of climate change in the electricity sector are also driven by non-climatic factors (e.g. population growth) and by the whole development of the sector itself (e.g. technological development) which is highly uncertain, the focus of this chapter is not to provide a detailed assessment of future scenarios of the electricity system.

The relevant impact of climate change on electricity demand was specifically taken into account in the field of activity "buildings: heating and cooling" but also with regard to demand of other energy carriers than electricity (see Chap. 13). In this chapter, we focus on relevant aspects of climate change costs in the electricity sector for the case of Austria. We are aware that a comprehensive study of climate change impact across the whole energy sector would have to include also other sectors, aspects and effects than those considered and quantified here (see also Table 14.1 and the list of considered impact chains).

14.2 Dimensions of Climate Sensitivity to Climate Change

The electricity sector exhibits several dimensions of sensitivity to climate change. However, for the purposes of the present study, only a sub-set of these dimensions is investigated in any detail (see Table 14.1).

Relevant topics are:

- Sensitivity of infrastructure to natural hazards and on the international scale to sea level rise (as a landlocked country the latter is not relevant for Austria): This includes impact on transmission infrastructure and impact on supply infrastructure (e.g. refineries, power plants, mining). In the present work, this aspect is not quantified.
- Sensitivity of electricity demand: Climate change has an impact not only on electricity consumption for heating and cooling but also on the related load

Table 14.1 Impact chains sector electricity

Climate change parameter	Impact chain	Quantified in the model
Precipitation and temperature: Change in precipitation or change of seasonal distribution, increase in temperature	*Change in river run-off levels for hydropower catchments* → Change in overall annual hydropower generation and change in seasonal hydropower generation profile → change in electricity generation mix [change in production cost]	Yes
	Change in river run-off and water temperature in summer → Lower availability of cooling water for thermal and nuclear power plants → change in electricity generation mix and/or reduction in reliability of the electricity system	No
Wind speed and solar radiation: Change of wind speed (including frequency of storms) and solar radiation	*Change in wind and PV power generation* → Change in electricity generation mix [change in production cost]	Yes
Temperature: Increase of mean values and heat waves	*Increased cooling energy demand in summer* → Increased electricity demand, change in load profile and increase in summer electricity peak load [change in final demand] → change in electricity generation mix [change in production cost]	Yes
	Decreased heating energy demand in winter → Decreased electricity demand, change in load profile and decrease in winter electricity peak load [change in final demand] → change in electricity generation mix [change in production cost]	Yes
Precipitation and temperature, wind speed and solar radiation: see impact chains above	*Change in supply and demand profiles and resulting residual loads* → Change in reliability of electricity supply and change in probability of blackouts (if no corrective actions are taken)	No
Storms, temperature increase, floods, drought and other extreme events: Increase of extreme events	*Natural hazards, sea level rise etc.* → Electricity infrastructure at risk (supply and transmission) → change in reliability of electricity supply and change in probability of blackouts (if no corrective actions are taken)	No

profiles. Moreover, climate change impact in other sectors such as transport and mobility, or manufacturing, might also have an effect on electricity demand and related load profiles. In our work, electricity demand for heating and cooling as well as related load profiles are based on a detailed techno-economic bottom-up model Invert/EE-Lab applied in Chap. 13.

- Sensitivity of energy supply: Electricity supply is affected in various ways by climate change: First, cooling water temperature and quantity has an effect on the availability and efficiency of thermal power plants or on the corresponding additional costs for cooling towers (see e.g. Förster and Lilliestam 2010; Klein et al. 2013). This is driven in particular by the maximum permitted temperature increase of cooling water in rivers. Second, ambient air temperature levels to some extent have an impact on the electrical efficiency levels of thermal power plants. Third, all renewable power plants are dependent on parameters such as precipitation/evaporation, wind velocity or radiation (cloudiness) and thus sensitive to shifts induced by climate change. In particular, run-off in river basins and hydropower availability will change as precipitation and evaporation levels adapt to new temperatures. In our work, the third aspect has been quantified by taking into account results from a hydrological model of Austrian river run-off and dependence on precipitation and temperature levels (Nachtnebel et al. 2013).

14.2.1 Climatic Factors

The following climatic factors are relevant for the electricity sector: (1) Temperature increases in winter and summer, in particular heat waves, have an impact on heating and cooling (see e.g. Aebischer et al. 2007; De Cian et al. 2007; Isaac and van Vuuren 2009; Olonscheck et al. 2011). (2) Temperature and precipitation are relevant for river run-off and affect hydropower and cooling water availability (see e.g. Koch and Vögele 2009; Nachtnebel et al. 2013; Felberbauer et al. 2010). (3) Solar radiation is relevant for PV and solar thermal generation. (4) Wind speed and the frequency of storms have an impact on wind power generation (see e.g. Pryor and Barthelmie 2010). (5) A greater prevalence of storms, flooding, avalanches and other natural hazards may lead to increased damage to electricity transmission infrastructure (see e.g. Altvater et al. 2011; Francis et al. 2011; Kirkinen et al. 2005; Mima et al. 2012).[1]

With respect to all these factors, particular attention has to be paid to potential changes in seasonal patterns since these determine the required additional fossil power plant capacity.

[1] Section 14.4.1 documents in a more detailed way the climate input data and Sect. 14.4.3 explains the methods how the related impact chains are assessed.

14.2.2 Non-climatic Factors

Within the last few years and decades, the electricity sector has developed in a highly dynamic fashion. Technology and energy carrier mix change continuously, as does the political framework. The implementation and compliance with policy targets will be a highly relevant factor for the future development of the electricity system. On the one hand, the state of the electricity system in 2050 and beyond will depend on how these targets are balanced. On the other hand, due to the complexities of global interaction within the energy sector, numerous exogenous non-climate factors such as prevailing geopolitical constellations, the overall development of energy demand and supply around the globe can all exert a major influence. Bearing this in mind, the following non-climatic factors will be particularly relevant in the sector's development up to 2050 and beyond:

- Transformation towards low-carbon electricity: the expected intensity of such a transformation is highly relevant to assess climate change impacts since renewable energy sources have other vulnerabilities than fossil sources.
- Development of a decentralized electricity system: The level of decentralization has consequences for the vulnerability of the electricity grid infrastructure.
- Development of electricity demand: The absolute level of electricity demand is a strong driver of the vulnerability of the electricity system towards climate change since it drives the need for additional infrastructure and capacities (for general drivers of the energy demand and the socio-economic framework in the reference scenario see Chap. 6).

Despite these challenges, in Austria, currently no official long term target, strategy or vision for the future of the electricity sector exists at national energy policy level, which could directly serve as a socio-economic reference scenario. Thus, for the future relevance of non-economic factors we rely on studies like Totschnig et al. (2013), Reichl et al. (2010), Schleicher and Köppl (2013), Streicher et al. (2010) or Köppl et al. (2011). Chapter 3 outlines how socio-economic scenario-assumptions have been considered in the quantitative assessment.

14.2.3 Identifying Combinations Causing Greatest Potential Damage

In general, periods of crisis in the electricity system are associated with increases in periods of high electricity demand, low electricity supply and interruptions in the transmission infrastructure (see e.g. Totschnig et al. 2013; Reichl et al. 2013; Kranzl et al. 2014). The increase in the frequency of such situations is related to the following: increasing demand for cooling energy (i.e. given that no passive counter-measures for reducing cooling loads are taken, and that the use of air conditioning rises to reflect heat wave periods and changes in personal comfort levels); low generation of hydropower and thermal power plants; low share of PV to cover this demand; low storage and grid capacities; large scale regional occurrence of such conditions; low flexibility of loads (cooling loads as well as other electric loads); high energy prices.

As the Austrian electricity sector is closely linked to that of neighbouring regions, conditions prevailing outside the country also impact on all the above factors.

14.3 Exposure to Climatic Stimuli and Impacts to Date

14.3.1 Past and Current Climatic Exposure and Physical Impacts

Exposure of the electricity system to climate change is mainly driven by the type and location of infrastructure, the number of thermal and nuclear power plants relying on cooling water availability and the number of hydropower plants. Moreover, the relevance of air conditioning is also a major driver of summer peak loads and related exposure. The increasing trend towards air conditioning is discussed in the Chap. 13.

Several authors have discussed the issue of growing electricity peaks in summer periods, in particular in countries with higher cooling loads (some of them also discussed in Chap. 13). Beccali et al. (2007) point out that summer electricity consumption in the building sector in Italy has grown steadily. According to the annual reports published by the Italian National Grid Operator, summer peak load for 2000–2005 showed a rise of 25 %, or 8.38 GW. Temperature and corresponding adjusted electricity demand for Spain have been discussed by Moral-Carcedo and Vicéns-Otero (2005). Pechan and Eisenack (2013) discuss the impact of the 2006 heat wave on electricity spot markets. They found that over a two week period in Germany, the heat wave and the resulting reduction in the availability of cooling water led to an average price increase of 11 % and to additional costs of 15.9 million euros.

14.3.2 Impact Chains

Based on the analysis of sensitivity and exposure of the electricity system to climate change, we identified the main impact chains as described in Table 14.1. Section 14.4 describes in more detail the approaches and data how these impact chains have been assessed.

14.4 Future Exposure to and Impacts of Climate Change

14.4.1 Mid Range Climatic Scenario for Electricity

The results for the sector electricity are based on the project PRESENCE (Nachtnebel et al. 2013; Totschnig et al. 2014; Kranzl et al. 2013). We selected the climate change scenario A1B from the model REMO (driven by ECHAM5) in order to allow the use of comprehensive model results based on Kranzl et al. (2014). This shows very similar climate change signals to those found in the COIN climate change scenario. For modelling the impact of climate change on river run-off and hydropower generation (Nachtnebel et al. 2013), we used bias-corrected and localized climate data. The bias-corrected RCMs and the observed gridded data (E-OBS data) had to be spatially downscaled from the 25 × 25 km grid to a 1 × 1 km grid. This was done using the high-resolution Austrian INCA data set (Haiden et al. 2011). Thus, it was possible to capture the major Austrian valleys and mountain regions. As the INCA data set only applies to the period from 2003 onwards it could not be used directly for bias correction, but it was possible to use it to estimate spatial variability e.g. of temperature and precipitation on a monthly basis. This information was then included in the localized RCM scenario data (Pospichal et al. 2010).

For the localization of the parameters, monthly means for the corresponding time period in the RCM data, the hydrological data, and the INCA data were calculated. Corresponding grid cells (1 × 1 km) in the INCA/hydrological model are assigned to RCM grid cells (25 × 25 km). For each month correction factors for each parameter were calculated for every INCA grid cell. These correction factors were subsequently applied to the daily values of the RCM data, thus inserting the spatial variability of the high-resolution data set into the model. This method assumes that the differences between the RCM data and the INCA data are the result of altitude and orographical effects, i.e. are constant over time. While this is likely to be true with respect to temperature and shortwave radiation, it is not likely to hold for precipitation. Nonetheless, it is still the best available method. Calculation of parameter correction factors is now described below.

Climate scenario data applied to the sector heating and cooling are further documented in Chap. 13.

The electricity sector was modeled using HiREPS. Three meteorological parameters were needed for the analysis: temperature, radiation, and wind speed (in addition to the input from the hydrological model regarding hydropower). The highest possible temporal resolution available was used (daily for temperature and radiation, 12-hourly for wind speed).

For wind speed and radiation monthly percentiles of the hindcast were calculated and then assigned to the control and scenario data to generate look-up tables for the HiREPs model. As radiation input, the global radiation calculated was used. Wind speed at a height of 850 hPa were considered for Austria and Germany for each grid cell. Then it was averaged over the entire domain and then the cubic root was calculated to provide input for the HiREPs model. For temperature, a similar approach to that used for radiation was employed. However, here an additional weight using the population density of the lspop (1 × 1 km, Dobson et al. 2000) was applied.

14.4.2 High and Low Range Climatic Scenarios for Electricity

The sensitivities for high- and low-range climatic scenarios were carried out for the aspect of temperature impact on heating and cooling. The evaluation of direct monetary effects was carried out for the change in electricity demand and electricity load for heating and cooling. Where the climate change scenario "low" results in only slightly reduced cooling electricity demand and loads, the impact of the "high" scenario is significant: cooling load increases by more than 45 %. However, as pointed out above, in more extreme climate scenarios the uncertainty regarding the market penetration of air conditioning units increases and might strongly affect this result, compare also the discussion in Chap. 13.

14.4.3 Specific Method(s) of Valuation and Their Implementation

The impact of climate change on supply and demand shifts in electricity was investigated using an integrated modelling approach. Cost evaluation of electricity generation costs needs to be applied to the impact chains described above. The decomposition of effects is not straightforward, since both demand and supply lead to a new electricity price level.

Figure 14.1 shows the documentation of the model cluster which has been applied in the project PRESENCE (Kranzl et al. 2014) and on which the results in the present study are based. HiREPS builds on data directly from the climate scenarios, from the hydrological modelling and from building stock model Invert/EE-Lab, see Chap. 13.

All impact chains which we labeled as "quantified" in Table 14.1 are covered in this approach (Fig. 14.1): change in river run-off levels, wind and PV power generation are taken into account in HiREPS via the hourly climate data described in Sect. 14.4.1 and on a monthly basis the derived results for river run-off in Austrian water basins. Increased cooling energy demand in summer and decreased heating energy demand in winter are considered in HiREPS via the total change of annual final energy demand as well as the change in hourly load profiles and thus also the changes in peak loads.

Fig. 14.1 Documentatio
deriving the impact of cli

Climate change le
below the supply cur
main indicator for m
electricity generation
This difference is de
In addition to the
electricity. As this is
The change in th
model HiREPS (Tots
The HiREPS model
electricity and heatin
fluctuating renewable
uses an approach wh
For the investigation
system in Austria an
individual effects for
model. The latter a
temporally highly re
detailed model of hy
ing startup costs and
electricity and heatin

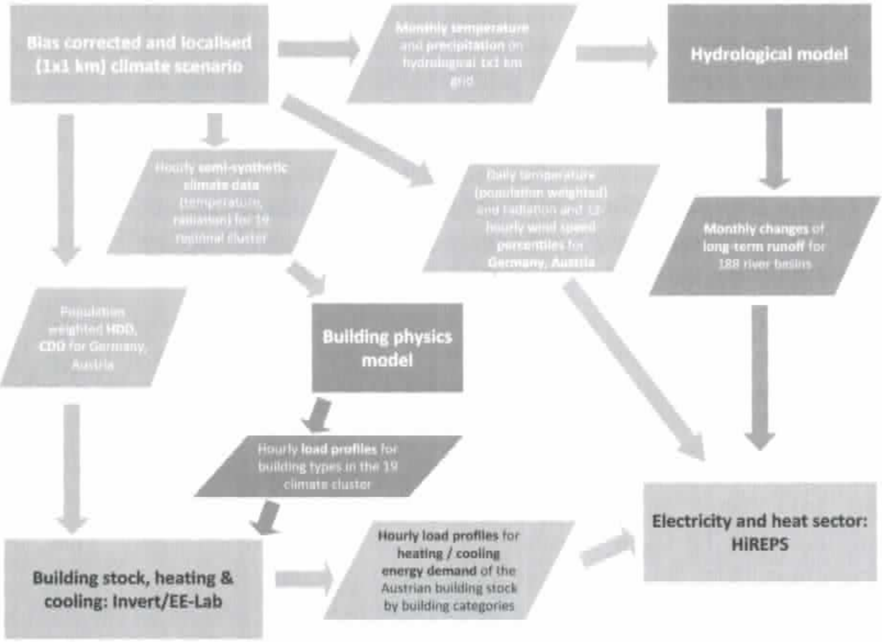

Fig. 14.1 Documentation of flow diagram of data, analytical steps and input of climate data for deriving the impact of climate change on the electricity sector in Austria

Climate change leads to a shift in both the supply and demand curves. The area below the supply curve corresponds to the overall electricity generation costs. The main indicator for monetary evaluation is the difference between the respective electricity generation costs in the baseline case and those in the mid-range scenario. This difference is derived on an hourly basis for the simulation year 2050.

In addition to the above effect, there is also a change in the final demand for electricity. As this is already covered in Chap. 13 and is not considered here.

The change in the electricity generation mix is modelled in the optimisation model HiREPS (Totschnig et al. 2013; Kranzl et al. 2013; Totschnig et al. 2014). The HiREPS model is a dynamical simulation and optimization model of the electricity and heating system. The model focuses on analyzing the integration of fluctuating renewable electricity generation into the power system, and specifically uses an approach whereby important system constraints are treated endogenously. For the investigation in the project COIN the model was applied to the electricity system in Austria and Germany. After optimising the model for both countries, the individual effects for Austria were then separated out for use as input in the HiREPS model. The latter addresses these aspects endogenously by using spatially and temporally highly resolved wind, solar and hydro inflow data, and by including a detailed model of hydropower and pumped storage, thermal power plants (including startup costs and efficiency losses during part-load operation), interaction of the electricity and heating systems, load flow calculation (including thermal limits of the electricity grid), and hourly temporal resolution. Therefore, it is highly suitable to deal with the question of climate change impact on the electricity sector and assessing the cost of climate change in this sector.

14.4.4 *Range of Sectoral Socio-economic Pathway Parameters That Co-determine Climate Impact*

Since the electricity sector in central Europe is closely interlinked, in order to undertake a dynamic investigation a purely national analysis is not sufficient. For this reason, the Austrian and German electricity sectors were investigated together. The reference scenario is based on the assumption that Austria and Germany meet their targets for renewable energy, energy efficiency and GHG-emissions in 2020 according to the corresponding EU directives (in particular 2009/28/EU, 2010/31/EU, 2012/27/EU). However, after 2020, it is assumed that no further ambitious measures will be taken to enforce a low-carbon electricity supply. Thus, the scenario includes only a moderate increase of renewable electricity generation for the investigated region of Austria and Germany. In the scenario, a total share of about 30 % renewable electricity generation (i.e. for Germany and Austria together) is assumed, with wind generation accounting for almost 12 and PV for 6 % (Totschnig et al. 2013).

Electricity consumption growth is based on Capros et al. (2013). According to this source, total electricity consumption increases by about 48 % for Austria from 2005 until 2050. The evolution of electricity demand for heating and cooling (the reference scenario) has been described in more detail in Chap. 13.

14.4.5 *Monetary Evaluation of Impacts*

14.4.5.1 Direct Sector Impacts (Costs and Benefits) Excluding Feedback Effects from Other Sectors

As pointed out above, there are mainly two aspects driving the costs of climate change in the electricity sector: (1) impact on electricity supply and (2) impact on electricity demand. While the impact on wind and PV generation is almost negligible, the shift of hydropower generation from summer to winter season is quite significant. Also, results from other studies show that this result is robust over a wide number of studies, see e.g. Bachner et al. (2013), Felberbauer et al. (2010), Nachtnebel et al. (2013), Kranzl et al. (2010).

The second major impact is due to the increase in cooling energy demand, see Chap. 13. However, not only the total increase in electricity demand (relatively moderate) is relevant, but also the strong increase in the cooling peak load.

As described in Chap. 13, climate change also leads to reduced heating loads during winter. However, due to the higher simultaneity in the cooling energy demand and the lower full load hours of cooling devices, the impact on electricity peak load is expected to be higher for cooling as for heating. For this reason we decided to take into account only the costs for increasing cooling peak loads.

In total, both in the baseline and in the mid-range climate change scenario electricity demand for heating and cooling declines from the base year until 2030 and 2050. Thus, the additional electricity consumption for cooling which occurs in both scenarios until 2050 is compensated by increasing energy performance for heating, because the latter is also partly covered by electricity for heat pumps or by direct electric heating. Until 2050, the baseline scenario results in a reduced electricity consumption for heating and cooling by 20 %, whereas in the mid-range scenario the reduction is only 18 % due to the increased relevance of cooling energy.

Both effects (supply and demand) lead to a change in the electricity generation mix and an increase in electricity generation costs. In particular the increase in summer peak loads as a result of greater cooling demand lead to a high electricity price, though this holds only for a very limited time over the whole year. Overall, the effects result in a slight increase of fuel costs for natural gas from 1,000 million euros in the baseline to about 1,040 million euros in the mid-range climate change scenario in 2030 and from 2,300 million euros to 2,420 million euros in 2050. The fuel expenditures for coal and biomass power plants are not affected by climate change according to the model results.

In order to deal with the higher peak load in summer, additional investments in power generation plants are required (assuming no countermeasures are taken to reduce this peak load) and higher electricity generation costs occur. The sums of these effects are shown in Table 14.2 and Fig. 14.2. The cost data are based on the assumptions regarding energy prices of the SSP (Shared Socio-economic pathways, see Chap. 6) and without discounting of cost of inaction.

In addition to the reference socio-economic scenario and the mid-range climate change scenario, results for low and high climate scenarios are included in Figure 14.2 and Table 14.2. They are driven by the additional electricity demand and related peak loads for cooling.

Table 14.2 Selected economic impacts of climate change on the electricity sector[a]

Projected future costs relative to Ø 1981–2010 (M€)			Climate change		
			Low-range	Mid-range	High-range
Ø 2036–2065	Socioeconomic development	Diminishing	207	207	355
		Reference	205	227	363
		Enhancing	435	435	638

[a]Results for low and high climate change scenarios have been calculated only for the change in cooling load. Effects of hydropower generation have not been evaluated in the low and high climate change scenarios and in the diminishing and enhancing socio-economic scenarios

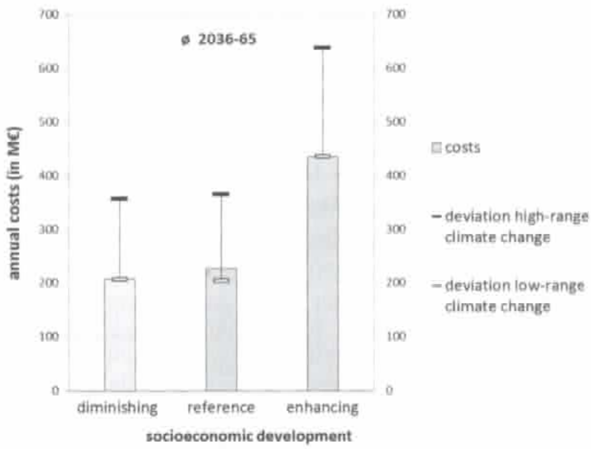

Fig. 14.2 Cost of inaction in the sector electricity

14.4.5.2 Macroeconomic Effects

In the macroeconomic model we implemented those impact chains, which trigger a change in electricity production mix (i.e. change in production costs) as well as a change in final demand, including investments requirements to meet higher peak loads in summer (see Table 14.1 for a detailed description of the individual impact chains).

Compared to the model base year (2008) production costs for the generation of electricity are changing: In the baseline scenario annual expenditures for gas and coal are rising until the 2030s (2016–2045) and the 2050s (2036–2065), whereas expenditures for biomass and biogas are decreasing (real price effects are included). In the climate change scenario the requirements to meet higher peak loads are met by additional gas turbines. Thus, there are higher expenditures for gas as more input is needed relative to the baseline. The change regarding the electricity production mix is implemented in relative terms. For absolute numbers see Sect. 14.4.5.1.

Furthermore, final demand is changing[2]: In the baseline scenario private households as well as the government are decreasing their consumption of electricity by −21.3 % in the 2030s and by −20.4 % in the 2050s (relative to the model base year).[3] This decrease in future electricity demand is driven by the underlying socio-economic development (less electricity demand for heating and a slight increase for cooling with a negative net effect). In the climate change scenario cooling demand is rising, relative to the baseline, as more air conditioning is assumed. Therefore, the before mentioned socio-economic driven decrease is less strong: Private

[2] Note that only changes of electricity demand are analysed in this chapter. Other energy carriers are not relevant for final demand changes.

[3] By assumption and due to lack of more detailed data the government final demand is showing the same relative demand changes as private households.

households as well as the government are reducing their demand for electricity by −20.5 % in the 2030s and by −18.3 % in the 2050s; relative to the model base year. The impacts regarding electricity demand is implemented in relative terms. For more information on that see Sect. 14.4.5 and Chap. 13.

Finally, the Electricity sector faces higher annual investments. Due to the assumed socio-economic development, additional investments are 99 million euros per year in the 2030s and 298 million euros in the 2050s. Due to climate change peak loads are assumed to be higher because of air conditioning demand. By assumption the higher peak load for cooling is provided by additional gas turbines. Therefore, in the climate change scenario annual investments are higher compared to the baseline scenario: Investments are rising by 130 million euros in the 2030s and by 390 million euros in the 2050s (see Sect. 14.4.5). Table 14.3 summarises the implementation of the stated impacts into the CGE model.

Table 14.4 gives an overview of sectoral effects of climate change impacts relative to the baseline scenario. All effects are given as average changes of annual values in million euros (m€) relative to the respective baseline scenario (price changes by feedback effects are included). Concerning the Energy sector (which is an aggregate including the Electricity sector) we see negative impacts on gross output value as additional investment requirements are leading to higher prices for electricity and therefore, despite the additional demand for cooling by private households and the government, overall demand is lower in the climate change scenario (industry demands less electricity and shifts to other energy sources instead). However, due to higher investments annual depreciation is higher, leading to a higher gross value added. In the climate change scenario annual gross value added is on average +5 million euros above the baseline level in the 2030s and

Table 14.3 Implementation of baseline and climate change scenario for electricity in the macroeconomic model, average annual effects for periods 2016–2045 and 2036–2065

	Ø 2016–2045		Ø 2036–2065	
Change relative to base year (2008)	Baseline	Climate change	Baseline	Climate change
Change of electricity production mix (change of average additional expenditure p.a.)				
Gas	+4.8 %	+5.0 %	+4.6 %	+4.7 %
Coal	+3.8 %	+3.8 %	+3.8 %	+3.8 %
Biomass	−0.3 %	−0.3 %	−0.5 %	−0.5 %
Biogas	−1.3 %	−1.3 %	−3.1 %	−3.1 %
Final demand				
Private households	−21.3 %	−20.5 %	−20.4 %	−18.3 %
Government	−21.3 %	−20.5 %	−20.4 %	−18.3 %
Additional annual investments (in M€ p.a.)	+99	+130	+298	+390

Note: baseline scenario = reference socioeconomic development without climate change; climate change scenario = reference socioeconomic development and mid-range climate change; quantified climate impact chains: change of electricity production mix, final demand changes, additional investments

Table 14.4 Sectoral and total effects of quantified climate change impacts in sector Electricity, average annual effects relative to baseline (for periods 2016–2045 and 2036–2065)

	Ø 2016–2045			*Ø 2036–2065*		
Changes in M€ p.a. relative to baseline	Gross output value	Inter-mediate demand	Gross value added	Gross output value	Inter-mediate demand	Gross value added
Gaining sectors	**+8**	**−6**	**+13**	**+10**	**−28**	**+39**
Energy (incl. Electricity)	−13	−18	+5	−55	−67	+13
Construction	+19	+11	+7	+59	+36	+23
Rest of extraction (incl. Gas)	+2	+1	+1	+6	+3	+3
Losing sectors	**−263**	**−105**	**−157**	**−748**	**−301**	**−448**
Trade	−39	−15	−24	−110	−42	−68
Real estate	−39	−11	−27	−108	−32	−77
Accommodation	−20	−7	−13	−56	−19	−37
All other losing sectors	−165	−72	−93	−474	−208	−266
Total effect (all sectors)	**−255**	**−111**	**−144**	**−738**	**−329**	**−408**
GDP at producer price			−0.04 %			−0.08 %
. . .thereof price effect			−0.01 %			−0.02 %
. . .thereof quantity effect			−0.03 %			−0.06 %

Note: baseline scenario = reference socioeconomic development without climate change; climate change scenario = reference socioeconomic development and mid-range climate change; quantified climate impact chains: change of electricity production mix, final demand changes, additional investments

+13 million euros above the baseline in the 2050s.[4] Intermediate demand of the Energy sector is also lower in the climate change case, because less output is produced.

In terms of value added, many other sectors are losing because of climate change; especially consumption goods coming from the sectors Trade, Real Estate or Accommodation (which covers a part of Tourism). This reflects the fact that private households face higher prices (at a higher demand) for electricity and therefore have lower consumption possibilities for other goods and services. The only two sectors which are gaining are Construction and Rest of extraction

[4] The interaction of price and quantity effect is leading to a negative net effect concerning gross output value of the Energy sector, reflecting that the negative demand (quantity) effect is stronger than the positive price effect.

(including the extraction of gas). The former is gaining because of additional power plant investments which are carried out by the construction sector; the latter is gaining because of higher demand for gas to meet the demand for air conditioning. Summing up, due to the implemented climate impact chains gross value added in the 2030s is by −144 million euros lower in the climate change scenario (compared to the baseline scenario). The effect is much stronger in the 2050s, where gross value added is lower by −408 million euros.

After adding indirect taxes less subsidies to the sum of sectoral value added, we obtain effects on GDP, which is shown in Table 14.5, together with effects on welfare and unemployment. After modelling the climate impacts chains with effects on electricity production, final demand as well as investments GDP is decreasing on average by −165 million euros p.a. in the 2030s and by −467 million euros in the 2050s. Note, that about three quarters of the GDP effect is induced by quantity effects and only one quarter by price effects. Regarding welfare—measured as the quantity of consumed goods and services at prices of the baseline level—we see similar effects as of GDP. The effect on welfare is less strong as on GDP, as a part of the losses is carried by the industry. As economy wide output is lower in the climate change scenario employment is lower as well; in the 2030s by −0.02 %–points and by −0.04 %–points in the 2050s. Together with less consumption this leads to lower government revenues which are shown in Table 14.6. Compared to the baseline scenario government revenues are lower by −61 million euros in the 2030s and by −173 million euros in the 2050s. As we assume equality between revenues and expenditures, expenditures decrease by the same amount (more unemployment benefits but a reduction of other transfers to households). By assumption, government consumption expenditures remain unaffected by climate change impacts (therefore not shown in the table).

14.4.6 Qualitative Impacts (Non-monetised)

We need to bear in mind that the monetary evaluation indicated above is far from complete. A considerable number of aspects were not quantified, e.g.:

1. Infrastructure at risk through more frequent natural hazards: In order to guarantee the same level of system reliability in the future as is existing today, higher levels of systemic redundancy and back up are required, both with respect to transmission and to power generating capacity.
2. An increased frequency of natural hazards and other extreme events, together with a growing frequency of adverse constellations in the power system (i.e. high demand peaks with lack of supply capacity, lack of storage and transmission capacity) could lead to a higher probability of black outs (for cost estimation of black outs see the following section uncertainties).

Table 14.5 Effects of quantified climate change impacts in sector Electricity on GDP, welfare and unemployment across different climate and socioeconomic scenarios, average annual effects relative to baseline (for periods 2016–2045 and 2036–2065)

		Ø 2016–2045			Ø 2036–2065		
	Socioeconomic scenarios						
Changes in M€ p.a. relative to baseline	Climate scenarios	Diminishing	**Reference**	Enhancing	Diminishing	**Reference**	Enhancing
GDP (changes in M€)	High						
	Mid		**−165**			**−467**	
	Low						
Welfare (changes in M€)	High						
	Mid		**−159**			**−443**	
	Low						
Unemployment rate (in % points)	High						
	Mid		**+0.02**			**+0.04**	
	Low						

Note: Empty cells not quantified

Table 14.6 Effects of quantified climate change impacts in sector Electricity on government budget, average annual effects relative to baseline (for periods 2016–2045 and 2036–2065)

Changes in M€ p.a. relative to baseline	Ø 2016–2045	Ø 2036–2065
Revenues	**−61**	**−173**
Production tax	−5	−13
Labour tax	−25	−69
Capital tax	−10	−29
Value added tax	−20	−57
Other taxes	−1	−4
Expenditures	**−61**	**−173**
Unemployment benefits	+22	+62
Transfers to households net of other taxes	−83	−234
Government budget in baseline (p.a.)	**148,480**	**204,500**
Climate change impact on government budget	−0.04 %	−0.08 %

Note: baseline scenario = reference socioeconomic development without climate change; climate change scenario = reference socioeconomic development and mid-range climate change; quantified climate impact chains: change of electricity production mix, final demand changes, additional investments

14.4.7 Specific Uncertainties for the Electricity Sector

Apart from those listed above several other factors could also have a substantial impact:

- **Autonomous adaptation by utilities**. Some of them were explicitly taken into account in our modelling approach (e.g. investment in additional power plant capacities) some others were not e.g. restricting maximum loads during peak times. This would result in some part of the demand for cooling having to remain unsatisfied.
- There is uncertainty regarding the need for current **electricity consumption for cooling**. In addition, the possible development and further uptake of AC-units in the course of heat waves is also subject to a considerable degree of uncertainty.
- Assumptions regarding **technological development**, in particular regarding the cost-evolution of PV and storage capacities have a strong impact on the future characteristics of the electricity system. Lower than expected cost reductions in PV and storage capacities would increase the cost of inaction in the sector.
- **Social acceptability and perceptions** with respect to new technologies and electricity grid expansion: we assume that there are almost no barriers to an expansion of the electric grid and thus to the provision of greater cross-regional flexibility. In reality, we know that there are acceptability barriers of grid expansion. The higher these barriers, the higher the cost of inaction, and the higher the risk of black outs.
- The standard assumption regarding **growth of electricity consumption** was taken from PRIMES (Capros et al. 2013). However, we need to be aware that strong growth in electricity consumption is not in line with current policy targets.

Note: Empty cells not quantified

A change in electricity consumption would also change the required additional power plant capacities and related costs.

- **Fluctuation of hydropower generation**: It remains an open question whether increasing fluctuations will lead to some threshold level being surpassed such that there will be a discontinuous jump in costs for the whole electricity system.
- We did not deal at all with potential interruption to supply or transmission **infrastructure** as a result of higher frequency of extreme events such as storms, floods or avalanches.
- There are other extreme events like heat waves and droughts which could—in combination—have a multiplier effect resulting in periods in which high cooling loads, low hydro power generation, and low output from thermal power plants, all occur simultaneously.
- Probability of black outs: All the aspects listed above could not only lead to higher costs in the electricity sector but also to an increased probability of electricity black outs.

Costs of Power Outages in Austria

Johannes Reichl*
*Energieinstitut at Johannes Keppler University Linz

Extreme meteorological events already cause power supply interruptions under current climate conditions every now and then, and a further increase of such events as a consequence of climate change is expected to result in a coeval increase of power outages. While science still lacks of quantifying the risks of the power system under climate change, simulation studies can provide estimates of the socio-economic damage of such disruptive events. A view on the simulation outcomes reveals the economic relevance of blackouts, and thus the importance of knowledge to prevent and deal with the threat of power outages in the light of climate change. As a first example it is assumed a power outage hits the whole of Austria on a weekday morning in summer and lasts for 6 h. The total expected damage of power outage summarises to about 350–400 million euros for the Austrian economy, of which the energy-intensive manufacturing sector is most vulnerable and thus bares the largest share of these outage costs. Considering the same outage scenario but assuming a duration of 24 h until electricity supply can be restored sums up to damage costs between 750 and 1,100 million euros (Reichl et al. 2013).

The damage costs presented in the last paragraph contain those values sustainably lost during and after the blackout event. This means that while some businesses can catch up with work once the electricity supply is restored, this will usually result in higher production costs and for many goods and services such an option does not exist at all. As a consequence, it is required to better understand the consequences of climate change in this

(continued)

particularly vulnerable field and to learn about its human dimension. Consequently, supporting society and policy makers in adapting to the increased risk of power outages, based on scenarios for future extreme meteorological events, should be much more considered.

References

Reichl J, Schmidthaler M, Schneider F (2013) The value of supply security: the costs of power outages to Austrian households, firms and the public sector. Energy Econ 36:256–261

Lower summer river flows can reduce the operating efficiency and output of hydro power plants. For a closer assessment for this effect, daily hydrological modelling would be required, which was not possible in the present study.

14.5 Summary of Climate Costs for Electricity and Conclusions

For Austria, our scenario results show that climate change leads to a slight reduction in overall hydropower generation. There is also a shift in hydropower generation to the winter period, where, normally, electricity prices are higher (see e.g. Nachtnebel et al. 2013). Reduced electricity demand for heating over the year compensates for the increase in electricity needed for cooling. However, cooling potentially leads to substantially higher electricity peak loads in summer, resulting in high electricity prices and higher requirements for back-up capacity, particularly in cases where the additional demand cannot be covered by PV/wind generation.

For the two impact chains described above, the mid-range climate change scenario reveals a moderate increase in costs for the sector for 2050 of about 230 million euros per year. Including spillover effects to and from other sectors, these costs translate into reductions in annual GDP of 467 million euros in the climate change scenario for 2050 (compared to the baseline scenario). Due to these quantified impact chains, prices for electricity are on average increasing leading to lower consumption possibilities for private households, and so the sectors trade, real estate, and accommodation are affected negatively as well. In contrast, construction and the extraction sector (which includes gas) are gaining due to higher investments into back-up capacity.

Taking into account the uncertain impact of cooling energy demand leads to an estimated increase from 230 million euros to about 640 million euros of direct costs in the case of enhancing socio-economic conditions and high-range climate change scenario. However, several additional impact chains were not quantified in the present study. These include the impact of extreme events on electricity supply and transmission infrastructure and the risk of black outs arising from some combination of effects. Lack of resources meant that such effects could not be dealt with sufficiently here.

One must bear in mind that huge uncertainties remain (see discussion on uncertainties above). Probably the most relevant uncertainty relates to the question of an increased probability of black outs. All the aspects listed above could lead not only to higher costs in the electricity sector but also to an increase in the probability of electricity black outs. The costs associated with such black outs are likely to be orders of magnitude higher than those associated with electricity generation. Given the high importance of the electricity sector to society, this is obviously a question which requires considerable attention. In particular, future research needs to focus on two related aspects, i.e. the potential impact of extreme events, and how such events might affect the probability of electricity black outs.

References

Aebischer B, Catenazzi G, Henderson G, Jakob M (2007) Impact of climate change on thermal comfort, heating and cooling energy demand in Europe. ECEEE 2007 Summer study: saving energy – Just do it!, pp 859–870

Altvater S, van de Sandt K, Marinova N, de Block D, Klostermann J, Swart R, Bouwma I, McCallum S, Dworak T, Osberghaus D (2011) Assessment of the most significant threats to the EU posed by the changing climate in the short, medium and long term – Task 1 report. Ecologic, Berlin

Arent D, Tol RSJ (2014). IPCC AR5. Climate change 2014: impacts, adaptation, and vulnerability. Key economic sectors and services, Chap 10. IPCC

Bachner G, Bednar-Friedl B, Birk S, Feichtinger G, Gobiet A, Gutschi C, Heinrich G, Kulmer V, Leuprecht A, Prettenthaler F, Rogler N, Schinko T, Schüppel A, Stigler H, Themessl M, Töglhofer C, Wagner T (2013) Impacts of climate change and adaptation in the electricity sector – the case of Austria in a continental european context (EL.ADAPT), Wegener Center Scientific Report 51-2013. Wegener Center Verlag, Graz

Beccali M, Cellura M, Brano VL, Marvuglia A (2007) Short-term prediction of household electricity consumption: assessing weather sensitivity in a Mediterranean area. Renew Sustain Energy Rev 12(8):2040–2065

Capros P, De Vita A, Tasios N, Papadopoulos D, Siskos P, Apostolaki E, Zampara M, Paroussos L, Fragiadakis K, Kouvaritakis N et al (2013) EU energy, transport and GHG emissions: trends to 2050. Reference scenario 2013

De Cian E, Lanzi E, Roson R (2007) The impact of temperature change on energy demand: a dynamic panel analysis. http://ssrn.com/abstract=984237

Dobson JE, Bright EA, Coleman PR, Durfee RC, Worley BA (2000) A global population database for estimating populations at risk. Photogramm Eng Remote Sens 66(7):849–857

Felberbauer K, Muster M, Schloffer M, Theißing M, Tragner M, Wanek M, Zisler M (2010) KRAKE – Kraftwerke im Klimawandel Auswirkungen auf die Erzeugung von Elektrizität. Endbericht im Rahmen des Programms "Neue Energie 2020

Förster H, Lilliestam J (2010) Modeling thermoelectric power generation in view of climate change. Reg Environ Change 10(4):327–338

Francis RA, Falconi SM, Nateghi R, Guikema SD (2011) Probabilistic life cycle analysis model for evaluating electric power infrastructure risk mitigation investments. Clim Change 106 (1):31–55

Grübler A, Johansson TB, Mundaca L, Nakicenovic N, Pachauri S, Riahi K, Rogner H-H, Strupeit L (2011) Energy primer. In: Gomez-Echeverri L, Johansson TB, Nakicenovic N, Patwardhan A (eds) Global energy assessment: toward a sustainable future. IIASA, Cambridge University Press, Laxenburg

Haas R, Nakicenovic N, Ajanovic A, Faber T, Kranzl L, Müller A, Resch G (2008) Towards sustainability of energy systems: a primer on how to apply the concept of energy services to identify necessary trends and policies. Energy Policy 36(2008):4012–4021. doi:10.1016/j.enpol.2008.06.028

Haiden T, Kann A, Wittmann C, Pistotnik G, Bica B, Gruber C (2011) The integrated nowcasting through comprehensive analysis(INCA) system and its validation over the eastern Alpine region. Weather Forecast 26:166–183

Isaac M, van Vuuren DP (2009) Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. Energy Policy 37:507–521. doi:10.1016/j.enpol.2008.09.051

Kirkinen J, Martikainen A, Holttinen H, Savolainen I, Auvinen O, Syri S (2005) Impacts on the energy sector and adaptation of the electricity network business under a changing climate in Finland. FINADAPT Working Paper 10, Finnish Environment Institute Mimeographs 340, Helsinki, p 43

Klein DR, Olonscheck M, Walther C, Kropp JP (2013) Susceptibility of the European electricity sector to climate change. Energy 59:183–193

Koch H, Vögele S (2009) Dynamic modeling of water demand, water availability and adaptation strategies for power plants to global change. Ecol Econ 68(7):2031–2039

Köppl A, Kettner C, Kletzan-Slamanig D, Schleicher S, Schnitzer H, Titz M, Damm A, Steininger KW, Wolkinger B, Lang R, Wallner, G, Artner H, Karner A (2011) Energy transition 2012/2020/2050. Strategies for the transition to low energy and low emission structures. Final report (No. 2011/019-2/S/WIFO Project No. 7407). Wien

Kranzl L, Formayer H, Haas R, Kalt G, Manfred L, Müller A, Nachtnebel HP, Redl C, Schörghuber S, Seidl R, Stanzel P (2010) Ableitung von prioritären Maßnahmen zur Adaption des Energiesystems an den Klimawandel.Endbericht im Rahmen der Programmlinie "Energie der Zukunft", Wien

Kranzl L, Matzenberger J, Totschnig G, Toleikyte A, Schicker I, Formayer H, Gorgas T, Stanzel P, Nachtnebel HP, Bednar T, Gladt M, Neusser M (2013) Modelling climate change impact on energy systems. Working Paper for the Second Review-Workshop in the project PRESENCE, Vienna

Kranzl L, Matzenberger J, Totschnig G, Toleikyte A, Schicker I, Formayer H, Gorgas T, Stanzel P, Nachtnebel HP, Bednar T, Gladt M, Neusser M (2014) Power through resilience of energy system. Final report of the project PRESENCE, Project in the frame of the Austrian climate research program, Vienna

Mima S, Criqui P, Watkiss P (2012) Technical policy briefing note no. 4. The impacts and economic costs of climate change on energy in the European Union. Final draft report. http://www.climatecost.cc/reportsandpublications.html

Moral-Carcedo J, Vicéns-Otero J (2005) Modelling the non-linear response of Spanish electricity demand to temperature variations. Energy Econ 27:477–494. doi:10.1016/j.eneco.2005.01.003

Nachtnebel HP, Stanzel P, Hernegger M (2013) Power through resilience of energy systems: energy crises, trends and climate change (PRESENCE). Contributions to work packages 4 – hydrology and hydropower and 5 – availability of cooling water for thermal power plants and the industry, Vienna

Olonscheck M, Holsten A, Kropp JP (2011) Heating and cooling energy demand and related emissions of the German residential building stock under climate change. Energy Policy 39:4795–4806. doi:10.1016/j.enpol.2011.06.041

Pechan A, Eisenack K (2013) The impact of heat waves on electricity spot markets. Oldenburg discussion papers in economics

Pospichal B, Formayer H, Haas P, Nadeem I (2010) 10th EMS annual meeting, 10th European conference on applications of meteorology (ECAM) Abstracts, Zürich, Switzerland, 13–17 Sept. http://meetingorganizer.copernicus.org/EMS2010/EMS2010-792.pdf. Accessed 14 Jan 2014

Pryor SC, Barthelmie RJ (2010) Climate change impacts on wind energy: a review. Renew Sustain Energy Rev 14: 430–437. (http://www.sciencedaily.com/releases/2011/05/110502151355.htm and http://www.mendeley.com/research/climate-change-impacts-wind-energy-review-1/ for abstracts)

Reichl J, Kollmann A, Tichler R, Pakhomova N, Moser S, Goers S, Lindorfer J, Greibl E, Fazeni K, Haas R, Müller A, Sagbauer N, Kloess M (2010) AWEEMSS – Analyse der Wirkungsmechanismen von Endenergieeffizienz-Maßnahmen und Entwicklung geeigneter Strategien für die Selektion ökonomisch-effizienter Maßnahmenpakete. Endbericht, Energieinstitut an der JKU Linz, Energy Economics Group, February 2010

Reichl J, Schmidthaler M, Schneider F (2013) The value of supply security: the costs of power outages to Austrian households, firms and the public sector. Energy Econ 36:256–261

Schleicher S, Köppl A (2013) Energieperspektiven für Österreich Zielorientierte Strukturen und Strategien für 2020. Im Auftrag des BMWFJ. Wien

Streicher W, Schnitzer H, Titz M, Tatzber F, Heimrath R, Wetz I, Hausberger S, Haas R, Kalt G, Damm A, Steininger K, Oblasser S (2010) Energieautarkie für Österreich 2050. Feasibility Study. Endbericht, Energie der Zukunft

Totschnig G, Kann A, Truhetz H, Pfleger M, Ottendörfer W, Schauer G (2013) AutRES100 – Hochauflösende Modellierung des Stromsystems bei hohem erneuerbaren Anteil – Richtung 100% Erneuerbare in Österreich. Endbericht im Rahmen des Programms Neue Energie 2020, Wien

Totschnig G, Müller A, Hummel M, Hirner R, Nachtnebel HP, Stanzel P, Schicker I, Formayer H (2014) Climate change impact on the electricity sector: the example of Austria. Paper submitted to the journal Energy

Chapter 15
Transport

Birgit Bednar-
Herbert Forma

Abstract 30 to
precipitation trig
As most transpo
structure are exp
road transport in
and investment
changed precipit
We find that pre
18 million euro
27 million euro
period 2036–20
caused by an in
change. While s
tation is decreas
the overall effe
induced addition
network extens
construction sec

B. Bednar-Friedl (
Department of Ec

Wegener Center fo
e-mail: birgit.fried

B. Wolkinger • G.
Wegener Center fo
e-mail: brigitte.wo

M. König • I. Offe
Environmental Im
Austria
e-mail: markus.ko
leitner@umweltbu

H. Formayer
Institute of Meteor
Austria
e-mail: herbert.for