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 quantifiable, 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
Economic Evaluation of Climate Change Impacts

Development of a Cross-Sectoral Framework and Results for Austria

Springer
Preface

Our current actions determine our future conditions. Beyond climate change, adaptation and potential impacts, appropriate response may entail a clear need for adequate information.

Climate change impacts on the built environment are subject to a high degree of uncertainty. To address this uncertainty, a broad set of disciplines and scientific methods need to be considered.

In this volume, we show how climate change impacts can be better understood and how the generation of information related to the physical manifestations of climate change is developed.

Climate scenario analysis, economic valuation, and associated with climate change, is an essential tool. The values are surrounded by a range of uncertainties. This volume also considers the potential range of uncertainties (and whether they will be increased in response). For example, increased coastal infrastructure in flood prone areas may increase the urban heat island effect. People’s homes are equipped with air conditioning, which is expected to increase the future heating and cooling costs. These costs may be crucial in determining a societal response.
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.

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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>
<thead>
<tr>
<th>Table 14.1</th>
<th>Impact chains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation and temperature</td>
<td>Change in precipitation or seasonal distribution, increase in temperature</td>
</tr>
<tr>
<td>Wind speed and solar radiation</td>
<td>Change of wind speed (frequency of storms) and solar radiation</td>
</tr>
<tr>
<td>Temperature</td>
<td>Increase of mean values, waves</td>
</tr>
<tr>
<td>Precipitation and temperature</td>
<td>Increase in precipitation, drought and other extreme events</td>
</tr>
<tr>
<td>Storms, temperature increase</td>
<td>Increase of extreme events</td>
</tr>
</tbody>
</table>
In the electricity sector it is clearly not the case that climate change only impacts one other sector. On the contrary: e.g. the demand for energy rises, hydropower as a source of energy is affected by changes in precipitation and evaporation, power lines are affected by increased frequency of storms and the water supply (quantitative and qualitative) infrastructure as a result of the changing climate. On a global scale, these impacts can be seen in the last few years and will continue to be seen in the future, the sector will therefore have to adapt to these impacts and the level of adaptation will be very important to assess the cost of climate change. Of equal importance are the costs of climate change. It is not just the non-climatic factors that are important (e.g. the level of the sector itself is not increasing faster than the focus of this chapter is the electricity sector). As such, the electricity system, and this system impacts and was specifically adapted to climate change, and cooling" but also more generally to "climate change" (see Chap. 13). In addition, the costs of adaptation in the electricity sector have not been systematically quantified (see above and included in the related load changes).

### Table 14.1 Impact chains sector electricity

<table>
<thead>
<tr>
<th>Climate change parameter</th>
<th>Impact chain</th>
<th>Quantified in the model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation and temperature: Change in precipitation or change of seasonal distribution, increase in temperature</td>
<td>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]</td>
<td>Yes</td>
</tr>
<tr>
<td>Wind speed and solar radiation: Change of wind speed (including frequency of storms) and solar radiation</td>
<td>Change in wind and PV power generation → Change in electricity generation mix [change in production cost]</td>
<td>Yes</td>
</tr>
<tr>
<td>Temperature: Increase of mean values and heat waves</td>
<td>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]</td>
<td>Yes</td>
</tr>
<tr>
<td>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]</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Precipitation and temperature, wind speed and solar radiation: see impact chains above</td>
<td>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)</td>
<td>No</td>
</tr>
<tr>
<td>Storms, temperature increase, floods, drought and other extreme events: Increase of extreme events</td>
<td>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)</td>
<td>No</td>
</tr>
</tbody>
</table>
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 (Nachtebel
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; Nachtebel 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, the electricity sector has been severely impacted by
highly dynamic factors, as does the political framework. The development of
policy targets will be a high priority for the Austrian power system. On the one hand,
they depend on how the countries will meet the targets set locally. On the other hand,
non-climatic factors need to be included in the development of energy systems in order
to create new incentives. Bearing that in mind, the following issues are particularly
relevant in the electricity sector:
- Transformation of the energy system: How the transformation is
depending on non-renewable energy sources is of vital importance.
- Development of energy efficiency: How the development of
electricity efficiency has consequences on the energy system.
- Development of demand side management: How the demand side
management can be used for the transformation of the energy system.

Despite these challenges, it is important to have a clear strategy or vision on the
policy level, which provides certainty in the long run. Thus, for the future, we refer to
Totschnig et al. (2010) or Lauber et al. (2010) for an overview of the scenario-assumptions.

14.2.3 Identifying New Approaches for Damage Mitigation

In general, periods of high electricity demand are times of increased transmission
infrastructure. Klöckl and Kranzl et al. 2014. Therefore, the following: identify possible
countermeasures to reduce the peaks: increasing generation capacity, or
cooling conditioning rises.
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-climatic 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

sect. 14.4.3 explains
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 Vicén-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

#### 14.4.1 Mid-Risk Scenarios

The results for the scenarios (Nachnebel et al. 2011) show how climate change is likely to affect the Austrian electricity sector, and in order to allow the study to be more comprehensive, this chapter shows very sensitive climates in order to allow the study to be more comprehensive. This was done by using high-resolution regionalized climate data (including detailed parameterizations of PV generation and demand) that had to be specially adapted for the analysis. This was done by using high-resolution regionalized climate data (including detailed parameterizations of PV generation and demand) that had to be specially adapted for the analysis. This was done by using high-resolution regionalized climate data (including detailed parameterizations of PV generation and demand) that had to be specially adapted for the analysis.

For the local assessment, the mid-risk scenario is calculated. Corresponding results are assigned to regional level; each parameter was then considered in each parameter who were subsequently aggregated to estimate spatially based. This is done by using high-resolution regionalized climate data (including detailed parameterizations of PV generation and demand) that had to be specially adapted for the analysis.

Climate scenarios for the future are documented in Chap. 14.5.

The electricity parameters were needed for each climate scenario (in addition to the highest possible radiation, 12-hour time period) and then assigned to a HiREPS model. A model predicts the output speed at a height of 80 m above the terrain for each cell. Then it was adjusted...
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.

Climate change leads to a change in the supply curve for electricity and heating. This difference is discussed in more detail in Chapter 13. In addition to the impact on electricity prices, as this is already shown in Figure 14.1, the climate change scenarios also affect the demand for electricity and heating. The HiREPS model uses an approach where the supply and demand for electricity and heating are integrated. The electricity price is calculated using the supply and demand for electricity and heating. The latter are calculated using a highly resolved model of the electricity and heating systems 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 energy 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 negli-
gible, 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), Felberauer et al. (2010),
Nachtebel 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 only 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*

<table>
<thead>
<tr>
<th>Projected future costs relative to Ø 1981–2010 (M€)</th>
<th>Climate change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low-range</td>
</tr>
<tr>
<td>Ø 2036–2065</td>
<td>Socioeconomic development</td>
</tr>
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<td></td>
<td>Reference</td>
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<td></td>
<td>Enhancing</td>
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</tbody>
</table>

*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.
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 socioeconomic 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

<table>
<thead>
<tr>
<th></th>
<th>Ø 2016–2045</th>
<th>Ø 2036–2065</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Change relative to base year (2008)</strong></td>
<td>Baseline</td>
<td>Climate change</td>
</tr>
<tr>
<td><strong>Change of electricity production mix</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas</td>
<td>+4.8 %</td>
<td>+5.0 %</td>
</tr>
<tr>
<td>Coal</td>
<td>+3.8 %</td>
<td>+3.8 %</td>
</tr>
<tr>
<td>Biomass</td>
<td>−0.3 %</td>
<td>−0.3 %</td>
</tr>
<tr>
<td>Biogas</td>
<td>−1.3 %</td>
<td>−1.3 %</td>
</tr>
<tr>
<td><strong>Final demand</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Private households</td>
<td>−21.3 %</td>
<td>−20.5 %</td>
</tr>
<tr>
<td>Government</td>
<td>−21.3 %</td>
<td>−20.5 %</td>
</tr>
<tr>
<td><strong>Additional annual investments</strong> (in M€ p.a.)</td>
<td>+399</td>
<td>+130</td>
</tr>
</tbody>
</table>

*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)

<table>
<thead>
<tr>
<th>Changes in ME p.a. relative to baseline</th>
<th>Ø 2016–2045</th>
<th>Ø 2036–2065</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gross output value</td>
<td>Intermediate demand</td>
</tr>
<tr>
<td><strong>Gaining sectors</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy (incl. Electricity)</td>
<td>+8</td>
<td>-6</td>
</tr>
<tr>
<td>Construction</td>
<td>-13</td>
<td>-18</td>
</tr>
<tr>
<td>Rest of extraction (incl. Gas)</td>
<td>+19</td>
<td>+11</td>
</tr>
<tr>
<td></td>
<td>+2</td>
<td>+1</td>
</tr>
<tr>
<td><strong>Losing sectors</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trade</td>
<td>-263</td>
<td>-105</td>
</tr>
<tr>
<td>All other losing sectors</td>
<td>-20</td>
<td>-7</td>
</tr>
<tr>
<td></td>
<td>-165</td>
<td>-72</td>
</tr>
<tr>
<td><strong>Total effect (all sectors)</strong></td>
<td>-255</td>
<td>-111</td>
</tr>
<tr>
<td>GDP at producer price</td>
<td>-0.04 %</td>
<td></td>
</tr>
<tr>
<td>... thereof price effect</td>
<td>-0.01 %</td>
<td></td>
</tr>
<tr>
<td>... thereof quantity effect</td>
<td>-0.03 %</td>
<td></td>
</tr>
</tbody>
</table>

*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*

14.4.6 Qualitative effects

We need to bear in mind that the quantitative results are only complete. A complete set of qualitative effects includes:

1. Infrastructure projects which at the same time ensure higher levels of system reliability (e.g., transmission and distribution systems)
2. An increased focus on sector coupling, which could lead to a more robust energy system and thus reduce the risk of black outs in the future.
(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 impact 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)

<table>
<thead>
<tr>
<th>Changes in M€ p.a. relative to baseline</th>
<th>Socioeconomic scenarios</th>
<th>Climate scenarios</th>
<th>Diminishing</th>
<th>Reference</th>
<th>Enhancing</th>
<th>Diminishing</th>
<th>Reference</th>
<th>Enhancing</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDP (changes in M€)</td>
<td></td>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mid</td>
<td>-165</td>
<td>-467</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Welfare (changes in M€)</td>
<td></td>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mid</td>
<td>-159</td>
<td>-443</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unemployment rate (in % points)</td>
<td></td>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mid</td>
<td>+0.02</td>
<td>+0.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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)

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

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.
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 Kepler 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

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. Nachtegebel 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.

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to an increase in the probability

of blackouts are likely to be

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Climate change on thermal

227 Winter study: saving

J, Swart R, Bouwma I,

not significant threats to

the long term – Task 1 report.

Translation, and vulnerability.

K, Heinrich G, Kulmer V,

Stigler H, Themessl M,

tribution in the electricity

(DAPT), Wegener Center

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area. Renew Sustain

Zampara M, Parousos L,

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be effective on energy demand: a

global population database

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Chapter 15: Transport Infrastructure

Birgit Bednar-Friedl
Herbert Formayer

Abstract

30 to 40% of global transport emissions are caused by aviation, with a significant share being due to precipitation triggered flights. As transport infrastructure is experiencing a major shift from road transport to rail and water transport, it is essential to characterize what changes will result from changed precipitation patterns.

We find that precipitation in Austria, which is expected to increase, will cause delays in the rail network and investment in new infrastructure. This will result in a significant increase in overall emissions.

The overall effect of precipitation on the rail and road network extension and construction sector will be significant, but the specific impacts will vary depending on the geographical location and the type of infrastructure being built.

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