PUBLIZIERBARER Endbericht Studien
(gilt nicht für andere Projekttypen)

A) Projektdaten

Titel:	Impacts of Climate Change and Adaptation in the Electricity Sector - The Case of Austria in a Continental European Context (EL.ADAPT)
Programm:	ACRP, 2nd Call
Koordinator / Projekteinreicher:	University of Graz, Wegener Center for Climate and Global Change, Research Group "Economics of Climate and Global Change" (WEGC-EconClim)
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Projektwebsite:	http://www.uni-graz.at/igam7www/igam7www_forschung/igam7www_econclim/igam7www_econclim_projekte-2/igam7www_eladapt.htm
Schlagwörter:	Climate change impacts, regional climate scenarios, hydrology, electricity generation, electricity demand, electricity market, macroeconomic effects.
Projektgesamtkosten:	333.755 (plus in kind contributions by university staff)
Fördersumme:	320.328
Klimafonds-Nr:	B060380
Projektstart & Ende	From Feb 1, 2011 to March 30, 2013

B) Project Overview / Projektübersicht

1 Executive Summary (English)

Power generation is not only an important source of carbon emissions, it is also vulnerable to changed climatic conditions amplified by the growing share of renewables. Temperature increase will also lead to significant impacts on demand. As electricity is supplied to all other economic sectors, changes in e.g. electricity infrastructure affect the whole economy. This project investigates the climate change impacts on the electricity industry and on the Austrian economy up to 2050. Due to the international linkage of the electricity sector, the analysis considers the continental European context. Based on high resolution climate change and hydrology models, and an econometric electricity demand model, a techno-economic electricity sector model (ATLANTIS) is coupled with a multi-country multi-sector CGE model. The uncertainties across models are addressed by a reliability analysis.

Due to the cross-cutting nature of the problem, an integration (or coupling) of different models is essential. The primary aim of this project was thus to develop an integrated modeling framework to describe and analyze the requirement for and economic consequences of adaptation in the electricity sector in Austria on a time scale up to 2050. In addition to the development of an integrated modeling framework, we analyze uncertainties involved in the overall modeling approach, from uncertainties in climate and hydrological scenarios (e.g. uncertainties due to the models' simplifications and errors) to uncertainties in economic modeling (e.g. assumptions on climate policy).

With this truly innovative approach, the following research questions were addressed in this project:

1. How vulnerable is power generation in Austria, and continental Europe, to climate change on a time scale up to 2050, given changes in runoff water, temperature, global radiation, and wind?
2. In which way is electricity demand in continental Europe affected by climate change on a time scale up to 2050, in particular with regard to heating and cooling?
3. What are the associated macroeconomic effects of climate change impacts in the Austrian and European electricity sector? How large are direct effects relative to indirect (i.e. spill-over) effects on other sectors?
4. How sensitive are results with respect to climatic / hydrological factors and economic factors? What are the ranges of uncertainties which have to be considered for the reported results?
5. What are suitable adaptation options for the electricity sector, distinguishing for different sources of energy (renewable and non-renewable)?

Answering these questions led to the following key results:

- Regarding meteorological forcing, four representative regional climate scenarios have been selected to ensure to cover the uncertainty range of expected climate change. The climate change signals of the selected scenarios range from +1.2°C to +2.8 °C for temperature, -0.27 to +0.3 mm/day for precipitation, -3.46 W/m² to +6.81 W/m² for global radiation and show no remarkable change for mean wind speed.
- The changes in runoff of all the 101 stations considered further in the project vary due to their different geographic positions within the Greater Alpine Region and depending on the time period and the climate scenario considered. Changes are given as relative in % and as

absolute runoff per area in l/s·km². In general, the variations in runoff are within -15 and +10 %, although decreases up to -35 % are estimated for Southern France and Northern Italy. In absolute values, the changes in runoff vary between -6 and +4 l/s·km².

- For the four climate scenarios, the absolute climate induced change in electricity consumption for 16 Continental European countries was investigated. Overall, warmer annual temperatures reduce the total electricity consumption in Continental Europe, depending on the climate scenario the reduction varies from -10,000 GWh to -25,000 GWh per year. The ratio between the absolute decrease in heating and the absolute increase in cooling electricity demand is still 2:1 to 6:1, depending on which climate scenario is considered. Yet, relative to current total electricity consumption these effects are comparatively small compared to other drivers of electricity demand. The overall long-term reduction for Continental Europe is -0.4 % to -1.1 % of total electricity use. However, in some countries with major electric heating or cooling activities climate induced changes are of course more pronounced, like up to -3 % in heating-dominated France and up to +0.6 % in cooling-dominated Italy.
- Regarding impacts of climate change on the electricity generation, the changes in standard capacity[1] due to climate change under the given assumptions are in the range of +3 % to -4 % (best case and worst case) of total standard capacity in Continental Europe, which is an average amount of approximately 45 TWh in the period 2031-2050. For Austria, the standard capacity may vary between +2.2 % and -5.1 %, respectively +1.14 TWh and -2.58 TWh, in the same period. Main drivers are run-of-river power plants (+/-1 TWh) as well as hydro storage power plants (+0.5 / -1.5 TWh). Relative to the standard capacity of each technology, the strongest climate change impacts can be observed at hydro storage power plants. Photovoltaic generation in Austria is more affected by climate change than run-off-river hydro power and shows comparably high and negative impacts throughout all climate scenarios. However, due to the small amount of installed capacities, photovoltaic generation does not play a major role for Austria's electricity system in terms of climate change.
- Regarding the indirect effects of climate change impacts in the electricity sector on other sectors, average output values for electricity intensive sectors (EIS) and non-electricity intensive sectors (NEIS) are investigated relative to a baseline scenario across regions for the two periods 2011-30 and 2031-50. Comparing the relative magnitude of direct and indirect costs of climate change in absolute output values for EIS, we find that in the best scenario total economic output increases range from +0.02 % for the aggregated model region Germany and Luxemburg (GERL) to +0.23 % for Eastern European Union countries (EEU, i.e. Czech Republic, Hungary, Poland, and Slovakia) for 2011-30 relative to a baseline scenario, while for the worst scenario the net loss ranges from -0.19 % for EEU to -0.04 % for GERL. Net effects for Austria range from -0.14 % to +0.03 %. Yet, contrasting the economic effects of climate policy up to 2030 (i.e. the implementation of the EU-20-20-20 targets) relative to those of climate change impacts themselves reveals that climate policy has a considerably stronger effect on EIS output: more than 99 % of the change relative to a baseline without policy is explained by climate policy, while less than 1 % is due to climate change impacts. To elicit the "true" costs of climate change, more research is needed in the form of a joint assessment of climate change impacts and effects of different climate policy regimes.

[1] „Standard capacity", or synonymously "standard operation capacity" or "standard production capacity", is the long-term average annual net electrical energy output.

1 Executive Summary (Deutsch)

Die Stromerzeugung stellt nicht nur einen wesentlichen Beitrag zu Treibhausgasemissionen dar, sie ist aufgrund des wachsenden Anteils an erneuerbaren Energieträgern auch verwundbar gegenüber veränderten klimatischen Bedingungen. Ein Temperaturanstieg führt zudem zu Veränderungen der Nachfrage nach Elektrizität. Da Elektrizität in alle Sektoren als Vorleistung einfließt, führen Veränderungen beispielsweise in der Kraftwerksstruktur zu Effekten in der restlichen Wirtschaft. In diesem Projekt wurden daher die Auswirkungen des Klimawandels auf die Elektrizitätswirtschaft sowie auf die österreichische Wirtschaft insgesamt bis 2050 untersucht. Ausgehend von hoch aufgelösten klimatologischen und hydrologischen Szenarien und einem ökonometrischen Elektrizitätsnachfragemodell wurden ein techno-ökonomisches Elektrizitätssektormodell mit einem Mehr-Länder-mehr-Sektoren Computable General Equilibrium (CGE)-Modell gekoppelt. Mittels einer Reliabilitätsanalyse wurden die Unsicherheiten über die Modellkette beleuchtet.

Die interdisziplinäre Fragestellung erforderte eine Kopplung von unterschiedlichen Modellen. Das primäre Ziel dieses Projekts war daher die Entwicklung eines gekoppelten Modellrahmens um die Auswirkungen des Klimawandels auf Österreichs Elektrizitätswirtschaft bis 2050 zu quantifizieren. Zusätzlich wurden die Unsicherheiten entlang der Modellkette, reichend von Unsicherheiten in Klima- und hydrologischen Szenarien (z.B. in Folge von Modellvereinfachungen und Modellfehlern) über Unsicherheiten in ökonomischen Modellen (z.B. Annahmen bzgl. der Klimapolitik) untersucht.

Mit diesem innovativen Ansatz wurden die folgenden Forschungsfragen untersucht:

1. Wie vulnerabel ist die Elektrizitätswirtschaft in Österreich und Kontinentaleuropa gegenüber klimatischen Veränderung bis 2050, gegeben Veränderungen in Abfluss, Temperatur, Globalstrahlung und Wind?
2. Wie ist die europäische Elektrizitätsnachfrage durch Klimawandelfolgen bis 2050 betroffen, insbesondere hinsichtlich Heiz- und Kühlbedarf?
3. Welche makroökonomischen Effekte sind mit den Klimawandelfolgen auf Österreichs und Kontinentaleuropas Elektrizitätswirtschaft verbunden? Wie groß sind die direkten relativ zu indirekten Effekten auf vor- und nachgelagerte Sektoren?
4. Wie sensitiv sind die Ergebnisse bezogen auf klimatologische, hydrologische, ökonomische und politische Faktoren?
5. Was sind geeignete Anpassungsmaßnahmen für die Elektrizitätswirtschaft je nach Energieträger (erneuerbar und nicht-erneuerbar)?

Die Beantwortung dieser Fragen führte zu folgenden zentralen Ergebnissen:

- Bezüglich der meteorologischen Veränderungen wurden vier repräsentative regionale Klimaszenarien ausgewählt, um die Unsicherheitsbandbreite der erwarteten klimatischen Veränderungen sicherzustellen. Die Klimawandelsignale der ausgewählten Szenarien reichen von +1,2°C bis +2,8 °C für Temperatur, -0,27 bis +0,3 mm/Tag für Niederschlag, -3,46 W/m² bis +6,81 W/m² für Globalstrahlung und zeigen keine nennenswerten Veränderungen für durchschnittliche Windgeschwindigkeiten.
- Die Veränderungen im Abfluss aller 101 im Projekt weiter betrachteten Stationen innerhalb des erweiterten Alpenraums variieren entsprechend ihrer geographischen Lage und hängen von der betrachteten Periode und dem Klimaszenario ab. Veränderungen werden sowohl relativ in % als auch als absoluter Abfluss pro Fläche in l/s km² angegeben. Allgemein liegen die Veränderungen des Abflusses zwischen -15 und +10 %, wobei Abnahmen bis zu -35 %

für Südfrankreich und Norditalien geschätzt werden. Absolut variieren die Abflussveränderungen zwischen -6 und +4 l/s·km².

- Für die vier Klimaszenarien werden zudem Veränderungen im Elektrizitätsverbrauch für 16 kontinentaleuropäische Länder untersucht. Insgesamt führen wärmere jährliche Durchschnittstemperaturen zu Verbrauchsrückgängen, je nach Klimaszenario von -10.000 GWh bis -25.000 GWh pro Jahr. Das Verhältnis zwischen absoluten Rückgängen im elektrischen Heizverbrauch und absoluten Zunahmen im Kühlbedarf beträgt dennoch je nach Klimaszenario zwischen 2:1 und 6:1. Relativ zum momentan gesamten Elektrizitätsverbrauch sind diese Effekte jedoch vergleichsweise klein, v.a. im Vergleich zu anderen Einflussfaktoren. Die gesamte langfristige Reduktion für Kontinentaleuropa beträgt zwischen -0.4 % und -1.1 % des Gesamtelektrizitätsverbrauchs. In manchen Ländern mit einem hohen Anteil an elektrischen Heizen oder Kühlen sind diese Effekte jedoch stärker ausgeprägt, wie zum Beispiel bis zu -3 % im vom Heizen dominierten Frankreich und bis zu +0.6 % im vom Kühlen dominierten Italien.
- Bezüglich der Auswirkungen des Klimawandels auf die Elektrizitätserzeugung betragen die Veränderungen des Regelarbeitsvermögens (RAV) zwischen +3 % und -4 % (bestes und schlechtestes Szenario) des RAV in Kontinentaleuropa, was durchschnittlich 45 TWh in der Periode 2031-2050 entspricht. Das RAV für Österreich variiert zwischen +2.2 % und -5.1 %, bzw. +1.14 TWh und -2.58 TWh, in der gleichen Periode. Primäre Triebkräfte sind Laufwaserkraftwerke (+/-1 TWh) sowie Speicherkraftwerke (+0.5 / -1.5 TWh). Je Technologie werden die stärksten Änderungen im RAV bei Speicherkraftwerken verzeichnet. Elektrizitätserzeugung aus Photovoltaik ist in Österreich durch Klimawandeleffekte stärker betroffen als Wasserkraft und zeigt vergleichsweise hohe und negative Auswirkungen in allen Klimaszenarien. Aufgrund der geringen Menge an installierten Kapazitäten spielt die Erzeugung aus Photovoltaik jedoch nur eine untergeordnete Rolle für Österreichs Elektrizitätswirtschaft.
- Bezüglich der indirekten Effekte klimatischer Veränderungen im Elektriztitätssektor auf andere Sektoren wurde die Veränderungen des Produktionswerts elektrizitätsintensiver (EIS) und nicht-elektrizitätsintensiver Sektoren (NEIS) für die Perioden 2011-30 und 2031-50 untersucht. Vergleicht man die relative Größe von direkten und indirekten Auswirkungen des Klimawandels, so zeigt sich dass der Nettoeffekt auf den Gesamtproduktionswert im günstigsten Szenario von +0.02 % für Deutschland und Luxemburg (GERL) bis +0.23 % für Osteuropa (EEU) reicht (für 2011-30 relativ zu einem Baseline-Szenario), während im ungünstigsten Szenario die Nettoeffekte zwischen -0.19 % für EEU und -0.04 % für GERL liegen. Die Nettoeffekte für Österreich liegen zwischen -0.14 % und +0.03 % des Gesamtproduktionswerts aller Sektoren. Vergleicht man jedoch den Effekt von Klimapolitik 2011-30 (d.h. Umsetzung der EU 20-20-20 Ziele) relativ zu jenen der Auswirkungen des Klimawandels, so zeigt sich, dass der Effekt von Klimapolitik erheblich größer ist: mehr als 99 % der Veränderungen relativ zu einer Baseline ohne zusätzliche Klimapolitik wird durch Klimapolitik verursacht, und weniger als 1 % durch klimatische Veränderungen. Es ergibt sich daraus ein Forschungsbedarf der Gestalt, dass die Auswirkungen des Klimawandels unter Zugrundelegung unterschiedlicher klimapolitischer Vorgaben abgeschätzt werden, um die „wahren“ Kosten der Klimafolgen ermitteln zu können.

2 Background and objectives / Hintergrund und Zielsetzung

The EU Green Paper (2007) on adaptation to climate change in Europe states mountain areas, particularly the Alps, as one of the most vulnerable areas in Europe. Austria already experiences rising annual average temperatures which are accompanied by significant and measurable impacts: Glaciers are retreating and snow covered periods are getting shorter, thus altering the timing and amplitude of melt water run-off. Also the intensity and frequency of precipitation in Austria is changing. With growing international recognition of the urgent need to adaptation to climate change, the mechanisms of adaptation, as well as the interplay with sectoral vulnerability, have to be better understood in order to devise cost-effective adaptation policies in the short, medium and long run.

This project intended to provide a sound scientific basis for assessing an adaptation strategy for Austria in the electricity sector, a sector highly vulnerable to climate change. Regarding power supply, especially hydropower plants but also new renewable energy sources will be affected by climate change. Changed evaporation and precipitation patterns and shrinking glaciers impact the operation of run-off-river as well as storage hydropower plants. On the other hand, higher ambient temperatures influence cooling processes, outages, efficiencies and effective power of thermal power plants. On the demand side, changing climatic conditions result in different consumption for cooling and heating as well as different patterns of electricity use.

Since the electricity sector is characterized by strong international linkages, the impacts and adaptation options for Austria have to be investigated within the European context. The increasing power generation from fluctuating renewable sources, like wind power in the north of the Alps or solar power in the Mediterranean countries, requires additional capacities for electricity storage and control. Climate change is associated with rising cooling demand in Southern Europe and declining heating demand in the north. The power exchange between Austria and its neighbouring countries is thus expected to increase dramatically such that any future outlook has to take into account the European context of the electricity market.

Another specific characteristic of electricity is its key role as an intermediate input in other sectors, particularly for energy intensive sectors, as well as in final demand. This necessitates not only a detailed analysis of the consequences for the sector itself but also an analysis of effects on the macroeconomy.

The aim of this project is to develop an integrated modeling framework to describe and analyze climate change impacts in the electricity sector in Austria and its macroeconomic feedback effects on a time scale up to 2050. Due to the cross-cutting nature of the problem, an integration (or coupling) of different models is essential. The first focus of the project lies thus on the adjustment and integration of the different models employed. To depict the consequences of climate change for electricity, high-resolution climate change scenarios are used as input to the hydrological model to determine changes in hydrology relevant for hydropower generation and as input to the electricity sector models (temporal and spatial high resolution temperature, precipitation, river discharge, global radiation, and wind data). The currently best available sectoral models for electricity are refined (in terms of temporal scale and adaptation detail): (i) techno-economic model of the electricity industry in continental Europe and (ii) econometric analysis to model the climate change impact on as well as adaptation options for the demand for electricity. The bottom-up electricity sector model is linked to a top-down, i.e. multi-country multi-sector, computable general equilibrium (CGE) model of Austria and other European countries to evaluate the sectoral and economy-wide climate change impacts and adaptation options for the electricity sector.

In addition to the development of an integrated modelling framework, we analyze uncertainties involved in the overall modelling approach, from uncertainties in climate scenarios (uncertainties in future greenhouse gas emissions, uncertainties due to the climate model's simplifications and errors) to uncertainties in economic modelling (assumptions on demographics, technological change, fuel prices).

3 Project content and results / Projektinhalt und Ergebnis

In this project, the following research questions were addressed:

1. How vulnerable is power generation in Austria, and continental Europe, to climate change on a time scale up to 2050, given changes in runoff water, temperature, global radiation, and wind?
2. In which way is electricity demand in continental Europe affected by climate change on a time scale up to 2050, in particular with regard to heating and cooling?
3. What are the associated macroeconomic effects of climate change impacts in the Austrian electricity sector, acknowledging Austria's openness to international trade in the continental European context? How large are direct effects relative to indirect (i.e. spillover) effects on other sectors?
4. How sensitive are results with respect to climatic / hydrological factors and economic factors? What are the ranges of uncertainties which have to be considered for the reported results?
5. What are suitable adaptation options for the electricity sector, distinguishing for different sources of energy (renewable and non-renewable)?

To address these research questions, five methods were applied and coupled, namely

- regional climate modelling (dynamical and statistical-empirical) to derive the climate scenarios as input for the hydrological and electricity sector models
- hydrological modelling to assess climate change effects on river flows
- econometric analysis of the electricity demand in continental Europe to assess the climate change impacts and adaptation options until 2050
- ATLANTIS, a techno-economic simulation model of the electricity sector in continental Europe
- multi-country multi-sector CGE modelling for continental Europe to evaluate the macroeconomic impacts as well as short and long-run adaptation options for the electricity sector
- reliability and uncertainty analysis to contrast the significance of the model system's response to climate change and economic drivers compared to the involved uncertainties

Regional Climate Modeling (WPs 1, 3)

The aim of regional climate modeling (conducted by P1, WEGC-ReLoClim) was the preparation of error corrected climate scenarios for Europe for the geographical extent shown in Figure 1 for further hydrological modeling, modeling of the energy demand as well as impact modeling for the electric sector.

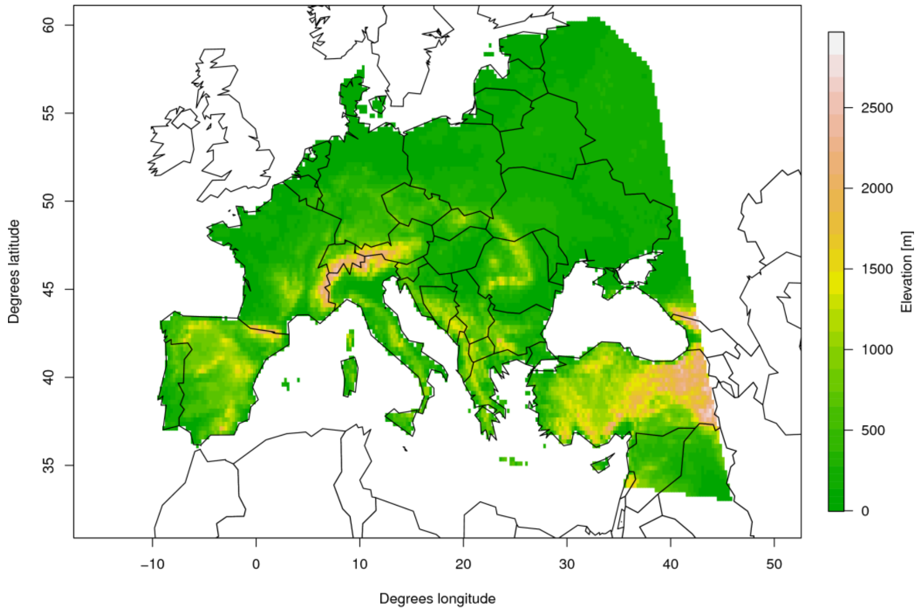

Figure 1: The study region for the development of tailored climate information in El.Adapt.

For this purpose four representative regional climate simulations have been selected from the ENSEMBLES multi-model dataset in order to cover the climate scenario uncertainty and its influence on run off and the energy production sector, as well as future heating and cooling energy demand. It is important to note, that all simulations regarded here are based on the A1B emission scenario. The selection was based on seasonal climate change signals (CCSs) of temperature, precipitation, windspeed, and global radiation between 1961-1990 and 2021-2050, calculated for different areas in Europe depending on the respective meteorological parameter (Figure 2). Due to the unequal importance of the different meteorological parameters concerning the electricity system, weights for each parameter were defined, which represent the impact of every meteorological parameter on the common electricity market of Germany and Austria. The weights are given in Table 1.

Table 1: Weighting of climatic parameters applied in the project

Parameter	Weight
Air temperature	0.5
Precipitation amount	0.21875
Wind speed	0.21875
Global radiation	0.0625

Figure 3 shows the result of the selection process. The spider-diagram displays the respective CCS for the summer (S) and winter season (W). The different meteorological parameters are normalized to yield comparable units. Selected RCMs are indicated by the bold lines. The parameter range covered by the selected RCMs covers a large part of the entire RCM ensemble, which ensures that uncertainty is not underestimated. Furthermore, the selected RCMs show different characteristics: Meteo-HC HadRM3Q0 being a hot and dry realization (called DESERT thereafter, red), C4IRCA3 being a warm and wet realization (called TROPIC, yellow), KNMI-RACMO2 being a moderate realization (called MODERATE, green) and CNRM-RM4.5 representing a special case, which shows stronger summer than winter warming (called AIR CONDITION, blue).

The climate change signals between 1961-1990 and 2021-2050 of the selected models are summarized in Tables 2 and 3. Based on the selected simulations, we expect changes ranging from +1.2°C to +2.8 °C for temperature, -0.27 to +0.3 mm/day for precipitation, -3.46 W/m² to +6.81 W/m² for global radiation and no remarkable change for mean wind speed.

These different characteristics are assumed to lead to different impacts for subsequent impact modelling ranging from “good” to “bad” for run-off, energy demand and energy production (e.g. an increasing mean of precipitation may lead to more river runoff and finally to more production of electrical energy in hydro power plants.)

Table 2: Mean climate change signal for temperature (air temp, °C), precipitation (prec, mm/day), windspeed (windsp, m/s) and global radiation (glob.rad, W/m²) for the winter season (December, January, February)

Model - **WINTER**	*air.temp m*	*prec m*	*windsp m*	*glob.rad m*
METO-HC_HadRM3Q0	2,406	0,045	0,017	1,918
C4IRCA3	2,297	0,295	-0,019	-1,379
CNRM-RM4.5	1,184	-0,162	0,085	0,086
KNMI-RACMO2	1,162	0,262	0,165	0,080

Table 3: Mean climate change signal for temperature (air temp, °C), precipitation (prec, mm/day), windspeed (windsp, m/s) and global radiation (glob.rad, W/m²) for the summer season (June, July, August)

Model - **SOMMER**	*air.temp m*	*prec m*	*windsp m*	*glob.rad m*
METO-HC_HadRM3Q0	2,787	-0,275	-0,001	3,876
C4IRCA3	2,023	0,171	-0,055	-3,458
CNRM-RM4.5	2,115	0,144	0,016	6,181
KNMI-RACMO2	1,441	-0,129	-0,001	0,529

Daily temperature and precipitation of the selected simulations have further been error corrected using an empirical-statistical method (quantile mapping), in order remove model errors as far as possible. Due to the lack of suitable long-term observational data for wind-speed and global radiation for entire continental Europe, these parameters have not been error corrected on daily basis. In these cases either the uncorrected data (wind speed) have been considered or a delta approach (global radiation) (Déqué 2007; Graham et al., 2007) was used. This method removes constant model errors, but potential changes in variability are disregarded, since variability is inherited from the observations.

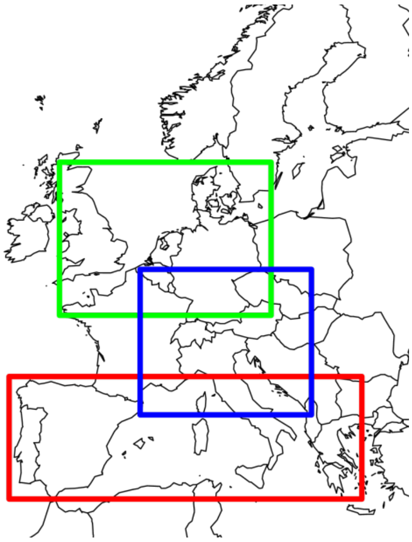

Figure 2: Definitions of the geographical locations for the calculation of the CCS of temperature, precipitation (blue box), wind speed (green box), and global radiation (red box)

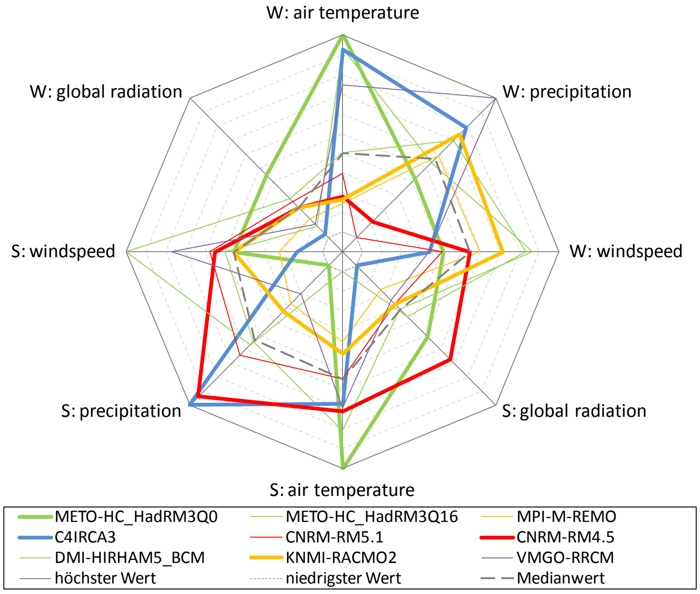

Figure 3: Overview of the pre-selected and finally selected scenario models.
The axes represent the normalized climate change signals of the different parameters for summer (S) and winter (W).

Hydrological modelling (WP1)

The aim of hydrological modeling (conducted by P2, UG-IES) is to provide runoff estimates at a monthly time step for various measurement stations along important rivers related to hydropower plants within the Greater Alpine Region. For this purpose an appropriate parsimonious, lumped parameter rainfall-runoff (water-balance) model was identified, based on the GR2M monthly water-balance model (Makhlouf and Michel, 1994; Mouelhi et al., 2006), and extended by a temperature-based snow model (as proposed by Xu et al.,1996) and potential evapotranspiration (PET) computed based on temperature and extraterrestrial solar radiation only (Oudin et al., 2005). Hence, temperature and precipitation are the only input data necessary (as extraterrestrial solar radiation is assumed to remain constant). This model approach uses a spatial, temporal and conceptual lumping, which is believed to be a suitable model structure for the purpose of monthly rainfall-runoff-prediction due to its parsimony (Edijatno et al., 1999; Perrin et al., 2001; Gupta et al., 2005). Processes accounted for are snow accumulation and snow melt, evapotranspiration, soil storage, routing storage, and water exchange with neighboring catchments.

The model was calibrated and validated using monthly EOBS observation data (1950 to 2010) provided by WEGC-ReLoCLim (temperature and precipitation as forcing input) and monthly discharge time series provided by various organizations like the "Hydrographische Dienst Steiermark" and the Global Runoff Data Centre (GRDC). Four model parameters were adjusted to calibrate the model to the available discharge data. Model validation was based on different efficiency criteria (multi-objective approach; trade-off in single efficiency criteria to have an overall consistency; the "closeness" of simulated and observed stream flow; Krause et al., 2005), visual inspections of the hydrographs, and split sample tests and proxy basin tests (Klemes, 1986; Xu, 1999). An example of a calibrated hydrograph including a split sample test is shown in Figure 4. Moreover, the model results were compared to other models (e.g. Kling et al., 2011; Stanzel and Nachtnebel, 2010; Klein et al., 2011; Kranzl et al., 2010; ZAMG/TU-Wien Studie, 2011).

The calibrated and validated hydrological models for the individual stations along the various rivers are used with the four climate scenarios as input to predict a range of runoff estimates for the two periods 2011-2030 and 2031-2050. Using the predicted temperature and precipitation, the predicted runoff under the conditions proposed by the respective climate change scenario is provided. Figure 5 shows for each of the four climate change scenarios the predicted seasonal change of the mean monthly runoff of the river Danube at the station Kienstock in the two time periods 2011-2030 and 2031-2050. The comparison of the predicted future mean monthly runoff with runoff simulated for the reference period 1961-1990 yields the expected change in monthly runoff for each of the 4 climate change scenarios (Figure 6).

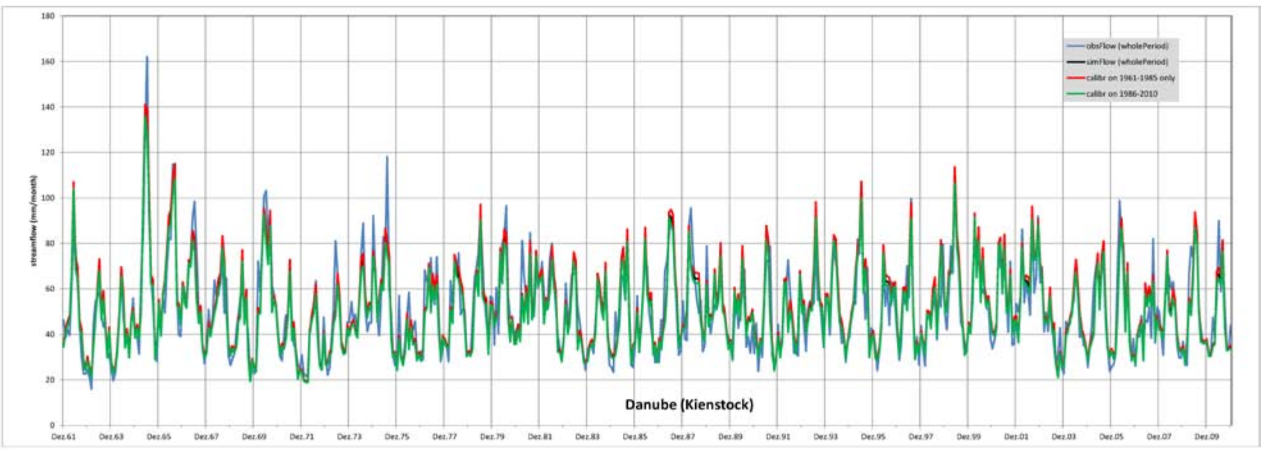

Figure 4: Hydrograph of the gauging station Kienstock (Danube River)
observational data (blue line), calibration over whole time span (black line), calibration over first half of data (red line) and calibration over second half (green line). Note good fit of drought period 2003 even for the model calibrated on the first half of the data (1961-1985).

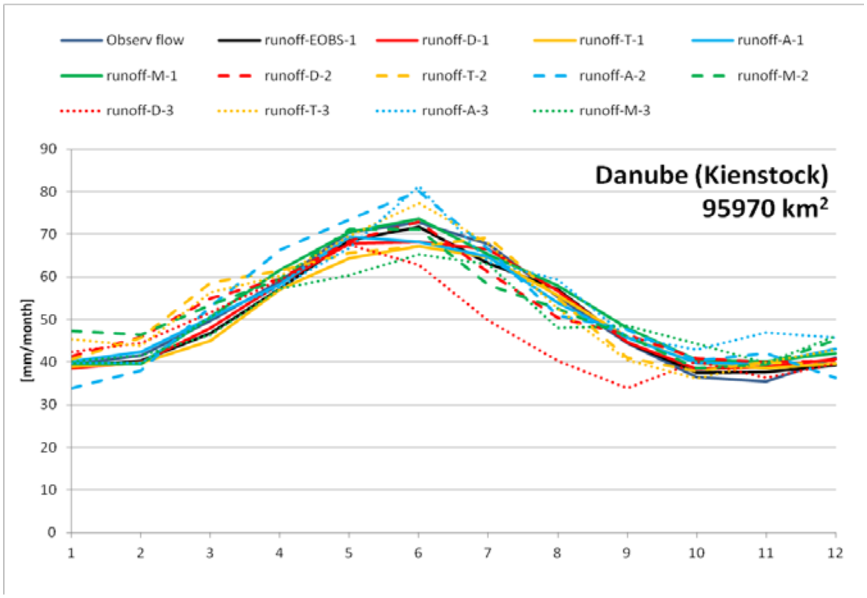

Figure 5: Seasonal change of the mean monthly predicted runoff of the station Kienstock (Danube River).

The color coding of the lines is based on the different scenarios. Red and the letter D ("Desert" = Meteo-HC HadRM3Q0) represents the hot and dry scenario; orange and T ("Tropic" = C4IRCA3) the warm and wet scenario; blue and A ("AirCondition" = CNRM-RM4.5) the scenario with stronger summer than winter warming; green and M ("Moderate" = KNMI-RACMO2) the moderate scenario. 1, 2, and 3 in the legend are related to the time periods 1961-1990, 2011-2030 and 2031-2050.

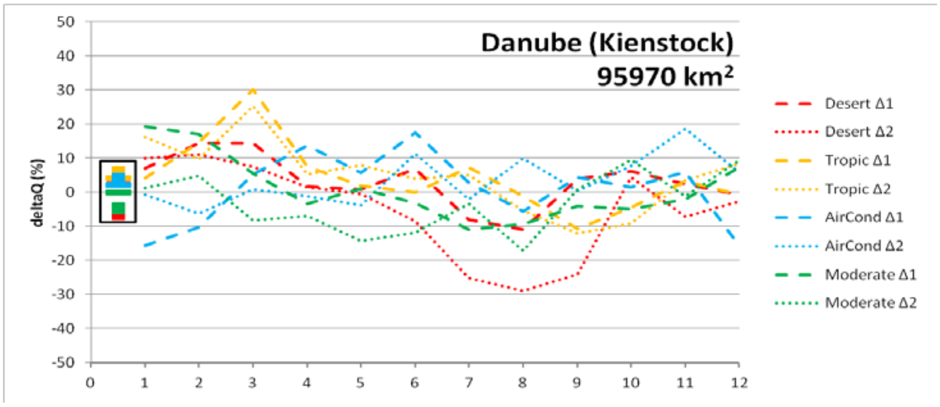

Figure 6: The difference per month of the runoff for two time periods (2011-2030 and 2031-2050) vs. the period 1961-1990.

The color-coding is similar to Figure 5. Note that small increases in the runoff during periods of low flow (e.g. in winter) might give the impressions of large changes (up to 100 %); however, these might not have a great influence on the difference in annual runoff indicated by the bars (period 1) and rectangles (period 2) at the left side of the plot.

Runoff changes for a large number of catchments have been computed using the calibrated and validated hydrological model and the four climate scenarios. Four large (almost 100,000 km^2) catchments covering the extent of the GAR are considered exemplary to indicate likely changes. On the one hand, seasonal changes produce increasing runoff early in the year; on the other hand, the hot and dry scenario indicates possible decrease in runoff of up to 35 % in the south and southwest of the Alpine region (Figure 7).

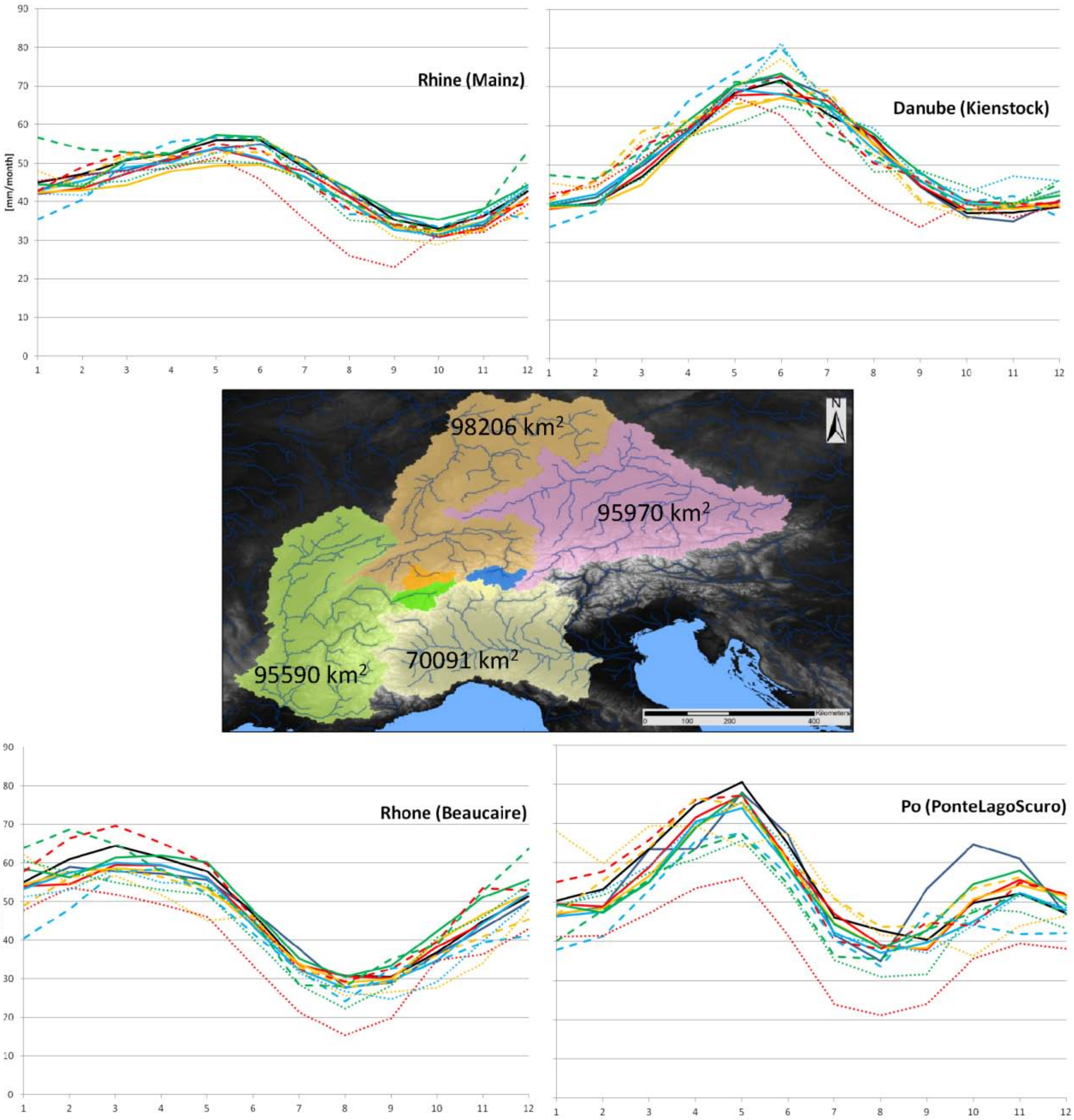

Figure 7: Estimated average monthly runoff for the time periods 2011-2030 and 2031-2050 compared to the period 1961-1990 for four large catchments draining the whole Alpine region. The color-coding is identical to Figure 5.

Climate Change Impacts on Electricity Demand in Continental Europe (WP2)

For Europe, recent studies have provided an overview on the likely impacts of temperature change on electricity use for heating and cooling using econometric regression models (Pilli-Sihvola et al., 2010; Eskeland and Mideksa, 2010). In WP2 (conducted by A, WEGC-EconClim, and P3, Joanneum Reserach), the present study seeks to further contribute to this issue by (1) using four different spatially and temporally highly resolved climate scenarios, which helps to provide impacts for a range of possible temperature changes, (2) doing calculations for altogether 16 Continental European countries (AT, BE, BG, CZ, FR, DE, HU, IT, NL, PL, PT, RO, SK, SI, ES, HR), which enables to study different regional response patterns, and (3) working with daily electricity data, which allows to examine the non-linear relationship between temperature and electricity demand by the means of advanced statistical techniques such as smooth transition regression (STR) models, recently also applied in Moral-Carcedo and Vicéns-Otero (2005) and Bessec and Fouquau (2008).

This combined use of sophisticated regression models and high frequency load data allows to study heating and cooling electricity demand in better detail than approaches which determine temperature impacts by regressing cumulative heating and cooling degree days (HDD and CDD) on monthly loads. On the one hand, STR allows to model the slow transition from temperatures where heating is needed to temperatures where cooling is needed, rather than arbitrarily choosing one exact threshold value for HDD and CDD. On the other hand, the use of daily data makes it possible to describe well-observed cooling effects for moderate-temperated countries such as Austria or Germany, while when using monthly data more pronounced effects like summer holidays may superimpose comparatively small but not negligible cooling effects for these countries.

From a methodological point of view we proceed in the following way: First, we create national temperature indices, which summarize both observational meteorological data (EOBS - Haylock et al., 2008) as well as climate scenario data (ENSEMBLES - van der Linden and Mitchell, 2009) in such a way, that the population distribution within a country is accounted for. For that we use both Corine Land Cover data (EEA, 2011) and NUTS-3 population data (Eurostat, 2011). Second, we correct daily national electricity load for non-climatic effects, such as the effects of public holidays and bridging days, Christmas time and summer holidays, weekdays as well as variations in economic activity. Third, we estimate the statistical relationship between temperature indices and the corrected load and estimate the effects of changing climate conditions. In order to analytically separate the impacts of temperature change from socio-economic developments, we do calculations under the strong assumption that consumers will react to temperature changes in the future in the same way as they currently (period 2006-10) do. This assumption is helpful, as the extent of future heating and cooling electricity consumption will heavily depend on uncertain future energy policy and consumer behaviour. However, the assumption is relaxed in a further step of modelling.

Summarizing the four climate models, the absolute climate induced change for our sample of 16 Continental European countries reveals some very interesting patterns. Overall, warmer annual temperatures reduce the total electricity consumption in Continental Europe (Figure 8).

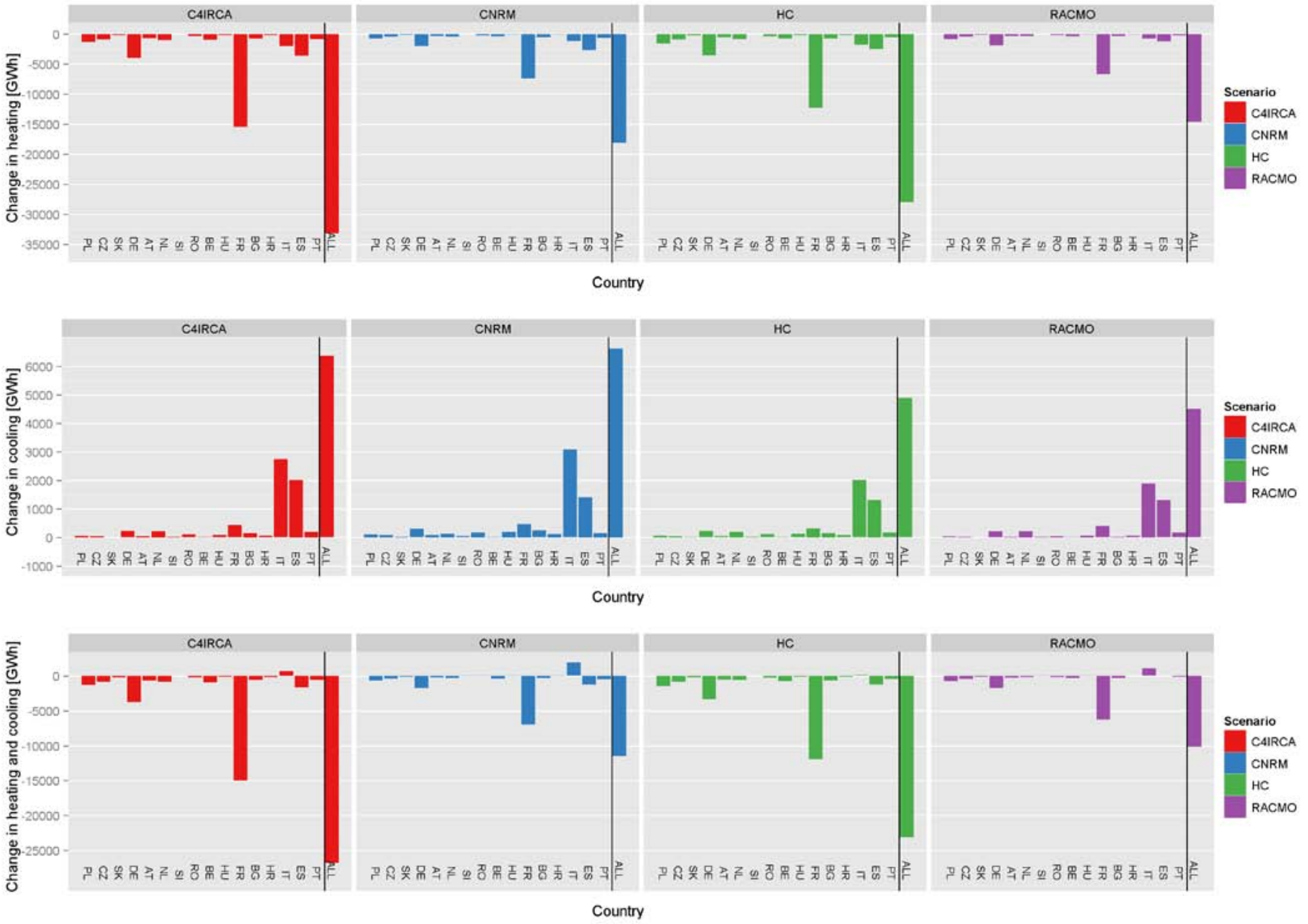

Figure 8: Average climate-induced change in annual heating and cooling electricity demand compared between the reference period 1961-90 and the scenario period 2011-50.

In particular, this dominance of changing heating electricity demand can be explained by French energy policy, where electric heating has been strongly promoted since the 1970s. Due to this policy, the reductions in heating electricity demand in an unusually warm winter in France alone more than outweigh the additional demand for cooling in an unusually warm summer observed in the 16 Continental European countries for which calculations are done. In addition, other moderate-temperatured countries like Germany and to a lesser extent also warmer-temperatured countries like Italy and Spain face reductions in heating electricity demand due to milder winter temperatures.

However, even if overall heating effects dominate, cooling effects are not negligible for some countries with warmer summer temperatures. In particular, in Italy even nowadays annual cooling electricity demand almost equals annual heating electricity demand, but is potentially more threatening to network reliability due to its concentration to fewer peak days. Notably, for Italy the increase in cooling electricity demand is predicted to be stronger than the decrease in heating electricity demand for all climate scenarios, while for other countries with comparatively warm summer temperatures (Spain, Hungary, Croatia) overall effects do not point in a clear direction and differ strongly between climate scenarios. On the other hand, in all other countries (12 out of 16) cooling effects are estimated to be relatively small compared to heating electricity effects, even if some of these countries exhibit warm summer temperatures (Portugal or Bulgaria).

Putting these climate-induced reductions in heating electricity demand and increase in cooling electricity demand in relation to current total electricity consumption reveals that effects of these long-term climate changes are comparatively small compared to other potential driver of electricity demand (Figure 9). The overall long-term reduction for Continental Europe is -0.4 % to -1.1 % of total electricity use. To provide a comparison, this amount roughly equals the growth in electricity consumption in the EU-15 which was observed on average every 3 to 6 months in recent decades. However, in some countries with major electric heating or cooling activities climate induced changes are of course more pronounced, like up to -3 % in heating-dominated France and up to +0.6 % in cooling-dominated Italy.

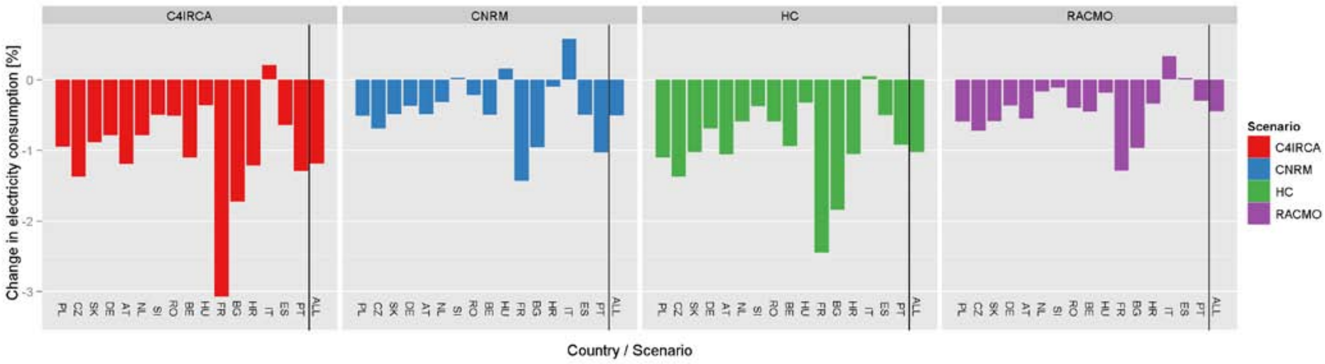

Figure 9: Share of the climate induced change in heating and cooling electricity demand on total electricity demand.

Simulation of the Electricity Sector in continental Europe (WP3)

Work package 3 (conducted by P2, TUG-IEE) can be divided into two major parts. In the first part, the modelling phase, the climatic model chain was developed, beginning with the climate scenario selection described in the paragraph of WP1. To develop and calibrate the models used in the chain, the exchange of data was necessary. Due to this, historic demand was delivered to WP2 (data source: ENTSO-E) and historic values (data source: E-OBS) as well as the corresponding climate model datasets of the selected climatic parameters were delivered by WP1 (WEGC-ReLoClim).

Within WP3, different approaches were developed to derive electricity generation from climatic parameters. Based on the fact that hydro power generation (especially by run-of-river power plants) plays an important role for Austria, an existing model of hydro power plants (Schüppel, 2010) has been improved and was used to simulate impacts on hydro power generation in Austria using the results of the hydrological model developed in WP1.

For wind power, an empirical approach was used to estimate changes in monthly means of wind energy generation based on the delivered wind speeds from WP1. The photovoltaics model utilises the linear relationship between global radiation and gained power from photovoltaic cells. In a master’s thesis carried out besides the project, it was shown that temperature and wind influence the efficiency of photovoltaic cells, too. However, these influences will need an hourly model to be taken under consideration. Due to the long-term investigation of this study using a delta approach with average climate change signals for periods of 20 years, the impacts of wind and temperature changes on photovoltaic generation will be less than the model uncertainties. Therefore, wind and temperature have been neglected in the model.

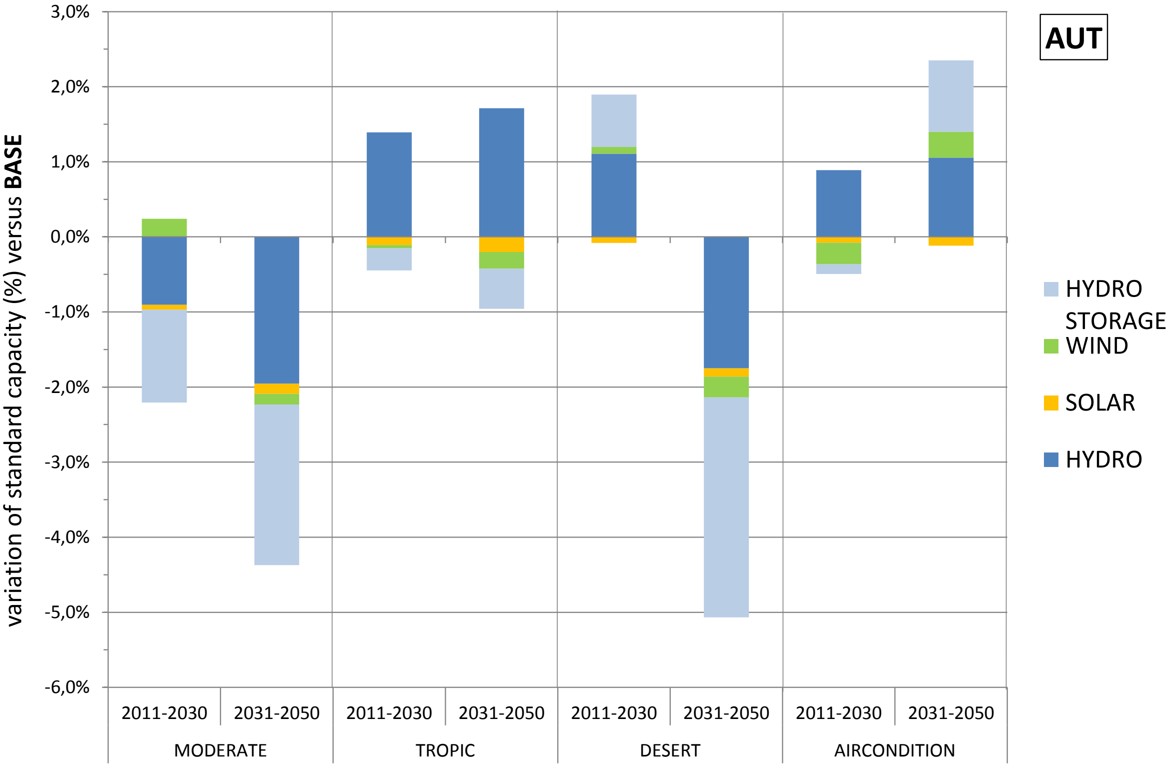

Figure 10: Direct impacts of climate change on the electricity generation in Austria; average changes of standard capacity per technology relative to the total average standard capacity of hydro power, natural inflow of storage plants, wind and PV.

Scenario labels: MODERATE = KNMI-RACMO2, TROPIC = C4IRCA3, DESERT = Meteo-HC HadRM3Q0, AIRCONDITION = CNRM-RM4.5

The results of the model chain are shown for Austria in Figure 10. The impacts of climate change may lead to an increase of standard capacity[2] in Austria by 2.5 % of Austria's total average standard capacity of hydro power, hydro storage (natural inflows), wind power and solar power in the best case. In the worst case, the standard capacity decreases by -5 %. Due to its huge share in the production of electricity in Austria, hydro power is the most vulnerable technology in terms of climate change.

The variation bandwidth of standard capacity in Continental Europe[3] is between -4 % and +3 % compared to the total average standard capacity. The most vulnerable technologies are wind power and hydro storage power plants.

These results were used – among others - as input parameters of simulations carried out with the simulation model ATLANTIS. With ATLANTIS, a techno-economic sectoral model of the electricity system in Continental Europe, it is possible to map the climate change impacts on the generation and demand side (WP2) and to simulate the consequences for the electricity system and the electricity market. To integrate the results of the upstream model chain and to couple ATLANTIS with the macro-economic CGE model described in WP4, certain improvements and developments had to be made:

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[2] „Standard capacity", „standard operation capacity" or „standard production capacity" is defined in this study as the long-term average annual net electrical energy output. These terms are commonly used with generation units using renewable energy sources.

[3] Hydro power plants and storage power plants in the Alpine region only are considered.

- Implementation of learning rates for power plant investments. This was needed to represent the technological progress of generation technologies, which influences the investment costs delivered to the CGE model in coupled simulations.
- Research and implementation of static investment costs and operating and maintenance costs regarding the transmission grid, in order to supply changed costs in the electricity sector to the CGE model.
- To import CGE model results, an econometric regional fuel-price model was integrated into ATLANTIS, to be able to consider regional price differences of fuels, mainly driven by transportation costs, automatically by importing the CGE model's worldwide oil price.
- To be able to consider the electricity demand of households and industry given by the CGE model, another import algorithm had to be developed, because electricity demand within the CGE model is mapped using monetary values, while ATLANTIS needs physical quantities as input
- An interface module was developed to be able to export data from ATLANTIS simulation results, which can be interpreted and imported automatically by the CGE model.

The second part consists of simulations with ATLANTIS and the CGE model. To provide a common basis for the simulations, a joint political scenario path had to be assumed in terms of energy and climate policies (see WP4 for more economic details). A comparably high share of renewable energy and a strict emission policy leading to high CO_2 emission certificate prices are the main features of this assumed path. Under these conditions, the simulation results show that no additional generation capacities are needed besides the assumed capacity development. In some cases, it may be necessary to build new capacities 1-2 years earlier than supposed, but this effect is not considerable. The direct impact of climate change will lead to decreasing CO_2 emissions in Continental Europe, justified by reduced electricity demand, even if low-carbon technologies will face a lower standard capacity. However, turning to indirect effects (e.g. spill-over effects), CO_2 emissions will rise in the MODERATE and the DESERT scenario, caused by a higher electricity demand in electricity-intensive sectors. CO_2 emissions in Austria are influenced by changes in demand of its neighbouring countries via changes in the import/export balance. Losses of standard capacity in other countries due to climate change may be compensated by generation units in Austria, conditioned by the internal electricity market. Therefore CO_2 emissions in Austria may rise throughout all climate scenarios except of the AIRCONDITION scenario. In this special case, a reduced demand[4] in combination with the maximum increase of standard capacity in Austria will lead to a reduction of CO_2 emissions, regardless of impacts in other countries.

Regarding total costs of electricity generation (production costs), climate change impacts have positive effects throughout all climate scenarios in Continental Europe as a whole. In numbers, this means a reduction by 1 to 1.5 % of overall generation costs, mainly caused by reduced electricity demand. Austria's location in the centre of the Continental European electricity system leads to the fact that there is no clear trend of development for production costs in this specific country. The effects on production costs strongly depend on changes in standard capacity, changes in Austria's electricity demand as well as changes in the import/export balance, and are hardly determinable. For example, the TROPIC scenario shows an increase of standard capacity combined with a rather marked demand reduction in Austria, which comes along with a sharp decrease of standard capacity in Germany, whose electricity market is linked with Austria without congestions. This combination along with other influences leads to increased electricity exports, which may even exceed the rising standard capacity. Hence, additional thermal capacities will be dispatched in Austria, resulting in an increase of production costs, although the direct climate change impacts seem to be very positive.

[4] The investigation of impacts does not take increasing cooling demand into account, which was defined as an adaptation measure in this study.

Another task of this work package is the investigation of adaptation measures for the electricity sector. Therefore, a comprehensive study was done on this topic within the scope of a dedicated master's thesis. The results regarding hydro power show that the recent development of this mature technology provides several improvement measures, which can also be applied as adaptation measure to fully compensate decreasing standard capacities. Furthermore, some measures show a good economic feasibility in some climate scenarios in addition. The results for wind power and photovoltaics concerning the identified adaptation measures show that the effects of climate change on standard capacities may not be totally compensated. However, in case of wind power, negative effects can be curtailed to a certain amount. Measures investigated for photovoltaic modules show, that an investment is not economically reasonable at the moment. If there is demand for low-temperature heat or if technical development of cooling systems advances, adaptation technologies may become economic feasible and reasonable.

Macroeconomic Modeling of climate change impacts in the European electricity sector (WP4)

Work package 4 (conducted by A, WEGC-EconClim) comprised the development of a multi-country multi-sector computable general equilibrium (CGE) model for Austria, its major (electricity) trading partners within the EU and other major world regions. To ensure data consistency between the sectoral ATLANTIS model and the CGE model, a major task was base year data adjustment regarding sectoral cost and investment structure of the electricity sector. Moreover, for the baseline without climate change (up to 2050) current climate and energy policy targets were assumed (in accordance with the New Policy scenario of the World Energy Outlook, IEA 2010). Climate policy targets up to 2020 reflect the EU 20-20-20 targets, up to 2050 the current policy path of the EU Roadmap 2050 is implemented (-40% of CO_2 emissions relative to 1990). Renewable energy targets are reflected in the development of generation capacities in ATLANTIS and transferred to the CGE model as different generation cost structures. Economic development (growth rates based on OECD, 2012) and fuel price forecasting (based on the International Energy Outlook, IEA 2010) was modelled. For autonomous energy efficiency improvements, an annual growth rate of 1 % was assumed.

Regarding the indirect effects of climate change impacts in the electricity sector on other sectors, average output values for electricity intensive sectors (EIS) and non-electricity intensive sectors (NEIS) are investigated relative to the BASE scenario across regions and across climate scenarios for the two periods 2011-30 and 2031-50. While effects on sectoral output in scenarios DESERT and AIRCONDITION are negligible (see Figure 11), in the MODERATE scenario there are almost only negative effects on EIS, yet of small magnitude relative to BASE (ranging from -0.86 % for EE to 0.003 % for ESP for 2011-30). The strongest effects for EIS can be observed in the TROPIC scenario, where all effects are positive, i.e. yielding higher output value compared to the BASE scenario for all regions in all periods (ranging from +0.02 % for ESP to +1.26 % for EEU), and with a stronger change in the latter period (up to +2.85 %). These impacts of climate change on output of EIS mainly result from changes in the fossil fuel use in the electricity generation and altered electricity prices.

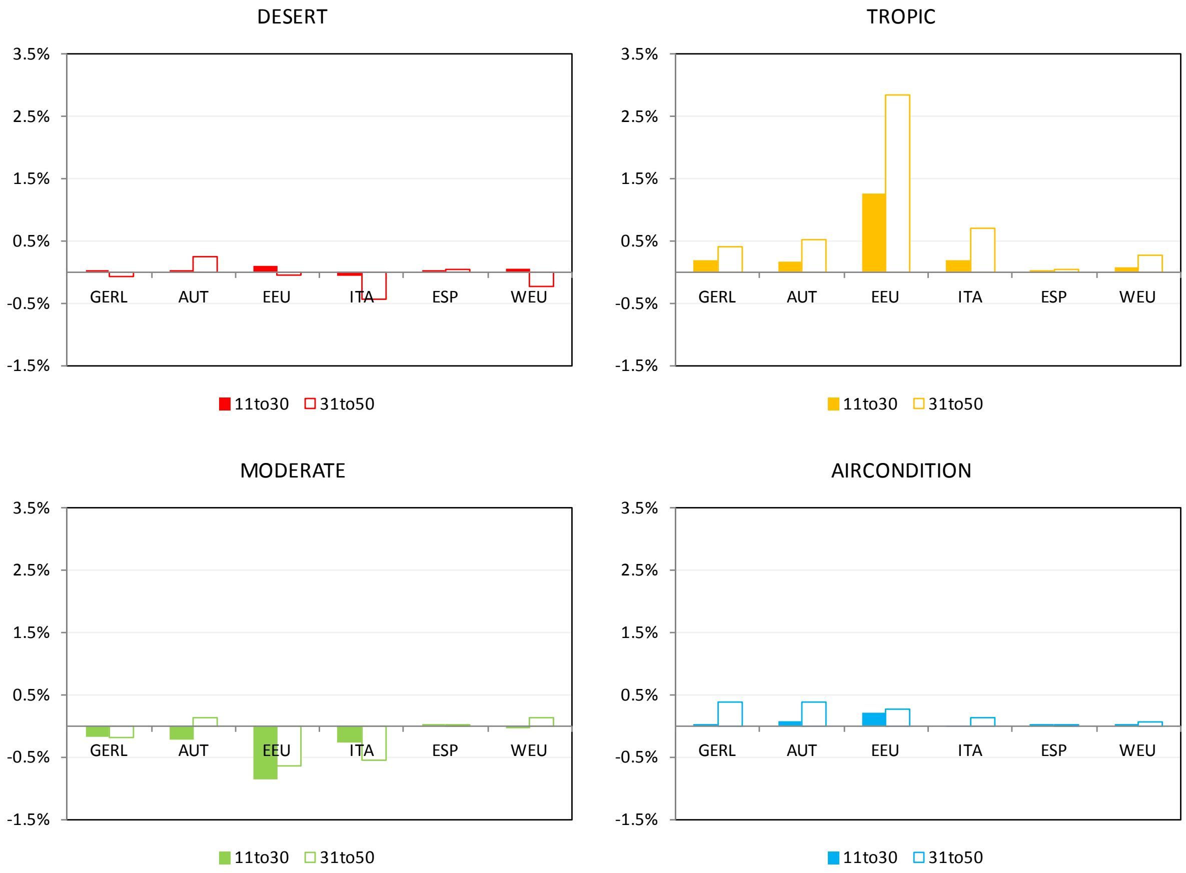

Figure 11: Impacts on output values (mio. EUR) of electricity intensive sectors (EIS) relative to Baseline scenario without climate change (in %)

Country labels: GERL = Germany, Luxemburg, AUT = Austria, EEU = Eastern EU countries, ITA = Italy, ESP = Spain and Portugal, WEU = Western EU countries. Scenario labels: MODERATE = KNMI-RACMO2, TROPIC = C4IRCA3, DESERT = Meteo-HC HadRM3Q0, AIRCONDITION = CNRM-RM4.5.

Comparing the relative magnitude of direct and indirect costs of climate change in absolute output values (see Figure 16 in chapter 4 for period 2011-2030), we find that in TROPIC output value of the electricity sector (ELY) is falling compared to BASE (positive direct costs) in period 2011-2030, but this loss is compensated by an increase in output value in EIS and NEIS in every region (negative indirect costs) such that the total increases in economic output range from +0.02 % for the regional aggregate Germany + Luxemburg (GERL) to +0.23 % for Eastern European Union countries (EEU, i.e. Czech Republic, Hungary, Poland, and Slovakia). In MODERATE, a net loss in output results as positive effects in ELY output value (gains) are compensated by much higher negative effects in EIS and NEIS (losses). The net effect thus ranges from -0.19 % for EEU to -0.04 % for GERL. In DESERT and AIRCONDITION, ELY experiences a loss in output value across all regions, whereas the direction of effects in EIS and NEIS varies, leading to net effects from -0.03 % to +0.02 %. Net effects for Austria range from -0.14 % in MODERATE to + 0.03 % in TROPIC.

In period 2031-2050, the direction and magnitude of effects partly change. For instance in DESERT the output value of NEIS falls strongly, implying net output losses for all regions. In contrast, in AIRCONDITION we see output gains throughout all regions due to strong positive effects in NEIS. In TROPIC and MODERATE, the results of the second period resemble the results of the first period in nearly all regions.

Since the electricity sector is affected by both climate change impacts and climate policy, we finally study the impacts of climate change relative to a non-climate policy BASE scenario (BASE0) to decompose the effects on output into a climate policy effect and a climate change impact effect (see Figure 12). Regarding the climate policy effect, reductions of average annual growth rates in EIS output value (relative to BASE0) range from -0.09 %-points for Spain and Portugal (ESP) to -0.38 %-points for GERL in the first period and in the second period from -0.24 %-points for ESP to -1.19 %-points for EEU, whereas decreases in NEIS are not higher than -0.16 %-points in the first period and between -0.18 % and -0.48 % in the latter. Yet, these "reductions" are relative to BASE0 such that output still rises, but at a lower rate. In contrast to the effects of climate policy, climate change impact effects on production value of both EIS and NEIS are substantially smaller compared to climate policy induced effects, ranging for EIS from -0.13 %-points to +0.07 %-points in the first period to -0.10 %-points to +0.08 %-points in the second. For NEIS, climate change impacts effects range from -0.03 %-points to +0.02 %-points in the first period to -0.04 %-points to +0.04 %-points in the second.

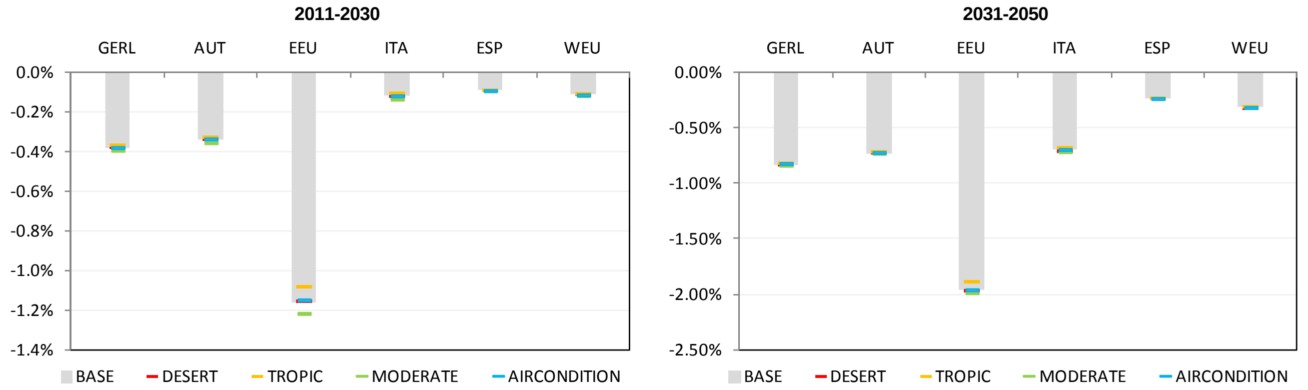

Figure 12: Change in EIS output (% change in value terms) induced by climate policy (gray bars) and climate change impacts, on average for periods 2011-30 and 2031-50 relative to BASE0.

For country and scenario labels, see Figure 11.

Reliability and Uncertainty Analysis (WP5)

As described earlier, the uncertainty in the meteorological forcing data was analyzed based on the multi-model dataset from the ENSEMBLES project. This dataset covers large part of model uncertainty, but is based on only one emission scenario. However, for the period before 2050, it is expected that the effect of different emission scenarios on climate will be largely similar. Remarkable differences are expected in the second half of the 21st century, however. The uncertainty analysis took care of ensuring that the four simulations selected for El.Adapt are representative for the uncertainty range spanned by the entire ENSEMBLES dataset and therefore provide pairs of wet or dry and hot or cool simulations.

An investigation of uncertainties regarding the impacts on standard capacities was carried out. Therefore, the installed capacities of RES technologies were varied to analyse the sensitivities of the results found in WP3. Due to the high share of renewables (75 % of net installed capacity) in the assumed political scenario in 2050, the uncertainty analysis was carried out with a reduced share of 50 % by mapping a "business as usual" development path. The analysis shows that the uncertainties regarding hydro storage power plants are quite high in a Continental European context. In context, all other technologies show more stable results. In Austria, photovoltaic generation shows the highest uncertainties. Hydro power potentials are widely developed and new capacities are rare in both scenarios. Thus, the results for hydro power are stable. Due to the highly concentrated generation capacities in the north-west of Austria, wind power shows stable results, too. However, electricity generation from photovoltaics is a quite young technology, and currently there is little capacity installed in Austria, compared to other countries like Germany, Italy and Spain. Thus, the geographical distribution of new units - influencing the intensity of climate change impacts - strongly depends on the chosen development path.

To be able to estimate the uncertainties of the coupled modelling environment, uncoupled simulations were carried out to analyse the so-called "direct" effects of climate change under "ceteris paribus" conditions, e.g. leaving fuel prices, CO_2 prices, industrial demand etc. unchanged. Comparing the results of coupled and uncoupled simulations, the results show that most values are at an equal level. However, some trends may be inverted due to spill-over effects of other sectors, which is well explainable with the results of the CGE model. One exception is the electricity demand, which is quite sensitive to technology shifts as described above.

4 Findings and recommendations / Schlussfolgerungen und Empfehlungen

The methodological results of this project are:

- Availability of an integrated climate-hydrological-energy sector-macroeconomic modelling framework to describe the requirement for adaptation in the electricity sector in Austria and Europe for a time scale up to 2050, taking account of the continental European embedding
- Identification of the major uncertainty components in the climate-hydrology-electricity sector-macroeconomic modelling framework
- Quantification of costs associated with climate change impacts for the electricity sector in Austria for a time scale up to 2050, taking account of macroeconomic feedback effects
- Assessment of adaptation options in the electricity sector in Austria for a time scale up to 2050
- Availability of a prototype modelling framework that can be extended for other climate sensitive sectors like water supply in the future
- Availability of a prototype modelling framework that can be used for cost-effectiveness analysis, and for assessing how adaptation contributes to climate change mitigation

In addition to these methodological results, several conclusions can be drawn for the electricity sector and beyond:

Regarding **meteorological forcing**, four representative regional climate scenarios have been selected to ensure to cover the uncertainty range of expected climate change. The climate change signals of the selected scenarios range from +1,2°C to +2,8°C for temperature, -0.27 to +0.3 mm/day for precipitation, -3,46 W/m² to +6.81 W/m² for global radiation and show no remarkable change for mean wind speed.

The changes in **runoff** of all the 101 stations considered further in WP3 vary due to their different geographic positions within the Greater Alpine Region (GAR) and depending on the time period and the climate scenario considered. Changes are given as relative in % and as absolute runoff per area in l/s·km² and are shown in Figure 13. In general, the variations in runoff are within -15 and +10 %, although decreases up to -35 % are estimated for Southern France and Northern Italy. In absolute values, the changes in runoff vary between -6 and +4 l/s·km².

For the Desert scenario and the first period (2011-2030 vs. 1961-1990), relative changes in runoff are estimated to be within -0.73 and +9.73 % with a median of +4.79 %. Absolute changes are within -0.09 and +3.81 l/s·km² with a median of +1.45 l/s·km². For the second period (2031-2050 vs. 1961-1990), the relative changes are within -34.96 and +0.35 % with a median of -7.80 %. Absolute changes are within -6.17 and +0.13 l/s·km² with a median of -1.88 l/s·km². This scenario shows the most diverse picture, as the two time periods are very different. For the Tropic scenario and the first period changes in runoff are within -7.51 and +8.13 % or -2.19 and +1.97 l/s·km². Median values are +1.79 % and +0.46 l/s·km². For the second period the changes are within -14.01 and +10.25 % or -5.56 and +3.57 l/s·km². Median values are 2.27 % and 0.51 l/s·km². For the Air Condition scenario and the first period changes are within -12.86 and +5.58 % or -2.97 and +1.95 l/s·km². Median values are +0.82 % and +0.22 l/s·km². For the second period the changes are within -6.45 and +9.48 % or -2.31 and +3.03 l/s·km². Median values are +3.25 % and +0.73 l/s·km². For the Moderate scenario and the first period changes are within -8.54 and +5.15 % or -2.00 and +2.42 l/s·km². Median values are -0.18 % and -0.04 l/s·km². For the second period the changes are within -15.42 and -2.52 % or -3.80 and -0.52 l/s·km². Median values are -5.99 % and -1.57 l/s·km². Despite the scenarios name, this is the only one besides the Desert scenario where for the second period a general decrease in runoff is observed for all the catchments analyzed. The spatial distribution of these runoff changes is shown in the final report (Bachner et al., 2013).

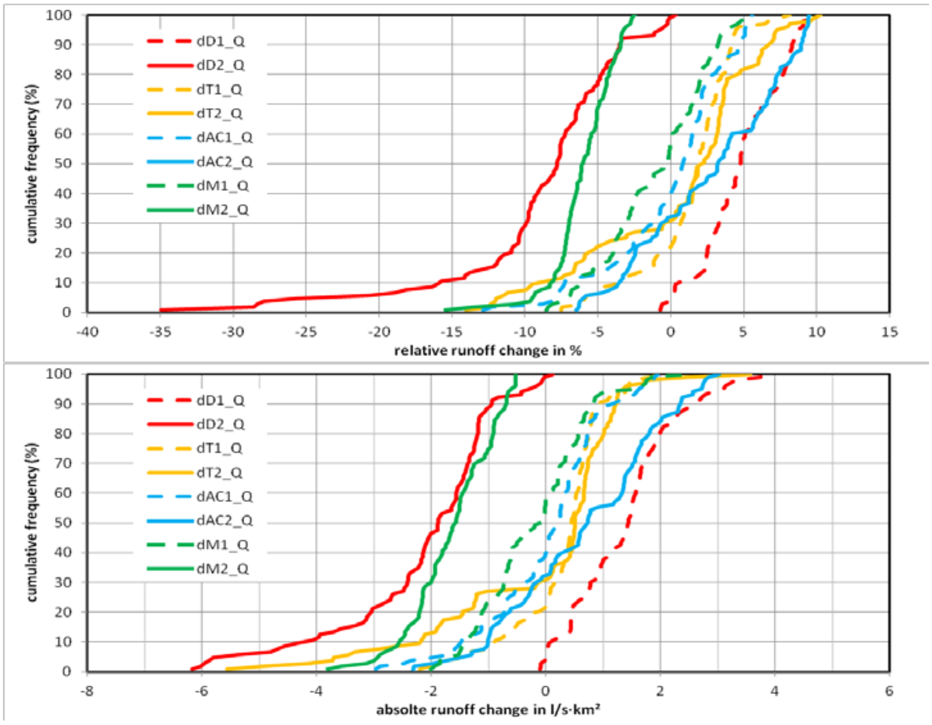

Figure 13: Cumulative frequency of relative (in %) and absolute (in l/s·km²) runoff change for all the analyzed catchments of the GAR.

Red lines represent the changes in runoff for the Desert scenario, orange ones for the Tropic scenario, blue ones for the Air Condition scenario and green ones for the Moderate scenario. Dashed lines relate to the difference in runoff for the time period 2011-2030 versus 1961-1990 and the solid lines to the period 2031-2050 versus 1961-1990.

Summarizing the four climate models, the absolute climate induced change in **electricity consumption** for a sample of 16 Continental European countries reveals some very interesting patterns. Overall, warmer annual temperatures reduce the total electricity consumption in Continental Europe, depending on the climate scenario the reduction varies from -10,000 GWh to -25,000 GWh per year (Figure 14). While this effect is not as clear for all countries as for Austria, the ratio between the absolute decrease in heating and the absolute increase in cooling electricity demand is still 2:1 to 6:1, depending on which climate scenario is considered.

Putting these climate-induced reductions in heating electricity demand and increase in cooling electricity demand in relation to current total electricity consumption reveals that effects of these long-term climate changes are comparatively small compared to other potential driver of electricity demand (Figure 15). The overall long-term reduction for Continental Europe is -0.4 % to -1.1 % of total electricity use. To provide a comparison, this amount roughly equals the growth in electricity consumption in the EU-15 which was observed on average every 3 to 6 months in recent decades. However, in some countries with major electric heating or cooling activities climate induced changes are of course more pronounced, like up to -3 % in heating-dominated France and up to +0.6 % in cooling-dominated Italy.

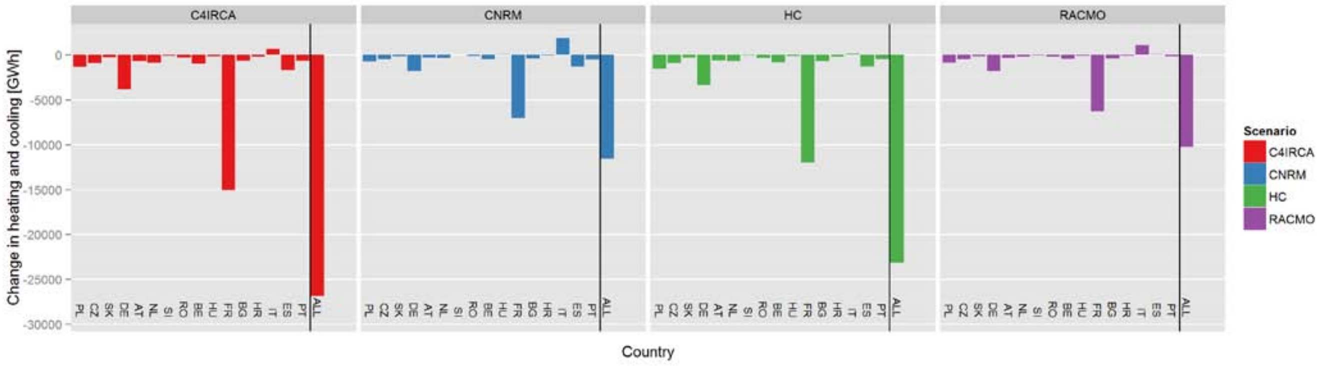

Figure 14: Average climate-induced change in annual heating and cooling electricity demand compared between the reference period 1961-90 and the scenario period 2011-50.

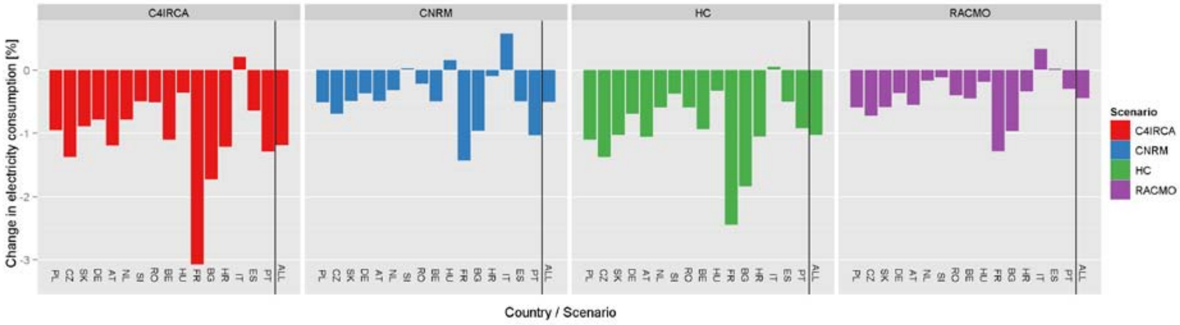

Figure 15: Share of the climate induced change in heating and cooling electricity demand on total electricity demand.

Regarding impacts of climate change on **electricity generation**, the changes in standard capacity due to climate change under the given assumptions are in the range of +3 % to -4 % (best case and worst case) of total standard capacity in Continental Europe, which is an average amount of approximately 45 TWh in the period 2031-2050.

For Austria, the standard capacity may vary between +2.2 % and -5.1 %, respectively +1.14 TWh and -2.58 TWh, in the same period. Main drivers are run-of-river hydro power plants (+/-1 TWh) as well as hydro storage power plants (+0.5 / -1.5 TWh) Refer to Table 4 for absolute numbers in TWh and Table 5 for relative changes in relation to the total standard capacity.

Related to the standard capacity of each technology, the relative numbers are different. As shown in Table 6, the strongest climate change impacts can be observed at hydro storage power plants. Photovoltaic generation in Austria is more affected by climate change than run-off-river hydro power and shows comparably high and negative impacts throughout all climate scenarios. However, due to the small amount of installed capacities, photovoltaic generation does not play a major role for Austria’s electricity system in terms of climate change.

Table 4: Standard capacity changes in Austria (absolute numbers)

AT (TWh)	Period	Hydro	Storage	Solar	Wind	Total
MODERATE	2011-30	- 0,41	- 0,56	- 0,03	0,11	- 0,89
	2031-50	- 0,99	- 1,09	- 0,07	- 0,07	- 2,22
TROPIC	2011-30	0,63	- 0,13	- 0,05	- 0,02	0,43
	2031-50	0,87	- 0,27	- 0,10	- 0,11	0,38
DESERT	2011-30	0,50	0,31	- 0,04	0,04	0,82
	2031-50	- 0,89	- 1,49	- 0,06	- 0,14	- 2,58
AIRCONDITION	2011-30	0,40	- 0,06	- 0,03	- 0,13	0,18
	2031-50	0,54	0,48	- 0,06	0,18	1,14

Table 5: Standard capacity changes in Austria in relation to total standard capacity

AT (%)	Period	Hydro	Storage	Solar	Wind	Total
MODERATE	2011-30	-0,9%	-1,2%	-0,1%	0,2%	-2,0%
	2031-50	-2,0%	-2,1%	-0,1%	-0,1%	-4,4%
TROPIC	2011-30	1,4%	-0,3%	-0,1%	0,0%	0,9%
	2031-50	1,7%	-0,5%	-0,2%	-0,2%	0,8%
DESERT	2011-30	1,1%	0,7%	-0,1%	0,1%	1,8%
	2031-50	-1,8%	-2,9%	-0,1%	-0,3%	-5,1%
AIRCONDITION	2011-30	0,9%	-0,1%	-0,1%	-0,3%	0,4%
	2031-50	1,1%	0,9%	-0,1%	0,3%	2,2%

Table 6: Standard capacity changes in Austria in relation to standard capacity per technology

AT (%/tech)	Period	Hydro	Storage	Solar	Wind	
MODERATE	2011-30	-1,4%	-5,1%	-5,7%	2,1%	
	2031-50	-3,4%	-8,5%	-5,9%	-0,9%	
TROPIC	2011-30	2,2%	-1,2%	-9,4%	-0,3%	
	2031-50	3,0%	-2,1%	-8,8%	-1,5%	
DESERT	2011-30	1,8%	2,9%	-7,0%	0,8%	
	2031-50	-3,1%	-11,7%	-4,8%	-1,8%	
AIRCONDITION	2011-30	1,4%	-0,5%	-6,6%	-2,5%	
	2031-50	1,8%	3,8%	-5,1%	2,3%	

Regarding the **indirect effects** of climate change impacts in the electricity sector on other sectors, average output values for electricity intensive sectors (EIS) and non-electricity intensive sectors (NEIS) are investigated relative to the BASE scenario across regions for the two periods 2011-30 and 2031-50. Comparing the relative magnitude of direct and indirect costs of climate change in absolute output values (see Figure 16 for period 2011-2030), we find that in TROPIC output value of the electricity sector (ELY) is falling compared to BASE (positive direct costs) in period 2011-2030, but this loss is compensated by an increase in output value in EIS and NEIS in every region (negative indirect costs) such that the total economic output increases range from +0.02 % for the aggregated model region Germany + Luxemburg (GERL) to +0.23 % for Eastern European Union countries (EEU, i.e. Czech Republic, Hungary, Poland, and Slovakia). In MODERATE, a net loss in output results as positive effects in ELY output value (gains) are compensated by much higher negative effects in EIS and NEIS (losses). The net effect thus ranges from -0.19 % for EEU to -0.04 % for GERL. In DESERT and AIRCONDITION, ELY experiences a loss in output value across all regions, whereas the direction of effects in EIS and NEIS varies, leading to net effects from -0.03 % to +0.02 %. Net effects for Austria range from -0.14 % in MODERATE to +0.03 % in TROPIC.

In period 2031-2050, the direction and magnitude of effects partly change. For instance in DESERT the output value of NEIS falls strongly, implying net output losses for all regions. In contrast, in AIRCONDITION we see output gains throughout all regions due to strong positive effects in NEIS. In

TROPIC and MODERATE, the results of the second period resemble the results of the first period in nearly all regions.

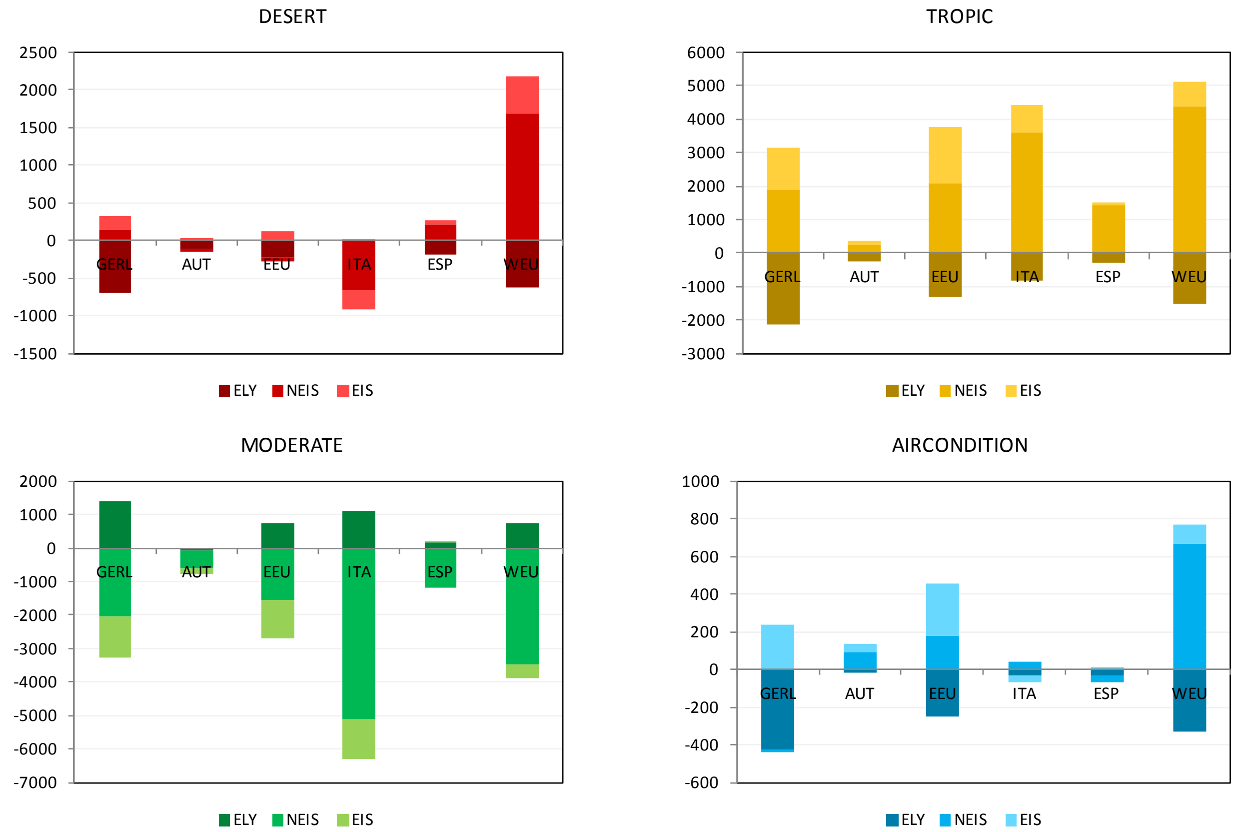

Figure 16: Output gain/loss [in Mio. EUR] of economic sectors relative to BASE for period 2011-2030. For country and scenario labels, see Figure 11.

Since the electricity sector is affected by both climate change impacts and climate policy, we finally study the impacts of climate change relative to a non-climate policy BASE scenario (BASE0) to decompose the effects on output into a climate policy effect and a climate change impact effect. Regarding the climate policy effect, reductions of average annual growth rates in EIS output value (relative to BASE0) range from -0.09 %-points for Spain and Portugal (ESP) to -0.38 %-points for GERL in the first period and in the second period from -0.24 %-points for ESP to -1.19 %-points for EEU, whereas decreases in NEIS are not higher than -0.16 %-points in the first period and between -0.18 % and -0.48 % in the latter. Yet, these “reductions” are relative to BASE0 such that output still rises, but at a lower rate. In contrast to the effects of climate policy, climate change impact effects on production value of both EIS and NEIS are substantially smaller compared to climate policy induced effects, ranging for EIS from -0.13 %-points to +0.07 %-points in the first period to -0.10 %-points to +0.08 %-points in the second. For NEIS, climate change impacts effects range from -0.03 %-points to +0.02 %-points in the first period to -0.04 %-points to +0.04 %-points in the second.

C) Project details / Projektdetails

5 Methodology / Methodik

The aim of this project was to develop an integrated modeling framework to describe and analyze the requirement for and economic consequences of adaptation in the electricity sector in Austria on a time scale up to 2050. Due to the cross-cutting nature of the problem, an integration (or coupling) of different models is essential. The first focus of the project lies thus on the adjustment and integration of the different models employed, as indicated in Figure 17. To depict the consequences of climate change for electricity, high-resolution climate change scenarios are used as input to the hydrological model to determine changes in hydrology relevant for hydropower generation and as input to the electricity sector models (temporal and spatial high resolution temperature, precipitation, river discharge, and wind data). The currently best available sectoral models for electricity are refined (in terms of temporal scale and adaptation detail): (i) techno-economic model of the electricity industry in continental Europe and (ii) econometric analysis to model the climate change impact on as well as adaptation options for the demand for electricity. The bottom-up electricity sector model is linked to a top-down, i.e. multi-country multi-sector, computable general equilibrium (CGE) model of Austria and other European countries to evaluate the sectoral and economy-wide climate change impacts and adaptation options for the electricity sector.

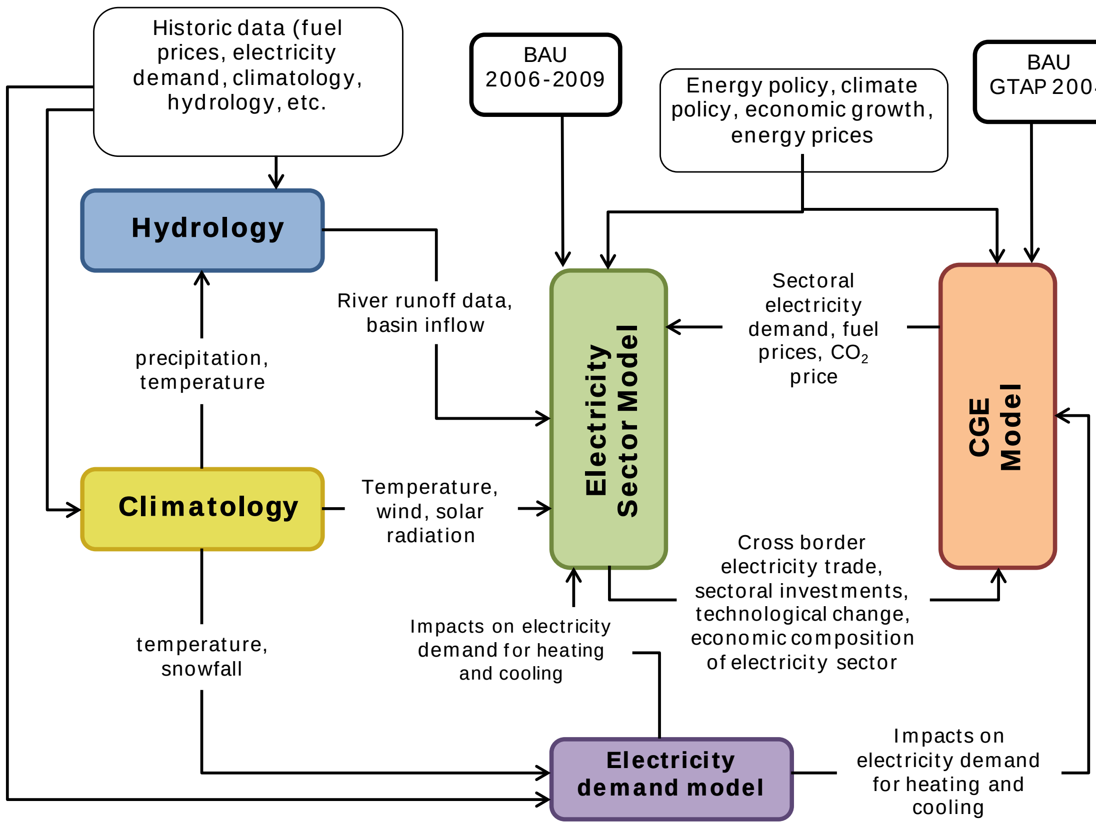

Figure 17: Model overview EL.ADAPT

In addition to the development of an integrated modelling framework, we analyze uncertainties involved in the overall modelling approach, from uncertainties in climate scenarios (uncertainties due to the climate model's simplifications and errors) to uncertainties in economic modelling (assumptions on climate policy). One outcome is the derivation of upper and lower bounds to results, the other is to elicit the importance of climate/hydrological variability and of economic/political assumptions.

Description of regional climate modelling approach

EL.ADAPT used the most recent regional climate simulations available and took advantage of recent methodological advancements in the field of regional climate modelling and bias correction. The basis for the EL.ADAPT scenarios have been provided by an ensemble of regional climate simulations generated in the project ENSEMBLES (Hewitt and Griggs, 2004; www.ensemble-eu.org, 23 simulations) which allows to estimate climate scenario uncertainty.. The IPCC SRES (Nakicenovic et al., 2000) global greenhouse gas emission scenario A1B is the basis for these regional climate scenarios which range from 1951 to 2050.

Although regional climate models are enhanced constantly, they are known to feature systematic errors (e.g. Suklitsch et al., 2008, 2011). Thus, the chosen climate scenarios have been statistically post-processed to provide spatially high resolved and high quality data. In the case of daily mean temperature and precipitation sum, a distribution based error-correction method (Quantile Mapping (QM), Themeßl et al., 2011, 2012) have been applied. Methodologically, QM adapts modelled time series to the observed empirical cumulative frequency distributions. By this means, errors in the mean, variability, as well as in extremes can be corrected on a daily basis. As the modelled data is mapped to finer resolved observed data, the error correction methods implicitly refines the model results spatially. Due to a lack of observational data, the parameters wind and global radiation couldn't be bias corrected on a daily basis, but a simple "delta" approach (e.g., Déqué, 2007) based on the available baseline climate in the ATLANTIS model has been applied for these parameters. This method strongly mitigates model errors by differencing a future and a control scenario, but does not account for changes in variability (e.g., extremes).

Ensemble based techniques have been applied to investigate plausible ranges of future climate evolution for all parameters and this information was used for the selection four representative climate simulations for the project.

Description of hydrological modelling approach

The aim of hydrological modeling is to provide runoff estimates at a monthly time step for various measurement stations along important rivers related to hydropower plants within the Greater Alpine Region. For this purpose an appropriate parsimonious, lumped parameter rainfall-runoff model was identified, based on the GR2M monthly water-balance model (Mouelhi et al., 2006), and extended by a temperature-based snow model (Xu et al.,1996) and potential evapotranspiration (PET) computed based on temperature and extraterrestrial solar radiation only (Oudin et al., 2005). Hence, temperature and precipitation are the only input data necessary (as extraterrestrial solar radiation is assumed to remain constant). Processes accounted for are snow accumulation and snow melt, evapotranspiration, soil storage, routing storage, and water exchange with neighboring catchments. The model was calibrated and validated using monthly E-OBS observation data (1950 to 2010) provided by WEGC-ReLoCLim (temperature and precipitation as forcing input) and monthly discharge time series provided by various organizations like the Global Runoff Data Centre (GRDC).

Four model parameters were adjusted to calibrate the model to the available discharge data. Model validation was based on different efficiency criteria (multi-objective approach; trade-off in single efficiency criteria to have an overall consistency; the “closeness” of simulated and observed stream flow; Krause et al., 2005), visual inspections of the hydrographs, and split sample tests and proxy basin tests (Klemes, 1986; Xu, 1999). Moreover, the model results were compared to other models (e.g. Kling et al., 2011; Stanzel and Nachtnebel, 2010; Klein et al., 2011; Kranzl et al., 2010; ZAMG/TU-Wien Studie, 2011). The calibrated and validated hydrological models for the individual stations along the various rivers are used with the four climate scenarios as input to predict a range of runoff estimates for the two periods 2011-2030 and 2031-2050. Using the predicted temperature and precipitation, the predicted runoff under the conditions proposed by the respective climate change scenario is provided. The comparison of the predicted future mean monthly runoff with runoff simulated for the reference period 1961-1990 yields the expected change in monthly runoff for each of the 4 climate change scenarios.

Description of electricity demand modelling approach

On the demand side of the energy system climate change affects the need for heating and cooling. The effects are either determined by bottom-approaches in that the sensitivities to temperature and global radiation changes are estimated by building simulations (e.g. Frank et al., 2005, Toeglhofer et al., 2009), or more frequently by top-down approaches, in that temperature impacts on energy demand (oil, gas, electricity) are estimated by econometric models (e.g. Sailor, 2001; Amato et al., 2005; Moral-Carcedo and Vicéns-Otero, 2005; Ruth and Lin, 2006; Mirasgedis et al., 2007; Bessec and Fouquau, 2008; Pilli-Sihvola et al., 2010). Following the latter approach and recent methodological developments (Moral-Carcedo and Vicéns-Otero, 2005; Bessec and Fouquau, 2008), in this project smooth transition regression models were used to estimate the non-linear relationship between temperature and (filtered) daily electricity load in continental European countries. Only this combined use of more sophisticated regression models and high frequency load data allowed us to avoid the pitfalls of approaches, which determine temperature impacts by regressing cumulative heating and cooling degree days (HDD and CDD) on monthly loads, namely their arbitrary choice of threshold values for HDD and CDD, and particularly their incapability to describe well-observed cooling effects for countries such as France and Germany. Furthermore, regional demographic data and scenarios were taken into consideration not only to weight the regional temperature data and scenarios for the estimation of the temperature-load interaction, but also to refine the demand module in the model ATLANTIS.

Description of electricity sector model ATLANTIS

ATLANTIS is a techno-economic model of the electricity industry in continental Europe (former UCTE) – a synchronous area with an installed capacity of about 650 GW and annual consumption of approximately 2,500 TWh (Gutschi et al., 2009a,b; Stigler, et al., 2012). The main part of the scenario model is a database of the most important facilities and companies in the investigated area. Based on this comprehensive database, the intention of ATLANTIS is to provide a simulation model which is close to reality in technical matters but which is also able to provide an explanation for the economic behaviour of electricity markets. The technical part of the model includes all necessary elements of the physical system (like transmission network and power plants as well as demand of consumers). The economic part of the model covers electricity trade, market coupling between states; major European power producers are described by simplified balance sheets and income statements.

Other models targeting similar tasks are being investigated by the North American Electric Reliability Commission (NERC) focusing the North American power system (NERC, 2010). All these models take the advantage of detailed, public available power system data for North America. For Europe, the power system data necessary for power system modeling on a comparable level of details are not available. ATLANTIS contains all this necessary data in an integrated database containing generation units, transmission lines (lines, cables, and transformers), river gauging stations, regional hourly electricity demand, etc. The database only contains non-restricted data and is updated and extended continuously. At the moment, the integration of the Scandinavian market area as well as the United Kingdom and Ireland is in progress.

Description of multi-country multi-sector CGE modelling approach

While the detailed, bottom-up model for the electricity sector is able to delineate impacts and available adaptation options, it lacks the feedback effects of other sectors and macroeconomic structures. To take account of these general equilibrium effects, we develop a multi-country multi-sector computable general equilibrium (CGE) model for Europe. This class of disaggregated CGE models (as e.g. the EPPA model by Paltsev et al., 2005) is in contrast to the spatial large scale aggregate Ramsey growth models used for the analysis of climate change mitigation (e.g. DICE and RICE models, see Nordhaus and Boyer, 2000). Methodologically, the model is based on Bednar-Friedl et al. (2012) and contributes to the literature on multi-sector, multi-regional CGE models analyzing climate and energy policy (e.g. Babiker and Rutherford 2005; Paltsev 2001; Böhringer 2000).

The CGE model distinguishes for 18 countries/world regions (Austria plus nine additional European regions, 8 additional world regions) and 17 sectors according to their relevance for electricity generation and demand (Table 7). The model is calibrated to the GTAP database version 7 (Base year: 2004), data consistency with ATLANTIS is ensured by replacing base year data for electricity sectors in Europe based on ATLANTIS as well as for electricity trade flows based on EURSTAT (2004), and by applying a balancing routine afterwards. A shared baseline (without climate change impacts but with current climate policies such as the European 20-20-20 targets) is developed jointly with ATLANTIS up to 2030 and 2050.

Table 7: Economic sectors and respective model code.

	Aggregated Sectors	Model Code
1	Electricity	ELY
	Electricity intensive sectors	**EIS**
2	Manufacture of paper products and publishing	PPP
3	chemical industry	CRP
4	manufacture of other non-metallic mineral products	NMM
5	Other mining	OMN
6	manufacture of basic iron and steel and casting	I_S
7	precious and non-ferrous metals	NFM

	Aggregated Sectors	Model Code
	Non-Electricity intensive sectors	**NEIS**
8	Coal	COA
9	Crude Oil	OIL
10	Refined oil products	P_C
11	Natural Gas	GAS
12	Transport	TRN
13	Agriculture	AGRI
14	Forestry and Fishery	FOF
15	Construction, real estate	CRE
16	Machinery, fabricated metal products	MPE
17	Other services and utilities	SERV
18	Capital Goods	CGDS
19	Other non-electricity intensive industries (textiles, food, tourism etc.)	NEII

Description of model coupling approach

In order to ensure consistency between both models, we iteratively link ATLANTIS and the CGE model in 5-year intervals. For each time step we carry out two iterations where ATLANTIS provides detailed information on the cost and structure of power generation in the various European regions, while the CGE model provides macro indicators for ATLANTIS, namely economy wide electricity demand, fossil fuel prices and the CO_2 price (for more details, see Bachner et al. 2013, pp. 38-41). As above mentioned, in the CGE model the production technology of ELY is exogenously given by ATLANTIS. Acknowledging the fact that electricity production is changing over time, input values change accordingly for each 5-year time-step; again derived from ATLANTIS. Thus it is possible to include the exogenously given technology shift, depending on the regarded point in time and climate policy scenario. The CGE model also accounts for investments in the ELY sector in order to ensure capacity and production volume of certain technologies, mainly due to expansion of renewable energy sources. Since electricity demand is a crucial parameter when it comes to climate policy and climate change impacts, the linkage with the CGE model enables an endogenous response in ATLANTIS.

For the coupling of the CGE model with ATLANTIS, joint assumption and interfaces between the two models were agreed (exchange of results on production costs, investments, annual electricity demand by other sectors and households, prices of energy carriers and CO_2) and implemented on a server platform. With this platform, results data was exchanged for time steps of 5 years up to 2030 and 2050, with two iterations in each time step.

Regarding climate change impacts, the effects of changing precipitation, wind, solar radiation and temperature derived from the given climate change signals (i.e. from climate and hydrological models) are converted into input parameters for ATLANTIS (see Figure 17). For instance, changes in precipitation within certain catchment areas affect water supply to hydro power and natural inflow of hydro storage plants fed by those areas. Likewise, changes in solar radiation affect solar power supply, and changes in mean wind speeds affect wind power supply. All these changes (wind, precipitation, global radiation) are then converted into changes of average energy yield per year and of the monthly share of production (comparable to the so-called Pardé coefficient, which is used in hydrology), which are calculated for every single unit in the respective observed area. Due to this, effects of climate change on more than 14.000 generation units in Continental Europe are simulated. Moreover, changed changed electricity consumption is fed from the electricity sector as annual changes into the CGE model while changed seasonal patterns are taken account of in ATLANTIS.

Description of reliability and uncertainty analysis approach

To estimate and quantify the uncertainties of the results over the modelling chain, each partner analysed the major uncertainties in each subsector/submodel (climate, hydrology, electricity sector, macroeconomy).

The uncertainty in the meteorological forcing data was analyzed based on the multi-model dataset from the ENSEMBLES project. The uncertainty analysis took care of ensuring that the four simulations selected for EL.ADAPT are representative for the uncertainty range spanned by the entire ENSEMBLES dataset and therefore provide pairs of wet or dry and hot or cool simulations.

The uncertainty of the hydrological model was analyzed by applying the principle of equifinality, where various different “equally like” parameter sets were used to compute runoff estimates. The difference in runoff due to the different parameter sets is compared to the difference in runoff due to the different climate change scenarios. Also a sensitivity analysis of the four free (to be calibrated) parameters has been conducted.

Regarding the economic and technological uncertainties, uncertainties were assessed by both running ATLANTIS and the CGE model separately or jointly. In the stand-alone simulations with ATLANTIS, the influence of the share of RES generation on the change of standard capacity was investigated. In a similar vein, two simulations are contrasted in the CGE model in its standalone version: one with and one without climate policy to see how strong the effect of climate change impacts is relative to the effects of climate policy. Moreover, the sensitivity of model results with respect to alternative parameter specifications (foreign trade elasticities; elasticities of substitution for electricity) was assessed. To give an idea on the uncertainty of the results of the coupled simulations, we finally compared results between simulations using ATLANTIS coupled with the CGE model and uncoupled (stand-alone simulations).

6 Work and Time Schedule / Arbeits- und Zeitplan

WP1: Climate change impacts on hydrological conditions for hydropower generation

M1.1 Tailored climate scenarios as input for hydrological and electricity demand models (July 11)

M1.2 Hydrological model calibrated and verified (Nov 11)

M1.3 Monthly river discharge from predictive model runs (Apr 12)

M1.4 Qualitative assessment of inter-monthly flow variability (Apr 12)

WP2: Climate change impacts on electricity demand in continental Europe

M2.1: Dataset on filtered load data (Aug 11)

M2.2: Report and dataset on regional population trends (May 11)

M2.3: Display and integrate country-specific smooth transition regression models (Dec 11)

M2.4: Report on climate impacts on electricity demand (Feb 11)

WP 3: Simulation of the Electricity Sector in continental Europe

M3.1: Tailored climate scenarios as input for electricity sector modelling (Aug 11)

M3.2: Delivery of historic values and statistics (power demand, climate dataset, …) for other WP1-2 (Mar 11)

M3.3: Report on scenario definitions for WP3 (Jan 12)

M3.4: Assessment report of climate change impacts on power generation (Jul/Aug 12)

M3.5: Report of impacts of climate change on electricity markets and development of generation and supply infrastructure (Jan 13)

WP4: Macroeconomic effects of impacts and adaptation in the electricity sector in continental Europe

M4.1 Static CGE model of climate impacts (baseline calibration) (Jan 12)

M4.2 Recursive dynamic CGE model of climate change impacts (May 12)

M4.3 Macroeconomic effects for continental Europe of CC impacts and adaptation options in the electricity sector (Feb 13)

WP5: Reliability and uncertainty analysis

M5.1 Description of climate and **hydrology uncertainties (Jul 12)**

M5.2 Description of economic and technological uncertainties (Jan 13)

M5.3 Simulation matrix for the integrated model system (Aug 12)

M5.4 Quantification of the general uncertainty in the modelled system (Feb 13)

WP6: Project Management and Model Coupling

M6.1 Kick-off workshop (Mar 11)

M6.2 Definition of interfaces and communication protocols between models (Aug 11)

M6.3 Platform for coupled model available (Mar 12)

M6.4 Interim report to funding institutions (Feb 12)

M6.5 Expert workshop to discuss preliminary results (May 12, Mar13)

M6.6 Publication of suitable preliminary results (Jan 13)

M6.7 Final report (including scientific papers) (Mar 13)

7 Publications and dissemination / Publikationen und Disseminierungsaktivitäten

Note: For updates on publication activities, please visit the project webpage.

1. List of publications

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, ISBN 978-3-9503112-8-0.

Bachner, G., Kulmer, V., Bednar-Friedl, B., Schüppel, A., Stigler, H., Themessl, M., Feichtinger, G., 2013, Climate Change Impacts On The Electricity Sector In Continental Europe: A Linked Modeling Approach, manuscript, to be submitted to *Mitigation and Adaptation Policies*.

Heinrich, G., Gobiet, A., Mendlik, D., 2012, Extended regional climate model projections for Europe until the mid-21st century: combining ENSEMBLES and CMIP3, manuscript, under review at *Climate Dynamics.*

Pattis, F., Modellierung der Stromerzeugung aus Photovoltaik in Deutschland, Diplomarbeit am Institut für Elektrizitätswirtschaft und Energieinnovation, Technische Universität Graz, November 2012.

Töglhofer C., Habsburg-Lothringen C., Prettenthaler F., Rogler N., 2013, Climate Change Impacts on Electricity Demand in Continental Europe, manuscript, to be submitted to *Weather Climate and Society*.

Töglhofer, C., Habsburg-Lothringen, C., Prettenthaler, F., Rogler, N., Themessl, M., 2012. EL.ADAPT: Impacts of Climate Change on Electricity Demand, Tagungsband 12. Symposium Energieinnovation, ISBN 978-3-85125-200-2, Verlag der Technischen Universität Graz.

Spindler, K., Anpassungsmaßnahmen der Elektrizitätswirtschaft an den Klimawandel, Masterarbeit am Institut für Elektrizitätswirtschaft und Energieinnovation, Technische Universität Graz, March 2013.

Wagner, T., Themeßl, M., Schüppel, A., Gobiet, A., Stigler, H., Birk, S., 2012. Auswirkungen des Klimawandels auf Abfluss und Wasserkrafterzeugung österreichischer Flüsse. Wasserbausymposium 2012: Wasser – Energie, Global denken – lokal handeln, Tagungsband, ISBN 978-3-85125-230-9, Verlag der Technischen Universität Graz.

Wagner, T., Themeßl, M., Schüppel, A., Gobiet, A., Stigler, H., Birk, S., 2013. Impacts of climate change on river discharge and hydropower generation for the Alpine region. *Geophysical Research Abstracts* Vol. 15, EGU2013-10965, 2013.

Wagner, T., Themeßl, M., Schüppel, A., Gobiet, A., Stigler, H., Birk, S., 2013. Impacts of climate change on river discharge and hydropower generation for the Alpine region, manuscript, to be submitted to *Journal of Hydrology*.

2. List of conference presentations

Bednar-Friedl, B., Bachner, G., Kulmer, V., Schüppel, A., Stigler, H., Themessl, M., Feichtinger, G., 2013, Climate Change Impacts On The Electricity Sector In Continental Europe: A Linked Modeling Approach, 2013 Economic Modeling (ECOMOD) conference, July 1-3, 2013, Prague.

Bednar-Friedl, B., Bachner, G., Kulmer, V., Schüppel, A., Stigler, H., Themessl, M., Feichtinger, G., 2013, Climate Change Impacts On The Electricity Sector In Continental Europe: A Linked

Modeling Approach, Annual conference of the European Association of Environmental and Resource Economists, June 26-29, 2013, Toulouse.

Bednar-Friedl, B., Bachner, G., Kulmer, V., Schüppel, A., Stigler, H., Themessl, M., Feichtinger, G., 2013, Climate Change Impacts On The Electricity Sector In Continental Europe: A Linked Modeling Approach, 2013 International Energy Workshop, June 19-21, 2013, OECD, Paris.

Bednar-Friedl, B.,Schüppel, A., Bachner, G.,, Birk, S., Feichtinger, G., Gobiet, A., Gutschi, C., Kulmer, V., Prettenthaler, F., Rogler, N., Schinko, T., Stigler, H., Themeßl, M., Töglhofer, C., Wagner, T., 2012. Klimawandelfolgen und -anpassung in der Elektrizitätswirtschaft: Österreich im kontinentaleuropäischen Kontext. Österreichischer Klimatag, June 14-15, 2012, Vienna.

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3. List of dissemination activities

During the project, two workshops were held to discuss results with experts:

EL.ADAPT Stakeholder Workshop:
Klimawandelfolgen und –anpassung in der Elektrizitätswirtschaft: Österreich im kontinentaleuropäischen Kontext
6. Juni 2012, Österreichs Energie Akademie, Wien

EL.ADAPT Experten-Workshop:
Volkswirtschaftliche Auswirkungen des Klimawandels in Österreich: Die Sektoren Landwirtschaft, Tourismus und Elektrizitätswirtschaft im Vergleich
22. März 2013, Wegener Center für Klima und Globalen Wandel, Graz

Moreover, the project was presented at the bi-annual meeting of University of Graz' Research Focus "Environment and Global Change" (date: March 3, 2011).

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