EFFECTS OF CLIMATE CHANGE ON REGIONAL ENERGY SYSTEMS FOCUSSING ON SPACE HEATING AND COOLING
A case study of Austria

by

Stephan HAUSL[a,b*]***, Matthias THEMESSL***[c]***, Sabine GADOCHA***[a]***, Ingrid SCHARDINGER***[a]***, Markus BIBERACHER***[a]***, Bernhard CASTELLAZZI***[a]***, and Andreas GOBIET***[c]

[a] Research Studios Austria – Studio iSPACE, Salzburg, Austria
[b] University of Technology, Munich, Germany
[c] Wegener Center for Climate and Global Change, University of Graz, Graz, Austria

Original scientific paper
DOI: 10.2298/TSCI1403771H

Climate change affects regions differently and therefore also climate change effects on energy systems need to be analysed region specific. The objective of the study presented is to show and analyse these effects on regional energy systems following a high spatial resolution approach. Three regional climate scenarios are downscaled to a 1 km resolution and error corrected for three different testing regions in Austria. These climate data are used to analyse effects of climate change on heating and cooling demand until the year 2050. Potentials of renewable energies such as solar thermal, photovoltaic, ambient heat and biomass are also examined. In the last process step the outcomes of the previous calculations are fed into two energy system models, where energy system optimisations are executed, which provide information concerning optimal setups and operations of future energy systems. Due to changing climate strong changes for the energy demand structure are noticed; lower heat demand in winter (between –7 and –15% until 2050) and – strongly differing between regions - higher cooling demand in summer (up to +355%). Optimisation results show that the composition of energy supply carriers is barely affected by climate change, since other developments such as refurbishment actions, price developments and regional biomass availabilities are more influencing within this context.

Key words: *climate change, energy system modelling, regional energy systems, regional climate models, energy system optimisation, space heating demand, cooling demand, renewable energies, GIS, RESRO*

Introduction

Climate change and its potential impacts today are some of the main challenges worldwide. It is expected that the limitation of global mean temperature increase to 2 °C until the year 2050 can only be achieved by great contributions on the global scale. But even with widespread and quick climate protection measures, climate change and its effects will still be noticed in the next years and decades due to the lifetime of emissions and the nature of the climate system [1]. Thus, there is a necessity to analyse likely climate change effects, in order to develop appropriate mitigation and adaption strategies. Publications dealing with this issue

* Corresponding author, email: stephan.hausl@researchstudio.at

are among others for Europe [2-4], where the effects and impacts of climate change on many sectors – also on the energy sector – are discussed. To summarise these publications draw rather positive effects for Northern Europe in terms of climate change effects on agriculture, forestry and energy due to better growing conditions for crops and trees and a reduced heating demand. Effects on Southern Europe and Mediterranean countries, on the contrary, are seen strongly negative due to higher summer temperatures and more frequent heat periods and droughts, which lead to significant problems in agriculture and forestry as well as severely rising cooling demand in summer. The effects on Central European countries are not that precise, as they differ between countries and even within countries. For the specific case of the Austrian energy sector the authors of [5] derive adaption measures to climate change. Results from [6, 7] indicate that space heating and cooling demand are very sensitive to the location within the Alpine region. That is why effects of climate change, differently characterised in different regions, may predominantly lead to changes in the energy demand structure but also influence optimised setups of future regional energy systems. Non-climate-driven developments like energy prices, technologies, policies, and availabilities of energy carriers are also affecting the future setup and operation of the energy system and therefore are considered in this study.

Methodology and data

Case study regions

The model framework was applied in three testing regions in Austria: Tamsweg (Salzburg), Wels-Land (Upper Austria) and Feldbach (Styria). The decision on these regions was mainly driven by the different climatic conditions (Tamsweg: Alpine, Wels-Land: Mid-European, Feldbach: Illyrian) of the regions due to their geographic location as well as their diverse land cover structures. While most parts of alpine Tamsweg are covered by coniferous forest, Wels-Land is mainly characterised by arable land. Feldbach has nearly equal shares of broad-leaved forest, complex cultivation patterns and arable land. The population, which has a major effect on the total energy demand, is low in Tamsweg (pop. 21,300), compared to Wels-Land (pop. 63,000) and Feldbach (pop. 67,200). The majority of the population is located in small municipalities, while the biggest towns in the regions are Tamsweg (pop. 6,000), Marchtrenk (pop. 12,500, region Wels-Land) and Feldbach (pop. 4,700). The location within Austria and the settlement structure of the case study regions are shown in fig. 1.

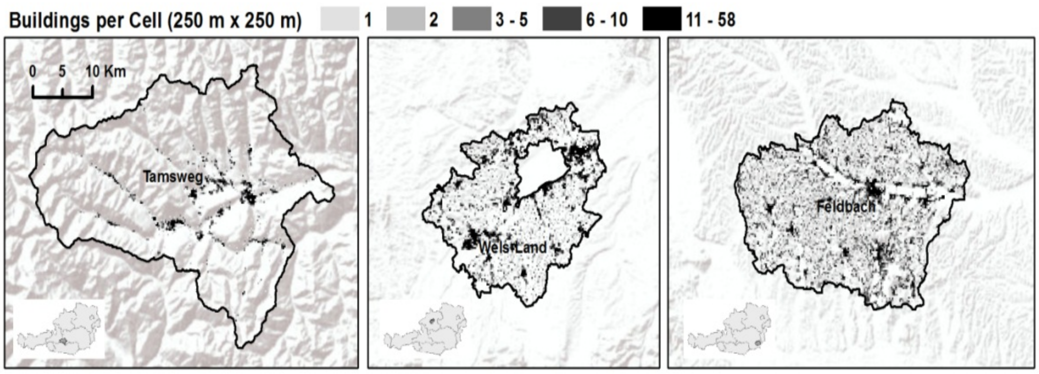

Figure 1. Selected case study regions: settlement structure and location within Austria

Climate data

Rising temperatures are the major direct effect of climate change, with a decisive influence on our energy system. Milder winters lead to less heating demand, while hotter summers and more frequent and stronger heat periods [8] cause higher need for cooling.

Within the prospected project, 24 available Regional Climate Models (RCM) from the projects ENSEMBLES [1] and reclip:century [9] were downscaled and error corrected from a 25 km to a 1 km resolution, based on daily observational record [10] to mitigate systematic RCM error characteristics [11, 12]. Solar radiation data were not error corrected due to the lack of suitable observational data. In order to provide the same spatial resolution as for temperature and precipitation, global radiation data, which were also used in this study, were interpolated from its 25 km RCM resolution to the 1 km grid, without accounting for orographic information. Three climate scenarios based on emission scenario A1B [13], which cover about 50% of the uncertainty space of the examined RCM, were selected for further analyses. The selection was based on seasonal climate change signals for temperature and precipitation between the 30-year periods 1971-2000 and 2021-2050. The three selected climate models were:

– DMI-HIRHAM5-ARPEGE,
– ETHZ-CLM, and
– SMHI-RCA-HadCM3Q3.

As for our upcoming modelling, the most recent 30-year period 1981-2010 was chosen as reference period and the upcoming decades until 2050 as testing periods.

Heat demand

Space heating demand was calculated under Austrian reference climate using typical specific space heating demand values (tab. 1, [14]) differentiated by building type and construction period and gross floor areas differentiated by building types and regions. Additional "service factors" (tab. 1, [7]), differentiated by building type and construction period, were considered by multiplication. These service factors lead to more realistic space heating demand results by considering aspects such as night setback, restricted heated floor area and user behaviour.

Table 1. Specific space heating demand [kWhm^{-2}a^{-1}] and service factors of space heating

<table>
<tr><th colspan="4">Specific space heating demand [kWhm^{-2}a^{-1}]</th><th colspan="4">Service factors of space heating</th></tr>
<tr><th>Construction period</th><th>Single-Family</th><th>Multi-Family</th><th>Non-Residential</th><th>Construction period</th><th>Single-Family</th><th>Multi-Family</th><th>Non-Residential</th></tr>
<tr><td>Until 1945</td><td>242</td><td>182</td><td>114</td><td>Until 1945</td><td rowspan="2">0.56</td><td rowspan="2">0.64</td><td rowspan="6">0.9</td></tr>
<tr><td>1945-1980</td><td>190</td><td>145</td><td>114</td><td>1945-1980</td></tr>
<tr><td>1981-1990</td><td>122</td><td>95</td><td>70</td><td>1981-1990</td><td rowspan="2">0.62</td><td rowspan="2">0.69</td></tr>
<tr><td>1991-2001</td><td>87</td><td>68</td><td>70</td><td>1991-2001</td></tr>
<tr><td>Later than 2001</td><td>63</td><td>48</td><td>36</td><td>Later than 2001</td><td rowspan="2">0.67</td><td rowspan="2">0.75</td></tr>
<tr><td>Low energy houses</td><td>42</td><td>36</td><td>–</td><td>Low energy houses</td></tr>
</table>

The calculated annual demand values were split up on the 12 months by typical load profiles differentiated by construction period. Furthermore, for the different time periods of interest (decade-wise) an actual, typical rate of refurbishment of 1% per year was assumed

[15]. In terms of modelling, refurbished buildings were chosen on the building raster depending on their construction period and they were given lower space heating demand values of the next younger construction period. This results in specific space heating demand reductions between 20% and 49% for refurbished buildings as derived from tab. 1. The spatial location of these refurbished buildings was selected randomly on the building raster, since this depicts reality best.

In the next step, specific climate information from the climate models was taken into account. The methodology for the climate-induced changes of space heating demand is based on [16], where the effects of changing temperature and global irradiation on space heating demand are analysed and quantified with an empirical approach based on real, historic feed-in data from gas and district heating grids in the city of Bern, Switzerland. This is done on a monthly basis and results in sensitivity coefficients* of temperature and irradiation, presented in tab. 2. Since climate in Austria is quite similar to climate in Switzerland, a transferability of the sensitivity coefficients from the city of Bern on the Austrian testing regions was assumed.

Table 2. Monthly sensitivity coefficients of space heating demand relating to temperature (per [°C]) and irradiation [$MJm^{-2}d^{-1}$] per changes. Source: [16]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature	–5.47	–6.23	–8.7	–13.46	–24.36	–30.77	–51.13	–38.97	–26.09	–14.23	–8.22	–6.01
Irradiation	–0.37	–0.57	–0.6	–0.25	–0.41	–0.6	–0.33	–0.25	–1.59	–1.62	–1.39	–0.21

The sensitivity coefficients are combined with climate data in the following calculations in eq. (1) and (2) of the space heating demand *SH*:

$$SH = k_{climate} SH_{Ref} \tag{1}$$

with

$$k_{climate} = \left(100 + (T_{climate} - T_{Ref}\right)k_T + \left(GI_{climate} - GI_{Ref}\right)k_{GI})/100 \tag{2}$$

The calculations result in a scenario, where both refurbishments and climate change are considered at the same time. Another scenario was added, taking into account the development of the number of households according to the official OROK assumptions [17]. According to these assumptions, household numbers rise (between year 2001 and the last model decade 2041-2050) in all of the testing regions (Tamsweg: +12%, Wels-Land: +41%, Feldbach: +18%). Household sizes remain constant under the assumptions applied in this study. Heat demand for the new households was calculated analogously to the heat demand calculations, but using specific space heating demands of low energy houses as illustrated in tab. 1. Total heat demand for the different scenarios was generated by adding climate-independent values for domestic hot water heating (12.75 kWh/m^2a for residential buildings, 4.75 kWh/m^2a for non-residential buildings, according to the Austrian Energy Certificate – "Energieausweis") to the space heating demand. Eventually, four heat demand scenarios were calculated, distinguished by refurbishment actions (yes/no), climate change (yes/no) and future household development (constant/OROK assumptions): "only refurbishment", "only

* Coefficients from May to August are irrelevant, because of (usually) non-existing space heating demand in these months.

climate", "climate and refurbishment" and "climate, refurbishment and household development".

Cooling demand

For the calculation of cooling demand, following parameters were considered:

– specific cooling demand (depending on cooling degree days),
– share of cooled areas in buildings, and
– efficiency of air-conditioning systems.

Cooling degree days (CDD) were calculated using daily temperature data from the climate models and a cooling threshold of 18.3 °C, as proposed in [6, 7, 18]. After inspecting the CDD results, own assumptions on the penetration of building areas with air-conditioning systems, based on [18-20] and shown in tab. 3, were created.

Table 3. Share of cooled areas in non-residential and residential buildings. Own assumptions based on [18-20]

Share of cooled areas in non-residential buildings						
		before 2010	2011-2020	2021-2030	2031-2040	2041-2050
Wels-Land	partially cooled	22%	25%	27%	30%	33%
	fully cooled	19%	21%	23%	25%	27%
Tamsweg	partially cooled	33%	37%	43%	48%	55%
	fully cooled	–	–	–	–	–
Feldbach	partially cooled	22%	25%	31%	38%	45%
	fully cooled	19%	20%	30%	40%	50%
Share of cooled areas in residential buildings						
Wels-Land		0%	4%	8%	13%	18%
Tamsweg		0%	0%	0%	0%	0%
Feldbach		0%	4%	8%	19%	33%

Conventional air-conditioning systems are in use, which are exclusively powered by electricity and therefore increase the electric power demand. This assumption seems as the most likely solution for the near future. The methodology is basically the same for residential and non-residential buildings, only the used parameters differ. For non-residential buildings a distinction between fully cooled and partially cooled areas is made.

For non-residential buildings, functions from [18] are used, which show the correlation between CDD and the specific electricity demand for cooling. These functions are based on an analysis of 100 office buildings in Switzerland and international office building simulations by [21, 22].

For residential buildings, assumptions of [20] are used and a coefficient of performance (COP) of 4, which results in a specific electricity demand for cooling of around 4 kWh/m^{2}a at CDD of 122 Kd (Kelvin days) in the year 2010. Climate-specific cooling demand in a region was then calculated with the relation of the region's CDD and the value 122 Kd. For future time periods slight specific energy reductions of 0.5% per year are assumed because of technologic progress [18].

Renewable energy potentials

Renewable Energy Sources (RES) are a key factor of a sustainable energy supply. Only RES were considered, which appear in the regional context according to [23]. There, emphasis on local heat supply and according RES in a regional energy system analysis is justified due to poor heat transmission characteristics. Wind and hydro power are excluded from the analysis, since these energies are rather seen within the superregional context, whereas photovoltaic (PV), which competes with solar thermal for available roof areas, is considered. Solar and ambient heat technologies were analysed spatially explicit based on the building raster and utilised spatially within the RESRO model (see section "Energy system optimisations"). For solar technologies available roof areas were calculated by multiplying building areas and typical mobilisation factors of 35% for pitched roofs (single-family) [14] and 50% for flat-roofs (multi-family and non-residential buildings) [24]. Monthly horizontal irradiation data from the climate models were transformed on a slope of 35% for PV and 60% for solar thermal by monthly transposition factors. Annual system efficiencies of 9% for PV and 30% for solar thermal were used [25]. Reasonable ambient heat supply (heat pump) is dependent on buildings with low temperature heating systems and high insulation standards and therefore only foreseen in the calculations for the heat demand of buildings with construction period 1991 or later. A coefficient of performance (COP) of 4 is used for ambient heat systems. Biomass potential modelling is based on the approach of [26]. Regional data of yield potentials on agricultural areas are derived from a national study [27]. In order to estimate regional manure available for biogas production, statistical data on regional livestock are used. The forestry biomass model published in [26] was enhanced and now distinguishes deciduous and coniferous forest. Regional growth rates of deciduous and coniferous forest from the Austrian forest inventory serve as input data (http://bfw.ac.at/rz/wi.home). Biomass potentials are assumed to be constant due to uncertainties concerning climate change effects (see also chapter *Results*, subchapter *Renewable energy potentials*).

Energy system optimisations

The energy system models ORES and RESRO

The outcomes of the energy demand and renewable energy potential calculations were fed into the optimisation models ORES [26] and RESRO [28], both used in regional energy system analyses such as [29] presented in [30], in order to calculate optimised setups of future regional energy systems. ORES is based on the model generator TIMES [31] and RESRO is developed directly in the modelling software GAMS (General Algebraic Modeling System). Both are linear programming models, which minimise the costs of the expansion and operation of the energy system with respect to certain constraints such as mandatory energy demand (heat, electricity) satisfaction or resource boundaries. The costs function includes costs for investment, operation and maintenance and fuel as well as costs and revenues from the electricity sector. While ORES is spatially aggregated but time-dynamic, RESRO focuses on the spatially disaggregated optimisation for one time period (snap-shot model). Thus, ORES optimises the entire time horizon until 2050 in 5-year-steps assuming a perfect foresight. RESRO calculates the heat supply for each 250 m raster cell including possible district heating network expansion and operation for one representative year (middle year of a decade) of the desired time period (here: one decade).

In contrast to RESRO, ORES considers competitive use of resources like energetic and material usage of wood. Consequently, regional wood potentials are divided into four different quality categories with corresponding typical prices. The two optimisation models are linked by transferring maximum, energetically used biomass from ORES to RESRO, which uses these values as useable biomass potential boundaries. Thus, the analysis profits from the strengths of both models, using the comprehensive, time-dynamic ORES approach and the spatially detailed approach in RESRO.

Regional wooden biomass can be used in small-scale wood log boilers, small-scale wood chip boilers and in centralised heating or Combined Heat and Power (CHP) plants feeding into the district heating (DH) network. DH transport losses in ORES are exogenously set to 12%. RESRO assumes DH transport losses of 2.6% per 100 m when transferring heat from cell to cell. Centralised plants (heating or CHP) are strictly biomass-based (wood chips, biogas). They must have a minimum capacity, if they are built, what makes the linear programming models contain mixed-integer variables. Wood pellets – useable in small-scale boilers – are seen as a supra-regional energy carrier, which can be imported to the testing regions. Other – non-biomass based – heating technologies incorporate renewable ambient heat (heat pump usage increases the electric power demand) and solar thermal systems as well as conventional oil and natural gas boilers.

Power generation technologies considered are PV on roofs and CHP. If electricity load is not covered by PV or CHP in certain time steps, grid power is imported. It is of course also possible to feed-in power to the grid, if there is an overproduction within the region. Since the electricity part of the optimisations works on a high temporal resolution (2-hours), typical load profiles for household power demand and typical cooling profiles from office and service sector buildings [32] for cooling power demand are used. Since a major part of cooling demand is caused by non-residential buildings, cooling loads concentrate on working hours of workdays.

Scenarios and assumptions

Strictly climate-induced changes of the optimised energy setup are assessed by comparing Scenario 1 (Scen. 1) assuming refurbishment actions at constant climate to Scenario 2 (Scen. 2) assuming refurbishment actions together with climate change (climate model SMHI-RCA-HadCM3Q3). Heat demand and electric power demand for households and cooling are considered, depending on the outcomes of the calculations in the demand sections (*Heat demand* and *Cooling demand*). Household power demand is calculated exogenously with slight future energy efficiency measures assumed. Heat demand in Scen. 1 equals heat demand scenario "only refurbishment", whereas heat demand in Scen. 2 is taken from heat demand scenario "climate and refurbishment". Cooling demand remains constant in Scen. 1, while in Scen. 2, cooling demand results under the assumption of climate change, as shown in the section *Cooling demand*, are used.

Existing heating infrastructure and supply, which can be derived from official data* from 2001, is only relevant – due to aged data (year 2001) and the lifetime of the facilities – and therefore considered in the optimisations until 2020.

Recent household energy prices for Austria are chosen for the first model period 2011-2020. Energy price developments are assumed according to [33] and can be seen in [34, (p.147)]. All energy carriers, except for oil (+54% until 2041-2050), are linked to the gas price development (+44% until 2041-2050). All financial assumptions, also concerning

* Statistik Austria: „Energy carriers of heating“, spatial resolution 250 m × 250 m, 2001

technologies, were collected within the underlying study [34]. Technology data for the year 2010 are illustrated in tab. 4. The development of technology parameters (costs, efficiencies) is illustrated in tab. 5. Parameters for the mid of a decade, as used in the decade-wise RESRO optimisations, were interpolated. Prices for solar technologies are expected to fall drastically. Biomass boilers and especially heat pumps show significant price reductions as well. Efficiency increases are assumed for PV (due to collector efficiency and performance ratio increases) and heat pumps.

Table 4. Technology data (year 2010). Source: Various sources, collected in [34]

	IVC	OMC	Annual Efficiency		Full load hours	Lifetime
	[€kW^{-1}]	[€kWa^{-1}]	Thermal	Electric	[ha^{-1}]	[a]
Gas (condensing boiler)	796	22	95%		2,000	20
Oil (condensing boiler)	1,054	17	93%		2,000	20
Pellets boiler	1,422	20	85%		2,000	20
Wood log boiler	1,048	20	85%		2,000	20
Wood Chip boiler	1,785	17	85%		2,000	20
Heat Pump Brine/Water	1,810	8	400%		1,950	20
District Heating (Heat exchanger)	769	37	100%		2,000	20
Solar Thermal	632	23	30%			20
PV	2600	26		9%		25
Wood Chip Heating Plant (Stirling)	750	23	85%		3,000	20
Biogas CHP	5,095	255	34%	26%	7,500	15
Wood Chip CHP	13,291	282	76%	11%	7,000	15

IVC (Investment costs) and OMC (Operation and maintenance costs) for CHP refer to $kW_{electric}$. For Solar thermal, IVC and OMC are in [€/m²]. For PV, IVC and OMC are in [€/kW_p].

Table 5. Technology development (100% in 2010 corresponds to respective value in tab. 4). Source: Various sources, collected in [34]

	Cost development (IVC, OMC)					Efficiency development				
	2010	2020	2030	2040	2050	2010	2020	2030	2040	2050
Fossil boilers	100%	97%	95%	95%	95%	100%	102%	103%	103%	103%
Biomass boilers	100%	88%	88%	81%	81%	100%	100%	100%	100%	100%
Heat Pump Brine/Water	100%	84%	71%	68%	64%	100%	110%	116%	119%	121%
District Heating (Heat exchanger)	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Solar Thermal	100%	69%	50%	44%	39%	100%	100%	100%	100%	100%
PV	100%	46%	38%	35%	34%	100%	115%	136%	140%	144%
Wood Chip Heating Plant	100%	92%	86%	83%	82%	100%	100%	100%	100%	100%
Biogas CHP	100%	97%	94%	93%	92%	100%	100%	100%	100%	100%
Wood Chip CHP	100%	94%	92%	92%	92%	100%	100%	100%	100%	100%

A discount rate of 5% was used for the present value calculations in ORES as well as for the calculation of annual investment costs in RESRO following the annuity method using technology lifetime as pay-back period. Some boundaries are set in order to accomplish realistic results. For wood log boilers, which have very low investment costs and are therefore favoured by the optimisation algorithm, an upper boundary of 15% of the heat supply is set, since a higher share at heat supply is unlikely due to uncomfortable, manual filling of wood log boilers. Pellet consumption per region is restricted to the double extent of recent per capita pellet consumption in Austria.

Results

Climate data

Until decade 2041-2050 an increase of mean annual temperatures between around 1 and 2 °C, compared to reference period 1981-2010, is noted. Model DMI shows much lower values than both other models from ETHZ and SMHI. For single raster cells and time periods more extreme results can occur, as shown in tab. 6, where temperature rises of up to more than 2.5 °C in winter and 3 °C in summer can be seen.

Table 6. Minimum, mean and maximum temperature change [°C] for winter (Dec, Jan, Feb) and summer (Jun, Jul, Aug) between model period 2041-2050 and reference period 1981-2010

Region	Model	Delta T Winter (DJF)			Delta_T Summer (JJA)		
		Min	Mean	Max	Min	Mean	Max
Wels-Land	DMI	1.47	1.54	1.58	1.41	1.47	1.57
	ETHZ	1.65	1.84	1.97	1.88	1.95	2.10
	SMHI	1.33	1.50	1.65	2.13	2.25	2.36
Tamsweg	DMI	2.04	2.31	2.52	1.64	1.77	2.12
	ETHZ	1.71	2.03	2.20	2.12	2.30	2.84
	SMHI	1.13	1.34	1.56	2.48	2.62	3.05
Feldbach	DMI	1.29	1.33	1.39	1.22	1.32	1.41
	ETHZ	1.54	1.60	1.68	1.98	2.11	2.25
	SMHI	1.98	2.07	2.13	2.20	2.27	2.39

Changes in solar irradiation are almost negligible (–2.8% – +1.8%), while absolute values differ slightly between the regions. Precipitation results show variances between the different climate models. However, trends such as increasing winter precipitation and decreasing summer precipitation can be recognised.

Heat demand

Climate-induced reductions of space heating demand for the regions' building stocks with a constant amount of buildings range between 7.5% and 16.8% for the last model period 2041-2050 depending on region and climate scenario. If additionally considering refurbishment actions, space heating demand reductions range between 20% and 28.3%.

Figure 2 illustrates heat demand (space heating and domestic hot water) results for the four different heat demand scenarios. "Only climate" reductions (2nd bar) reach values between 7% and 15%. Reductions in scenario "climate and refurbishment" reach up to 25%, while rising household numbers in scenario "climate, refurbishment and household development" lead to an increasing heat demand compared to the scenario without consideration of household development, especially in the region of Wels-Land (41%-increase of households). So, under the assumptions of climate model DMI, refurbishment is far more decisive than climate change in terms of decreasing heat demand, while for climate models ETHZ and SMHI, the effects of refurbishment and climate change are quite similar.

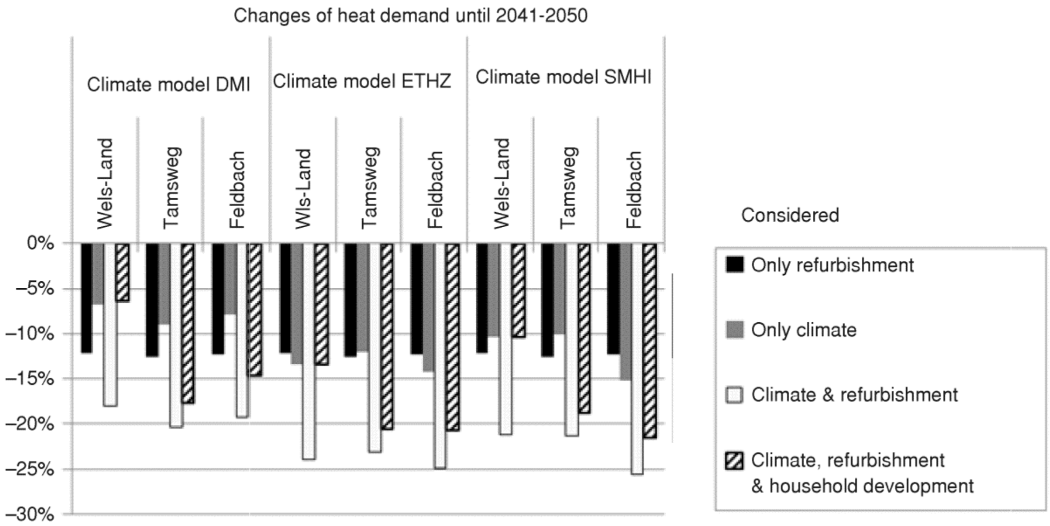

Figure 2. Relative changes of total heat demand (space heating and domestic hot water) between time period 2041-2050 and 1981-2010 for different climate models, regions and scenarios

Cooling demand

The trend of increasing numbers of cooling degree days (CDD) is significant, especially in Wels-Land and Feldbach, although the number of CDD between the regions differs substantially. The region of Tamsweg only shows very low CDD values, even in the last model decade 2041-2050. The strongly varying cooling demand within a region is shown by high divergences between occurring minimum and maximum CDD values within one region and one model period, which reach up to 150 Kd (Kelvin days).

Accordingly, cooling electricity results show a very low demand for the alpine region of Tamsweg, a notable increase at a moderate level in Wels-Land, while the electricity demand for cooling in Feldbach rises tremendously (up to +355%) between the last model period 2041-2050 and the reference period 1981-2010. Under the applied assumptions , the major part (at least 87%) of the cooling demand is caused by non-residential buildings, as shown in fig. 3, where electricity demand for cooling in the first (left image) and the last (right image) model period is illustrated (results for climate model ETHZ for period 2011-2020 cannot be shown due to climate data errors). Results also differ quite notable between the different climate models, especially in the last model decade 2041-2050, which shows a strong sensitivity of the cooling demand results towards climate change.

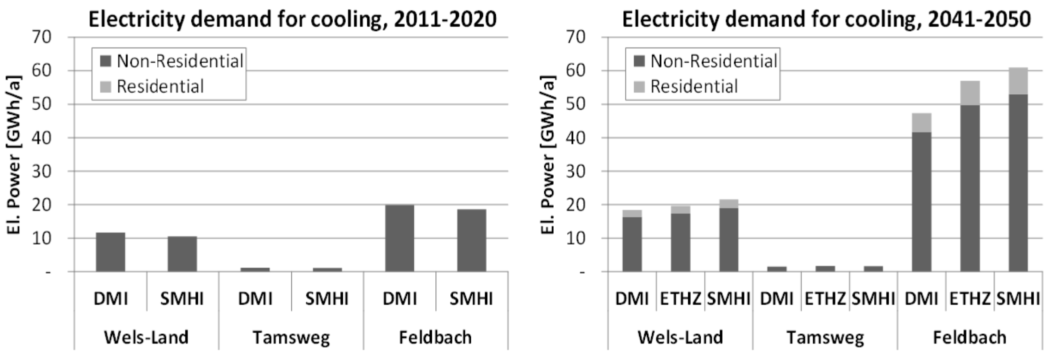

Figure 3. Electricity demand for cooling for model periods 2011-2020 and 2041-2050 under climate change scenarios without household development (household numbers constant)

Renewable energy potentials

Rather small climate-induced differences – if examined – for the renewable energy potentials are noticed. Changes in solar irradiation are almost negligible, so technical solar potentials mostly change because of efficiency improvements. The number of buildings suitable for ambient heat systems will increase due to modernisations of the building stock and therefore increase the total potential of ambient heat. Rising air and soil temperatures of 1-2 °C can be neglected compared to this development. Biomass forestry potential data show differing potentials between the regions [34], depending on the region’s forest areas and structure. Agricultural areas are rarely used for energy purposes in Austria due to missing subsidies and land use competition. Therefore farmyard manure constitutes the major part of realisable biogas potentials in the regions. However, climate-induced changes on biomass potentials, which are only discussed here, depend on future temperatures, precipitation and negative events (*e.g.* droughts, storms, diseases), which differ between regions, and are still subject of on-going research. In general, rising temperatures lead to higher forestry net primary productivity as long as water, *e.g.* in form of precipitation, is sufficiently available. So according to [5, 35], forestry potentials will increase in high-lying alpine regions such as Tamsweg, where temperatures rise, but precipitation does not decrease significantly. The opposite might be the case for low-lying warm regions like Feldbach, if not enough water is available. Still, the effects of climate change on the energetic usage of forestry biomass in Austria until the mid of the 21st century are seen rather low.

Energy system optimisations

Energetically used biomass

The results for energetically used, regional biomass are transferred from ORES to RESRO. They are illustrated in fig. 4 and mainly result from the land use differences between the testing regions (see section *Case study regions*), especially regarding wood potentials derived from forest areas. Energetically used wood (wood logs and wood chips) includes the amount of firewood and pulpwood in the regions. Biogas strictly originates from farmyard manure and pellets thresholds are set exogenously (see chapter *Scenarios and assumptions*).

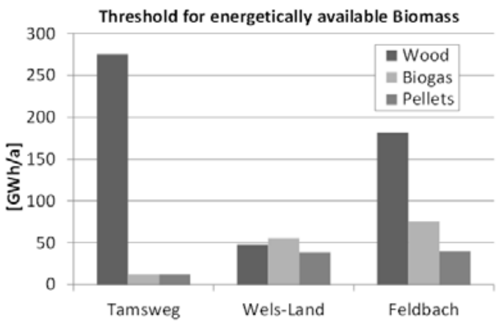

Figure 4. Maximum, energetically used biomass in model ORES

Heat supply

Heat results are strongly dependent on regional circumstances, such as the availability of wooden biomass or an existing natural gas grid (Tamsweg: no option of gas supply, Wels-Land: option of 100% gas supply, Feldbach: low option of gas supply). Figure 5 shows spatially aggregated results for heat supply from the optimisation runs with the model RESRO for the second (2021--2030) and last (2041-2050) model period. Therefore the temporal development of the scenario solutions as well as climate change induced differences (Scen. 1 *vs*. Scen. 2) can be recognised. For model period 2021-2030 climate change effects do not yet show a strong impact on the energy system, in contrary to model period 2041-2050, where heat demand has decreased much stronger. For reasons of comparability, heat supply based on official data from 2001 is illustrated additionally in fig. 5. However, heating facilities from 2001 or earlier do not influence model results from 2021 or later, since they have exceeded their lifetime then.

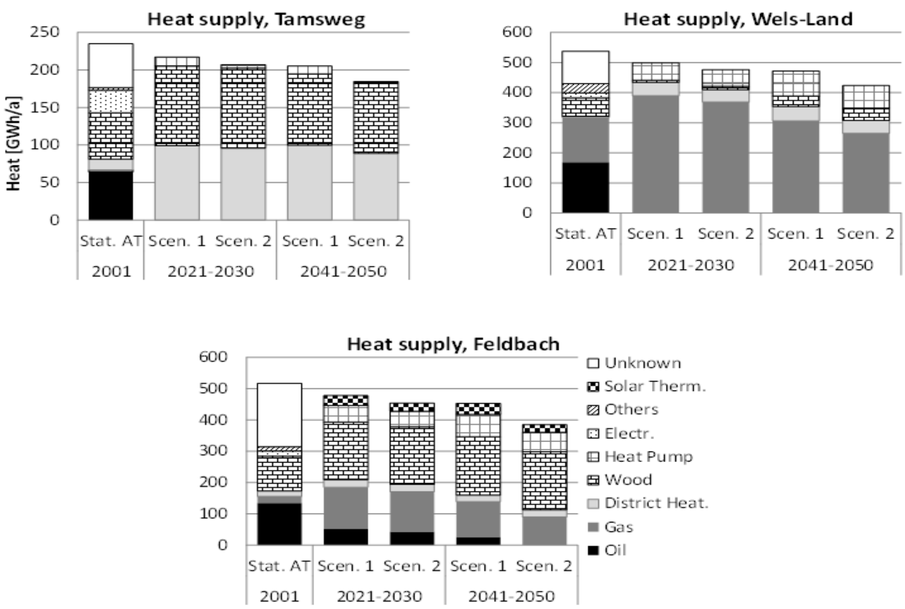

Figure 5. Heat supply based on official data from 2001 (Stat. AT) and optimisation results from RESRO model (Scen. 1, Scen. 2)

Left bar "Stat. AT, 2001" calculated with heat demand (resp. climate data) from reference period 1981-2010 and regional data about energy carriers of heating from Statistik Austria. "Unknown" fraction in "Stat. AT, 2001" results from data protection regulations in sparsely populated areas. "Wood" includes small-scale wood log-, wood chip- and pellets-boilers

Strong differences between the regions in terms of heat supply structure are noted, resulting from regional circumstances in terms of biomass availability and gas supply options. In scenario 2, heat demand is decreasing more rapidly than in scenario 1 due to climate change. District heating supply is not influenced by the decreasing heat demand, which also results in a lower heat demand density. This leads to the implication that in already DH-compatible areas (areas whose recent heat demand density is sufficient for DH supply), DH supply is still more cost-efficient than competing, decentralised heat technologies for scenarios with decreasing demand. Therefore, DH supply in the tested regional energy systems is not sensitive to refurbishment actions and climate change. Oil boilers are not favoured by the cost-driven optimisation algorithm, which is a result of high oil prices (92 €/MWh already in the first model period 2011-2020) and also reflects the recent situation in Austria, where oil boilers lose market shares.

Heat supply of Tamsweg with its high biomass potentials shows a high share of DH (up to 49%). Besides that, regional biomass (wood chips and wood log) is also used in decentralised small-scale boilers, while heat pumps serve the rest of the demand. In Scen. 2, 2041-2050, heat pumps are not used anymore. High biomass potentials in combination with strongly decreasing demand lead to a situation, where heat demand can be covered entirely by regional biomass.

Contrary to the situation in Tamsweg, heat supply of Wels-Land is dominated by natural gas. This amount of gas supply declines strongly over time due to demand decreases and increases of heat pump usage, which serve a considerable amount of heat. DH supply remains about at the same level, while wood log and pellet boilers serve a rather small share of the demand.

Feldbach shows a highly diversified heat supply composition, which is mainly a result of low biomass potentials and the small existing gas grid. Since wood chips are utilised more efficiently (in terms of heat generation) in decentralised systems (no DH transport losses), it is barely used in centralised plants. Instead, biogas is the major energy carrier feeding the DH network through biogas CHP plants. Due to the regional circumstances and general scenario assumptions, Feldbach is the only region that needs oil and solar thermal to cover the entire heat demand, even though this would not be cost-optimal under different circumstances (higher gas option, more biomass, *etc*.). The difference between scenarios 1 and 2 is that oil is no longer used in scenario 2, 2041-2050, because of the strongly decreased heat demand.

However, comparing both scenarios 1 and 2, there are no major effects of climate change on the composition of the heat supply mix. The composition of energy carriers is primarily influenced by economic issues such as investment costs and fuel prices, potentials of RES (biomass, ambient heat) and existing connections to the natural gas grid. Climate change is another heat demand decreasing factor, as the refurbishment actions are, which leads to lower primary energy consumption and greenhouse gas emissions in the heat supply sector.

Electricity demand and supply

Due to differing demands for cooling, the power demand varies significantly between the testing regions. The use of heat pumps also shows increasing effects on the power demand. With high cooling demand, the power load profile is affected significantly during the summer season. As a result of rising electricity prices and dropping PV system investment costs, all scenarios show a high PV expansion and hence a significant share of PV power generation.

In Tamsweg cooling is not a relevant issue also in future scenarios, so power demand is slightly decreasing due to expected energy efficiency measures in the household sector. Power demand in scenario 1 (without climate change) is even slightly higher than in scenario 2 because of higher heat pump usage in scenario 1. As a consequence, climate change can occasionally even have an indirect decreasing effect on power demand (less heat demand $\rightarrow$ less heat pump usage $\rightarrow$ less power demand). In Wels-Land and especially in Feldbach, increases of power demand because of rising demand for cooling in scenario 2 are noted. Increased heat pump usage also leads to an increase of power demand in both scenarios 1 and 2. By using typical power load profiles for households and cooling, strong peak loads for cooling during daytime in summer are recognised, if high cooling demand appears in the region. In the optimisation model outcomes, high PV generation – strongly time-correlated to cooling loads – is shown and therefore PV generation is able to cover the mentioned peak loads from cooling.

Conclusions

The effects of climate change on regional energy systems were examined, emphasising the heating and cooling demand of buildings and the possible composition of future heat supply. Therefore, high spatial resolution climate, building and land use data for three Austrian regions were used.

Rising temperature levels represent one of the major effects of climate change on the energy demand of buildings and consequently also on future energy supply. The scenarios presented in the study show that heat demand will decrease in future due to climate change. On the other hand, it was noticed that also other developments play an important role for the development of heat demand like building refurbishment or household developments. Rising mean temperatures and especially more frequent heat periods will lead to a significantly higher cooling demand in some regions. An indicator for the specific cooling demand, the cooling degree days value, is rising drastically, while more areas in non-residential buildings as well as in private households are expected to be cooled using conventional air-conditioning systems. This will increase the electricity demand in summer notably. In warm regions, this will be quite relevant, concerning the electricity suppliers' ability to cover peak loads.

Our considerations and climate data show that climate change will not affect the potentials of the examined renewable energy sources (solar thermal, PV, ambient heat) significantly. Climate-induced effects are almost negligible compared to other effects, such as technology developments. For biomass potentials, there are still uncertainties concerning climate change effects, which were not considered in this analysis. However, studies for Austria (*e. g.* [5]) show that climate change effects on forestry biomass differ regionally, but don't influence the energetic usage of such energy carriers substantially.

The results from the optimisation runs show low climate-induced effects on the optimal energy system setup. Regional circumstances and price developments of technologies or energy carriers have more influence on the optimisation results. Contrary to what was expected, district heating supply is not influenced by the decreasing heat demand. However, decreasing heat demand leads to lower energy consumption and therefore usually to lower greenhouse gas emissions. Increasing cooling demand could be perfectly covered by PV generation due to their strong time-correlation, as the optimisation results show. Still, it would be much better to prevent cooling demand as much as possible by appropriate architecture or passive cooling methods such as solar shading and night ventilation. Also alternative active cooling methods other than the conventional electric air-conditioning systems should be a more sustainable option for the future and be considered in research and planning.

Nomenclature

cd – specific cooling demand for fully cooled non-residential areas, [$\mathrm{kWhm^{-2}a^{-1}}$]
cd_{part} – specific cooling demand for partially cooled non-residential areas, [$\mathrm{kWhm^{-2}a^{-1}}$]
CDD – cooling degree days, [Kd]
$GI_{climate}$ – global irradiation from climate model, [$\mathrm{MJm^{-2}d^{-1}}$]
GI_{Ref} – global irradiation from reference climate, [$\mathrm{MJm^{-2}d^{-1}}$]
$k_{climate}$ – factor of climate-induced change of space heating demand, [–]
k_{GI} – sensitivity coefficients global irradiation, [$\mathrm{m^2dMJ^{-1}}$]
k_T – sensitivity coefficient temperature, [$\mathrm{°C^{-1}}$]
SH – space heating demand, [$\mathrm{kWha^{-1}}$]
SH_{Ref} – space heating demand with reference climate, [$\mathrm{kWha^{-1}}$]
$T_{climate}$ – temperature from climate model, [°C]
T_{Ref} – temperature from reference climate, – [°C]

Acknowledgment

This paper is based on the results of the project CLEOS [34] („Climate sensitivity of regional energy systems – a spatial optimisation approach"), which was supported by the Climate and Energy Fund (Klima und Energiefonds) of Austria within the Austrian Climate Research Program (ACRP). Additionally, we gratefully acknowledge the comments from three anonymous reviewers.

References

[1] Van der Linden, P., Mitchell, J., ENSEMBLES: Climate Change and its Impacts: Summary of Research and Results from the ENSEMBLES project, Met Office Hadley Center, Exeter, UK, 2009
[2] ***, European Environment Agency (EEA), Climate Change, Impacts and Vulnerability in Europe 2012, EEA Report No 12/2012, Copenhagen, 2012
[3] ***, Intergovernmental Panel on Climate Change (IPCC), Climate Change 2007: Impacts, Adaptation and Vulnerability, Cambridge, UK, 2007
[4] ***, Center for European Policy Studies (CEPS), Future Impacts of Climate Change across Europe, CEPS Working Document No. 324/February 2010, Brussels, 2010
[5] Kranzl, L., *et al*., KlimAdapt – Derivation of Priority Measures for the Adaptation of the Energy System to Climate Change (in German), Vienna, 2010
[6] Christenson, M., *et al.*, Climate Warming Impact on Degree-Days and Building Energy Demand in Switzerland, *Energy Conversion and Management, 47* (2006), 6, pp. 671-686
[7] Toglhofer, C., *et al.*, HEAT.AT, Climate Change Impacts on Energy Use for Space Heating and Cooling in Austria II (in German), Graz, 2009
[8] ***, Intergovernmental Panel on Climate Change (IPCC), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, Intergovernmental Panel on Climate Change, Cambridge, New York, USA, 2012
[9] Loibl, W., *et al.*, reclip:century 1 Research for Climate Protection: Century Climate Simulations: Models, Data and GHG-Scenarios, Simulations, Vienna, 2011
[10] Beck, A., *et al.*, Institutional and Regulatory Questions of Supplying Weather Data (in German), Graz, 2009
[11] Themesl, M., *et al.*, Empirical-Statistical Downscaling and Error Correction of Regional Climate Models and its Impacts on the Climate Change Signal, *Climatic Change, 112* (2011), 2, pp. 449-468
[12] Themesl, M., *et.al.*, Empirical-Statistical Downscaling and Error Correction of Daily Precipitation from Regional Climate Models, *International Journal of Climatology, 31* (2011), 10, pp. 1530-1544
[13] Nakicenovic, N., *et al.*, IPCC Special Report on Emissions Scenarios, Cambridge, UK, 2000
[14] Biberacher, M., *et al.*, Spatial Models as Decision Support for the Utilization of Regional Energy Potentials for the CO_2-Neutral Coverage of Local Heat Demand (in German), Research Studios Austria, Salzburg, Austria, 2010

[15] ***, "House of the Future"-program, Passive house sanitation in social housing – development of a planning tool (in German), Federal Ministry for Transport, Innovation and Technology, 2012, http://www.hausderzukunft.at/results.html/id4643
[16] Hofer, P., *et al.*, Temperature and Irradiation Influence on the Energy Consumption in the Heat Market (in German), Swiss Federal Office of Energy, Bern, 2008
[17] Hanika, A., Small-Scale Population Projection for Austria 2010 until 2030 with Prospect until 2050 (in German), Statistik Austria, Vienna, 2011
[18] Aebischer, B., *et al.*, Impact of climate Change on Thermal Comfort, Heating and Cooling Energy in Europe, Proceedings, EEECE 2007 summer study, La Colle sur Loup, France, 2007
[19] Kranzl, L., *et al.*, Heating and Cooling 2050 – Climate Change and other Influence Factors (in German), 7th International Symposium of Energy Economy (IEWT 2011), TU Wien, Vienna, 2011
[20] Hofer, P., Energy Consumption of Private Households – 1990-2035 (in German), Swiss Federal Office of Energy, Bern, 2006
[21] Adnot, J., Energy Efficiency and Certification of Central Air conditioners, Study for the D. G. Transportation-Energy (DGTREN) of the Commission of the EU, Paris, 1999
[22] Adnot, J., Energy Efficiency and Certification of Central Air Conditioners, Study for the D. G. Transportation-Energy (DGTREN) of the Commission of the EU, Paris, 2003
[23] Hausl, S., Biberacher, M., Spatial Aspects in Regional Energy System Optimisation (in German), *Proceedings* (J. Strobl, *et al.*, Applied Geoinformatics), 24. AGIT-Symposium, Salzburg, Austria, 2012, pp. 492-501
[24] Lodl, M., *et al*., Estimation of Photovoltaic-Potentials on Roof Areas in Germany (in German), *Proceedings*, 11 Symposium Energieinnovation, Graz, Austria, 2010
[25] Hausladen G., Hamacher, T., Guideline Energy Usage Plan (in German), TU Munchen, Bavarian State Department of Interior, Munich, Germany, 2011
[26] Schardinger, I., *et al.*, Integrating Spatial Models into Regional Energy System Optimisation: Focusing on Biomass, *International Journal of Energy Sector Management*, *6* (2012), 1, pp. 5-32
[27] Prinz, T., *et al*., Energy and Space Development – Spatial Potentials of Renewable Energies (in German), Austrian Conference on Spatial Development (OROK), Vienna, 2009
[28] Hausl, S., *et al.*, RESRO – A Spatio-Temporal Model to Optimise Energy Systems Emphasising Renewable Energies, EPJ Web of Conferences, *Proceedings*, 2nd European Energy Conference, Maastricht, The Netherlands, 2012, pp. 1-8
[29] Biberacher, M., *et al*., BioSpaceOpt – Regional Integrative Assessment of Bioenergy Use Paths Based on Spatial Aspects (in German), Salzburg, Austria, 2012
[30] Schmidt, J., *et al*., Regional Energy Autarky: Potentials, Costs and Consequences for an Austrian Region, *Energy Policy, 47* (2012), Aug., pp. 211-221
[31] Loulou, R., *et al.*, Documentation for the TIMES Model: PART I, 2005, available at: http://www.etsap.org/Docs/TIMESDoc-Intro.pdf
[32] Fink, C., *et al.*, Passive Cooling Concepts of Office and Administration Buildings through Air- and Water-Perfused Soil Heat Exchangers (in German), Vienna, 2002
[33] ***, International Energy Agency (IEA), World Energy Outlook 2010, Paris, 2010
[34] Hausl, S., *et al*., CLEOS: Climate Sensitivity of Regional Energy Systems – a Spatial Optimisation Approach (in German), Research Studios Austria, Salzburg, Austria, 2013
[35] Dobbertin, M., Giuggiola, A., Tree Growth and Increased Temperatures (in German), Forum fur Wissen 2006, pp. 35-45, 2006

Paper submitted: December 18, 2013
Paper revised: March 24, 2014
Paper accepted: April 15, 2014