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Modeling transition paths towards decentralized regional energy autonomy: the role of legislation, technology adoption, and resource availability

Claudia R. Binder[1,4] · **Christof Knoeri**[1,3] · **Maria Hecher**[2]

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Abstract Decentralized energy systems are increasingly seen as a key factor for a transition towards a low-carbon, renewable energy based society. Within the transition process, regional demand and supply of renewable energy carriers have to be aligned, while considering the environmental conditions of the region. This paper focuses on the energy demand from buildings, which makes up 35 % of the total energy demand. It presents an approach for aligning the regional supply potential of renewable energy carriers with the dynamics of regional energy demand from buildings. The approach consists of two components. First, a dynamic model simulates regional energy demand from buildings taking into consideration envelope renovation, legislative standards, and adoption of heating technologies. Second, the regional supply is estimated based on the technical maximum possible, taking into consideration competing uses and spatial limitations. We show a first application in the case of the energy region Weiz-Gleisdorf, Austria, which aims to achieve CO_2 neutrality and energy self-sufficiency by the year 2050. Our results show that in the year 2050 (i) energy demand from buildings will decrease by 40–55 %, depending on envelope renovation rates and legislative standards; (ii) demand for the different renewable energy carriers will be determined by the choice of heating technology; (iii) the demand for wood could be met from regional forest resources, as long as there are no additional demands for other purposes; (iv) the demand for biomass for district heating would require 5–10 % of the agricultural area to be used for the production of energy plants rather than food; and (v) in contrast to other forms of energy, the demand for electricity will remain constant or increase slightly over time. This demand could only be regionally met if significant areas of façades or gardens are used for photovoltaic electricity production in addition to roofs. Overall we identified several issues related to spatial planning and a need for further research regarding the transition towards decentralized energy systems. First, if biomass for central district heating systems is to come from regional production, areas should be allocated for cultivating energy crops used specifically to produce fuel. Second, if wood is used for district heating purposes, the extent to which the import of wood from neighboring regions would be a useful ecological solution must be evaluated; this would involve extending regional energy planning beyond the typical jurisdictional boundaries while considering ecological issues.

Keywords Regional energy demand · Energy supply · Spatial limitations · Renewables · Energy transition

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All authors contributed equally to this publication.

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✉ Prof. Dr. Claudia R. Binder
claudia.binder@epfl.ch

[1] Department of Geography, Human-Environment Relations, LMU University of Munich, Luisenstraße 37, 80333 Munich, Germany

[2] Institute for Systems Science, Innovation and Sustainability Research, University of Graz, Graz, Austria

[3] Sustainability Research Institute, School of Earth & Environment, University of Leeds, Leeds, UK

[4] Institute of Environmental Engineering, EPFL, Laboratory for Human-Environment Relations, CH-1015 Lausanne, Switzerland

Modellierung von Transformationspfaden hin zu einer dezentralisierten regionalen Energieselbstversorgung: Die Rolle von Gesetzen, Technologieadoption und Ressourcenverfügbarkeit

Zusammenfassung Die Dezentralisierung des Energiesystems wird als zentrales Element der Energiewende betrachtet. Dabei spielt die Abstimmung zwischen Angebot und Nachfrage regionaler Energieträger eine entscheidende Rolle. In diesem Beitrag wird der Energienachfrage im Gebäudesektor nachgegangen und untersucht wie diese im Jahr 2050 aus regionalen und erneuerbaren Energieträgern gedeckt werden könnte. Dazu wird eine Methodik entwickelt, die es erlaubt, die Nachfrage über die Zeit dem regionalen Angebot gegenüber zu stellen. Dieser Ansatz beinhaltet ein dynamisches Energienachfragemodell, welches die Energienachfrage (aufgesplittert nach Energieträgern) aus dem Gebäudesektor in Abhängigkeit von Renovierungsraten, Energieeffizienzstandards und Heizungstechnologien simuliert. Das regionale Angebot wird berechnet, indem das technisch maximale Potential, unter Berücksichtigung der Flächenverfügbarkeit, ermittelt wird. Wir zeigen eine erste Anwendung dieses Ansatzes am Beispiel der Energieregion Weiz-Gleisdorf in Österreich. Weiz-Gleisdorf hat sich zum Ziel gesetzt, bis zum Jahr 2050 CO_2-neutral zu sein und sich ausschließlich aus eigenen erneuerbaren Energien zu versorgen. Unsere Untersuchungen zeigen, dass im Jahr 2050 (i) die Energienachfrage aus dem Gebäudesektor je nach Renovierungsraten und Energieeffizienzstandards zwischen 40 und 55 % liegen wird; (ii) die Differenzierung der Energienachfrage auf die spezifischen Energieträger von der Wahl des Heizungssystems abhängig sein wird; (iii) die Nachfrage nach Holz als Energieträger regional gedeckt werden könnte, wenn das Holz ausschließlich zu Energiezwecken genutzt werden würde; (iv) zwischen 5–10 % der landwirtschaftlichen Fläche für die Produktion von Energiepflanzen genutzt werden müsste, um die Nachfrage von Fernwärme zu decken; (v) die Nachfrage nach Elektrizität – im Gegensatz zu den anderen Energieformen – konstant bleiben oder leicht ansteigen wird. Die Nachfrage nach Elektrizität könnte nur gedeckt werden, wenn neben den Dächern auch größere Anteile der Fassaden oder Gärten für die Elektrizitätsproduktion mit Photovoltaik genutzt werden. Die Ergebnisse unserer Untersuchungen weisen auf einige wichtige Aspekte in der Raumplanung hin und zeigen weiteren Forschungsbedarf im Rahmen dezentraler Energiesysteme auf. Zum einen, falls Biomasse einen wesentlichen Beitrag zur Energieversorgung leisten sollte (z. B. Fernwärme), muss evaluiert werden, inwiefern Brachflächen sich für die Produktion von Energiepflanzen eignen bzw. spezifische Flächen zur Produktion von Energiepflanzen ausgeschieden werden müssen. Zweitens, wenn Holz ein wichtiger Energieträger werden sollte, ist zu beachten, inwiefern Importe aus Nachbarregionen aus ökologischer Sicht sinnvoll sein könnten. Dies würde voraussetzen, dass die energiebezogene Regionalplanung über die administrativen Grenzen hinausgeht und ökologische Aspekte berücksichtigt werden.

Schlüsselwörter Regionale Energienachfrage · Energieangebot · Landnutzungskonflikte · Erneuerbare Energien · Energiewende

1 Introduction

Decentralized energy systems are increasingly seen as being a key factor for a low-carbon, renewable energy focused transition (GEA 2012: 1597). As such, the role of the regional level has gained importance in energy transition. This has already been acknowledged by the European Union and various countries (see also United Nations 1992: Agenda 21, Chapter 28; for example see also Climate and Energy Fund 2013 (for Austria), DECC 2014 (for the UK), Julian 2014 (for Germany)). In Austria, for example, energy regions have been supported by national funding since 2009 through a funding instrument called "climate and energy model regions", which fosters regionally embedded bottom-up approaches in the field of climate change and energy (Climate and Energy Fund 2013). Since the 1990s, 106 "climate and energy model regions", including 1,113 municipalities with 2.5 million inhabitants, have developed in Austria. Numerous similar initiatives have also emerged, such as "climate communities" (*Klimabündisgemeinden*) and "e-5 communities" (*e-5 Gemeinden*), and are developing and implementing regional energy and climate protection measures (Alber 2009; Climate and Energy Fund 2013). In Germany, similar initiatives have emerged at the regional (Aretz/Hauber/Kreß et al. 2009; Moser 2013; IdE 2015), city (Müggenburg/Biesgen/Wörner et al. 2013; IfaS 2015) and community level (Schmuck/Eigner-Thiel/Lackschewitz 2003; Eigner-Thiel 2004). Some have been quite successful in energy transformation, achieving a new institutional structure and increasing the share of local renewable energy sources in their energy supply (Binder/Hecher/Vilsmaier 2014; Böschen/Gill/Kropp et al. 2014; Hecher/Vilsmaier/Akhavan et al. 2016). A number of communities even export energy (Pfefferkorn/Rauzi/Wyss 2009; Brickmann/Kropp/Türk 2012; Meyer/Mueller/Koeberle et al. 2013; Radzi/Droege 2013).

In Austria and Germany, several studies have analyzed the transitions of these energy regions. They have investigated the role of guiding visions (*Leitbilder*), the actors and arenas involved in the transition process, the institutionalization process, and the development of energy

Tab. 1 Socio-economic characteristics of the energy region Weiz-Gleisdorf

Socio-economic characteristics	2010
Inhabitants	41,800
Population density [inhabitant/km^2]	158
Working population	22,594
Agricultural sector	1433
Production sector	7021
Service sector	13,477
Workplaces	3755
Employees	26,048
Forestry and agricultural enterprises	1504
Employees in forestry and agricultural enterprises	5508
Employment participation rate	54 %
Unemployment rate	3 %

Source: Statistics Austria 2010b, Statistics Austria 2012

and material flows over time (Späth/Koblmüller/Kubeczko et al. 2007; Binder/Hecher/Vilsmaier 2014; Böschen/Gill/Kropp et al. 2014; Hecher/Vilsmaier/Akhavan et al. 2016). This research identified the following issues: (i) guiding visions are essential for initiating the transition (Binder/Hofer/Wiek et al. 2004; Späth/Koblmüller/Kubeczko et al. 2007; Späth/Rohracher 2010; Böschen/Gill/Kropp et al. 2014); (ii) there is a significant delay between the initial vision and the point at which physical changes can be observed (Hecher/Vilsmaier/Akhavan et al. 2016; Binder/Hecher/Vilsmaier 2014); (iii) the engagement of communal and regional stakeholders is key to establishing a new governance structure through connecting actors in collaborative networks and regional action arenas (Gailing/Röhring 2014); and (iv) there is often a hiatus a few years after the initial enthusiasm (Ufertinger/Zuber 2013), as the expected outcomes in energy self-sufficiency have not been reached within the time envisioned.

Such "failures" relate, on the one hand, to the time required for planning and constructing new facilities. On the other hand, they are linked to the actions of individuals, such as investments in envelope renovation and in new heating technologies (Friege/Chappin 2014). These are dependent, for instance, on the lifetime of buildings, building age, technology development (e. g. heating systems), technology adoption, and the end-use behavior of individuals (UNEP 2009; Knoeri/Steinberger/Roelich 2015). There is still little knowledge on how scenarios of envelope renovation rates, legislative standards, and heating technology adoption affect the demand for different energy carriers over time.

Some studies have analyzed whether hypothesized future demand can be covered with the available regional sources of renewable energies, and what the potential effects on landscape and land-use could be (Becker/Gailing/Naumann 2013). However, how competing land uses play out in the context of changing demand structures is still an open question. In sum, to achieve the transition towards a decentralized energy system, there is a need for (i) understanding the effect of building stock dynamics on regional energy demand according to energy carrier, and (ii) estimating the regional supply potentials of these energy carriers.

We present an approach to support policy planning at the regional level which takes into consideration the alignment of energy supply and the demand for energy from buildings[1]. This focus was chosen as energy demand from buildings and activities in buildings accounts for approximately 31 % of global final energy demand (GEA 2012: 653). Furthermore, the long lifetime of buildings and building technologies not only requires immediate action to reduce energy demand, but also presents a significant risk of lock-in. Our approach allows the demand for energy carriers to be analyzed over time – taking into account changes in heating demand due to envelope renovation and changes in heating systems – and this demand to be related to the potential regional supply. In particular, we address the following questions:

- How will future energy demand (for different energy carriers) from the housing sector develop in view of envelope renovation rates, changes in legislation standards, and technological development in heating systems?
- What are the regional supply potentials for photovoltaics (PV), solar-thermal technology and biomass for energy production (from agriculture and forests)?
- What do the different energy demand scenarios imply for the exploitation of these potentials and what are the policy implications thereof?

In the following we first present the study area and describe the approach in depth. Second, we exemplify its application to the case of the energy region Weiz-Gleisdorf. We thus depict the results of the simulation of different scenarios considering envelope renovation rates, legislation standards, and heating system changes. Then we provide an analysis of the potential for renewable energies in the region. Finally, we discuss the potential alignment of regional demand and supply, and derive policy implications on this basis.

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[1] Energy demand from buildings refers to energy used for thermal comfort (heating, cooling, ventilation), hygiene (hot water and cleaning), sustenance (cooking and food conservation), illumination, and communication purposes.

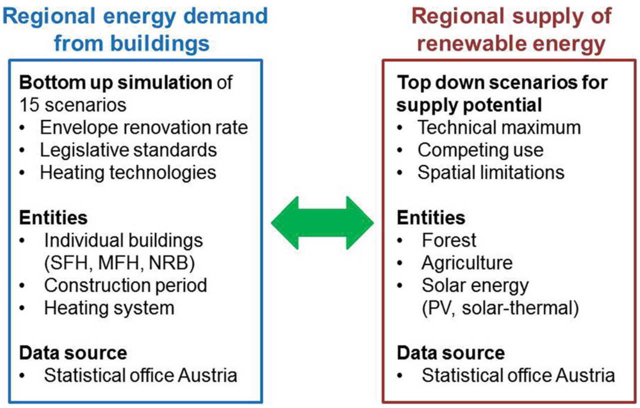

Fig. 1 Conceptual approach to align supply of and demand for energy carriers (*SFH*: single family house, *MFH*: multifamily house, *NRB*: non-residential building)

2 Study area

The "*Energieregion* Weiz-Gleisdorf" (EWG) was established in 1996. It includes 18 municipalities in Styria, along with the towns of Weiz and Gleisdorf, and covers an area of 264 km². EWG is an industrial region with a high proportion of large and medium scale enterprises, and a comparatively low unemployment rate (Tab. 1). In EWG, energy demand from buildings accounts for 35 % of the regional energy demand (Statistics Austria 2010a). The region boasts a number of finished energy projects such as innovations in passive-house building methods, highly energy-efficient renovation of buildings, and major applications of solar technologies. Besides the focus on renewable energy and energy efficiency, in recent years the region has also made progress with electro-mobility (Energieregion Weiz-Gleisdorf 2007).

3 Methods

3.1 Conceptual approach

Sustainable regional energy strategies and planning depend to a large extent on an accurate analysis of future energy demand from buildings and potential supply of renewable energy sources. These two aspects are addressed as follows (Fig. 1).

The regional energy demand from buildings is made up of heat and electricity demand (i. e. resulting in the demand for different energy carriers). We simulated the future regional energy demand from buildings with a bottom-up building stock model in different scenarios, which differ in terms of (i) envelope renovation rates; (ii) legislative standards for envelope renovations and new buildings; and (iii) changes in the heating systems, leading to demand for different energy carriers. We applied a state-of-the-art bottom-up building stock modeling approach (e. g. Swan/Urgusal 2009, Kavgic/Mavrogianni/Mumovic et al. 2010). It was set up as an agent-based model to allow for behavioral extensions to address the limitations of bottom-up equation-based models, as outlined by Natarajan/Padget/Elliott (2011).

The regional supply of renewable energy includes the supply potential of renewable energy carriers (i. e. wood and solar-thermal energy), renewable heat for district heating systems (DHS), and renewable electricity generation. We estimate the regional supply potentials of renewable energy using the following parameters: (i) maximal technical feasibility; (ii) competing land use; and (iii) spatial limitations. To calculate the supply potential of renewable energy in the EWG, various assumptions have to be made. These assumptions are mainly based on two studies that provide the energy potentials of Austria on a regional basis (Stanzer/Novak/Dumke et al. 2010) and the climate protection plan of Styria (Klimaschutzplan Steiermark) (Wegener Zentrum TU Graz/Joanneum Research 2010), the federal state in which the EWG is located.

3.2 Agent-based model of the regional energy demand from buildings

3.2.1 *Building stock model description*

To analyze the regional energy demand from buildings, a bottom-up building stock model was developed based on statistical data about different building types and their energy demand (Knoeri/Goetz/Binder 2014). The model aims to portray the building stock's energy demand and the transition of heating systems in the energy region. Furthermore, it is designed to test the effectiveness of different policy measures on overall energy demand, cumulative energy savings, and energy carriers used. It is based on census data from the year 2000 from the statistical office in Austria and a literature review of buildings' and heating systems' efficiencies, renovation rates and cycles, and stock change.

The two entities modeled are buildings and a system-level policy entity. Buildings are categorized according to type of building (i. e. single family house [SFH], multifamily house [MFH], non-residential building [NRB]), construction period (i. e. building age), and type of heating system. A building's end-use energy demand is equal to the sum of its heating, hot water and electricity energy demand (kWh/m^2) multiplied by the heated gross floor area (GFA) (i. e. useful dwelling floor area (UFA) times a reference factor). Heating demand is determined by the building's envelope standard, which itself depends on type, age and renovation of the building. For hot water and electricity, fixed reference values from the literature were used. End-

Tab. 2 Energy demand scenarios modeled

Scenarios	Business-as-usual (BAU)			Legislation (LEG)			Renovation (REN)			Stagnation (STAG)			Transformation (TRANS)		
Parameter															
Renovation rate [%]	0.8			0.8			1.6			0.4			1.6		
Legislation standards	Low			High			Low			Low			High		
Heating scenarios	BAU	ALT	BIO	BAU	ALT	BIO	BAU	ALT	BIO	BAU	ALT	BIO	BAU	ALT	BIO

Tab. 3 Utilization factor (u) in regional energy supply scenarios

Supply scenarios Utilization factor (u)	Maxi in %	Midi in %	Mini in %
Forest area (A_F)	100	60	40
Agricultural area (A_A)	100	40	10
Suitable roof area ($A_{S/R}$)	100	40	10
Suitable façade area ($A_{S/F}$)	100	25	0
Suitable garden area ($A_{S/G}$)	100	25	0

use energy is provided through main heating systems and – in about 50 % of the buildings – through additional secondary or supporting heating systems, which are primarily for heating water. The main heating systems are differentiated by the type of centrality (i. e. district heating, central building heating, or room or flat heating systems) and energy source used (i. e. oil, wood, woodchips, coal, electricity, gas, solar or heat pumps, waste-heat, etc.), both of which define their conversion efficiency. Additional electricity demand from heat pump systems is added to the building's electricity demand. The system-level policy entity sets measures to influence the general building stock fluctuation (i. e. new construction and demolition rates), the building's envelope renovation rates and standards, and renovation rates, standards and types of heating systems. The model has a one to one scale for the energy region, so that each building is represented. A distribution-based artificial space representation is used for demonstrative purposes.

In the model, energy demand changes through four interrelated processes: (i) stock fluctuations (i. e. demolitions and new buildings), (ii) envelope renovations that change heating demand per m^2, (iii) heating system renovations that change efficiency and, consequently, the type of energy carriers used, and (iv) occupants' heating, hot water, and electricity demand patterns. Each one of these processes is influenced by several individual behaviors and interactions as well as political framework conditions (i. e. regulation and incentives). Since including all aspects for each individual process might blur the explanatory power of the model, a probabilistic approach was used to approximate the individual processes. This approach allows for a first sensitivity analysis of the regional energy demand under different scenarios. For a full description of the model see the electronic appendix (EA), Sect. 1.1.

3.2.2 Energy demand and heating system scenarios

In developing the scenarios for EWG, we varied both envelope renovations and energy standards (i. e. renovation rates and legislative standards), as well as the adoption rate of new heating systems (for new buildings and replacements). We thereby combined five energy demand scenarios (i. e. changing renovation rates and standards) with three heating system scenarios (i. e. adoption of different heating systems) for a total of 15 scenarios (Tab. 2; please see EA, Tab. E2 for details on processes and parameters varied in the scenarios).

Energy demand scenarios: First, in the business-as-usual scenario (BAU) the renovation rate and efficiency standards remain at the current level. Second, in the legislation scenario (LEG) the renovation rate stays at the current level but efficiency standards are tightened (i. e. decreasing to 25 and 50 [kWh/m^2 × a] respectively). Third, in the renovation scenario (REN) the renovation rate increases and efficiency standards remain at the current level. Fourth, in the stagnation scenario (STAG) the renovation rate drops drastically and the new standards are not enforced. The fifth scenario is a mildly forced transformation (TRANS), which combines a doubled renovation rate and drastically increased efficiency standards.

Heating system scenarios: The simulated energy demand could be supplied from a range of different energy carriers depending on the new heating systems installed. Therefore, three heating system scenarios were designed to demonstrate the implications of particular technology preferences, focusing on: (i) the current distribution of energy carriers (BAU); (ii) solar-thermal and heat pumps (ALT); or (iii) wood and woodchips as energy carriers (BIO). (For details please see EA, Tab. E3).

3.3 Regional potential for supply of renewable energy

Besides analyzing the energy demand from buildings, we investigated the potential regional energy supply for both biomass (i. e. forestry and agriculture) and solar energy.

Biomass: The basis used to assess the energy potential from biomass is the regional surface area covered by forest (A_F) or agricultural land (A_A). For agricultural land, two methods were applied. First, the total agricultural area was assumed to be planted with energy crops (EC). Second, the most common crops (CC) cultivated in the study region were identified and proportionally distributed across the total agricultural area[2]. Based on land use data, we investigated the annual wood increment (a_F) and the annual crop yield ($a_{A/EC,}$ $a_{A/CC}$), of which a certain percentage (u) is used for energetic purposes. The potentially available amount of harvested wood, crops and weeds was then multiplied by the lower heating values (LHV), the energy efficiency of the conversion technologies applied (η), and the energy lost through heat distribution (l). The LVH determines the amount of energy that can potentially be generated from the respective energy carrier. The formulas used to assess the energy carrier and district heat potential from forestry (FP) (Eq. 1) and agricultural land (AP) (Eq. 2) are presented below. In Tab. E6 and E7, the definitions, units, and corresponding data sources of the variables used for the calculations are provided.

$$FP = A_F \times a_F \times u \times LHV \times \eta \times l \tag{1}$$

$$AP = A_A \times a_{A/EC,\ A/CC} \times u \times LHV \times \eta \times l \tag{2}$$

Solar potential: To assess the regional solar potential (SP), the total roof area ($A_{S/R}$) and façade area ($A_{S/F}$) of buildings, as well as garden area ($A_{S/G}$) suitable for solar energy installations, were identified. The sum of these areas ($A_{S/R}$ + $A_{S/F}$ + $A_{S/G}$), of which a certain percentage is used (u), was then multiplied by the global solar radiation (a_S) and the energy efficiency (η) of the installed solar technology (Eq. 3). Similar to above, two methods were applied to calculate the different potentials for solar-thermal collectors and PV cells by varying their respective energy efficiency ($\eta_{ST,PV}$). Thus in the first case, the entire area is used to install solar-thermal collectors, while in the second case it is used to install PV cells.

$$SP = (A_{S/R} \times u + A_{S/F} \times u + A_{S/G} \times u) \times a_S \times \eta_{ST,PV} \tag{3}$$

To calculate the roof and façade area, we differentiated between five different types of buildings and six different construction periods. This resulted in 30 different building categories for which an average floor area was determined. The latter was used to estimate the number of floors and the respective floor height for each building category (Schriefl 2007). The buildings were assumed to have a quadratic form and to be equipped with saddle roofs with 40° inclination. Additionally, it was assumed that only 50 % of the roof and façade areas of buildings face south. Of the roofs, 20 % were additionally eliminated for being shaded and 10 % for having windows, chimneys, etc. Of the façades, 40 % were eliminated for shading and 12–18 % for door and window areas, depending on the building category. Besides roof and façade areas, 5 % of the regional garden area was assumed to be suitable to install solar energy technologies (Schriefl 2007; Stanzer/Novak/Dumke et al. 2010; Wegener Zentrum TU Graz/Joanneum Research 2010).

We considered competing uses of regional biomass resources and solar technologies, and competition for suitable surface area by compiling three different regional supply scenarios. In these scenarios, the utilization factor (u) was varied assuming that only a certain percentage of the forest area (A_F), agricultural area (A_A), suitable roof area ($A_{S/R}$), façade area ($A_{S/F}$), and garden area ($A_{S/G}$) is used for energetic purposes (Tab. 3). The Maxi scenario represents the respective maximum technical potential; this is assuming that the total available area of land as well as the total suitable roof, façade, and garden area is used for energy generation and unrestricted by any other purpose or technology. The Mini scenario illustrates the minimum potential oriented towards the status quo, roughly reflecting the potential currently realized in the region; the Midi scenario reflects a balanced approach that lies between these two scenarios.

4 Results and discussion

In the following, we first present the results for the scenarios of energy demand from buildings; we then show the calculated regional supply potential for renewable energies. Finally, we elaborate on the alignment of future demand and regional supply of renewable energy carriers.

4.1 Regional energy demand from buildings

Fig. 2 shows the results of our scenario analysis (for details please see EA, Tab. E5). We distinguish between the regional energy demand from buildings in the year 2050 (in GWh/a) and the cumulative energy demand over the period 2000–2050 (in TWh). Given that the building stock model was based on census data from the year 2000, this year was chosen as the reference baseline. Furthermore, we show how the energy demand is distributed among the different energy carriers, taking into consideration envelope renovation and heating system scenarios.

4.1.1 Energy demand in different scenarios

Business as usual (BAUxBAU): In 2050, for the BAUxBAU (current legislation, envelope renovation rate, and adoption

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[2] We identified grain maize and soybeans as the most common crops in the region, together with weeds from grasslands. Since it is the most valuable type of utilization in terms of end energy output, grain maize and soybeans were used for fuel production (68 %), while grass silage is used to produce biogas (32 %).

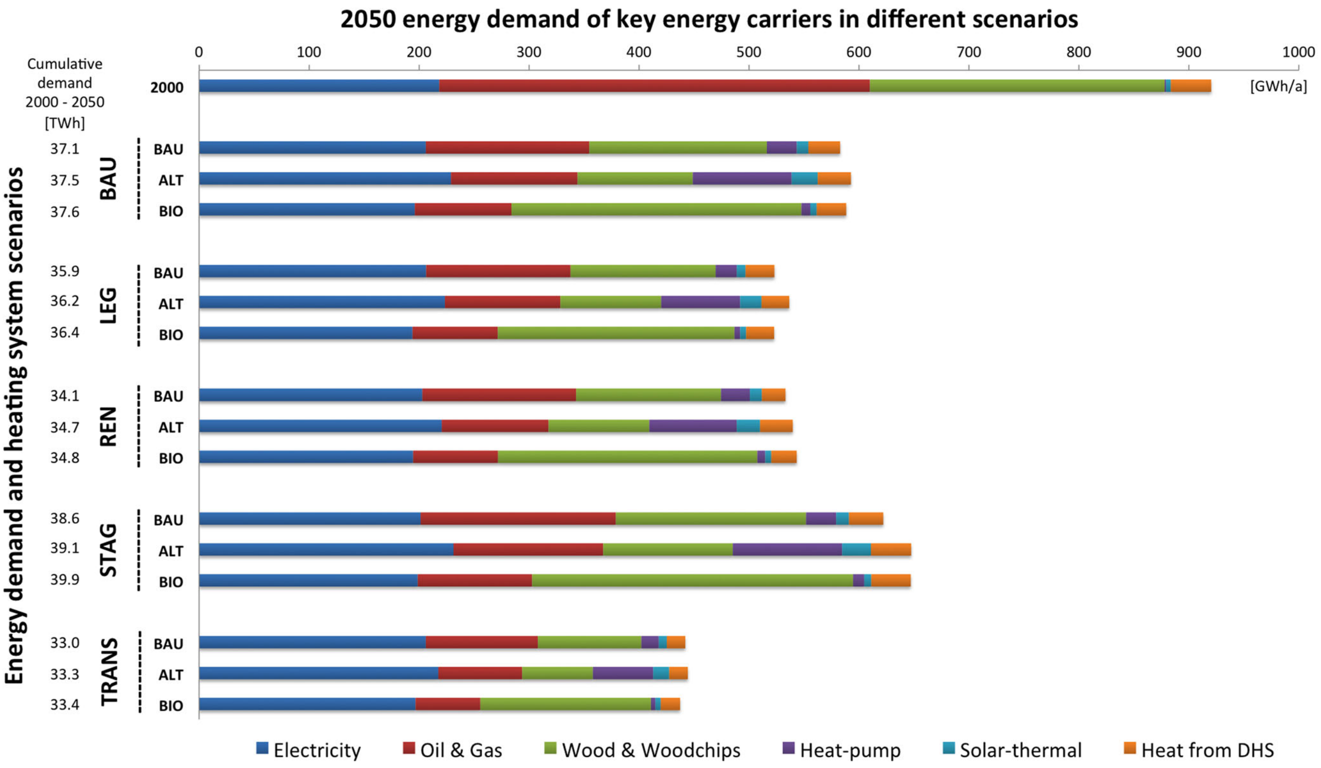

Fig. 2 2050 energy demand of key energy carriers in different scenarios and cumulative energy demand 2000–2050 (own investigation)

of heating systems), the energy demand from buildings in EWG will be around 590 GWh/a, which is a reduction of about 40 % compared to 2000. The choice of heating system (i. e. BAU, ALT, or BIO) has only a marginal effect (2 %) on the total energy demand from buildings. The cumulative energy demand from the year 2000 to 2050 will amount to about 37 TWh (Fig. 2).

Renovation rates vs. legislation standards: Key issues are the effects of increasing or decreasing envelope renovation rates (REN and STAG) versus tightening the legislative standards (LEG). The tightened legislation has the highest impact on the final energy demand in 2050, reducing the annual regional energy demand by 45 % (LEGxBAU) compared to 2000. Increasing the renovation rate by a factor of two leads to a similar reduction of 44 % in the final energy demand in 2050 (RENxBAU). However, if we consider the cumulative savings over 50 years, an increased renovation rate is almost three times more effective than the tightened standards. Compared to the BAUxBAU scenarios, the LEGxBAU scenarios would save about 1 TWh over the years, while the RENxBAU scenarios could save 3 TWh (Fig. 2). The role of the renovation rate is further illustrated in the stagnation scenarios (STAGxBAU): here, by 2050, a reduction in demand of 35 % compared to 2000 can still be achieved but, cumulatively, 1.5 TWh more would be consumed than in the BAUxBAU scenario. As a result, maintaining constant legislative standards might be more reasonable than having overly rigid standards at the expense of an eventually lower renovation rate. We should instead aim to increase renovation rates.

Combined legislative and renovation scenarios: Clearly the largest impact on both the annual energy demand in 2050 and the cumulative energy demand is shown in the transformation scenario (TRANS). In this scenario, a reduction of 53 % in the annual regional energy demand (TRANS) compared to 2000 and a cumulative reduction of 4 TWh can be achieved (Fig. 2).

4.1.2 Regional demand of energy carriers

Fig. 2 shows that in the year 2050 fossil fuels (i. e. oil and gas) have much less importance compared to their dominance in 2000 (i. e. 41 %). Independent of the heating scenario, we observe a reduction in fossil fuel consumption of 55 % in the STAGxBAU, and 85 % in the TRANSxBAU scenarios. Furthermore, there are only a few scenarios in which more energy from renewables will be needed in 2050 than that already produced in 2000. Whereas changes in the heating system have only a minor effect on the overall energy demand from buildings, they significantly affect the distribution of energy carriers. In the BAUxALT scenario, for example, heating energy gained from wood and woodchips would be 105 GWh/a in 2050; whereas, in the

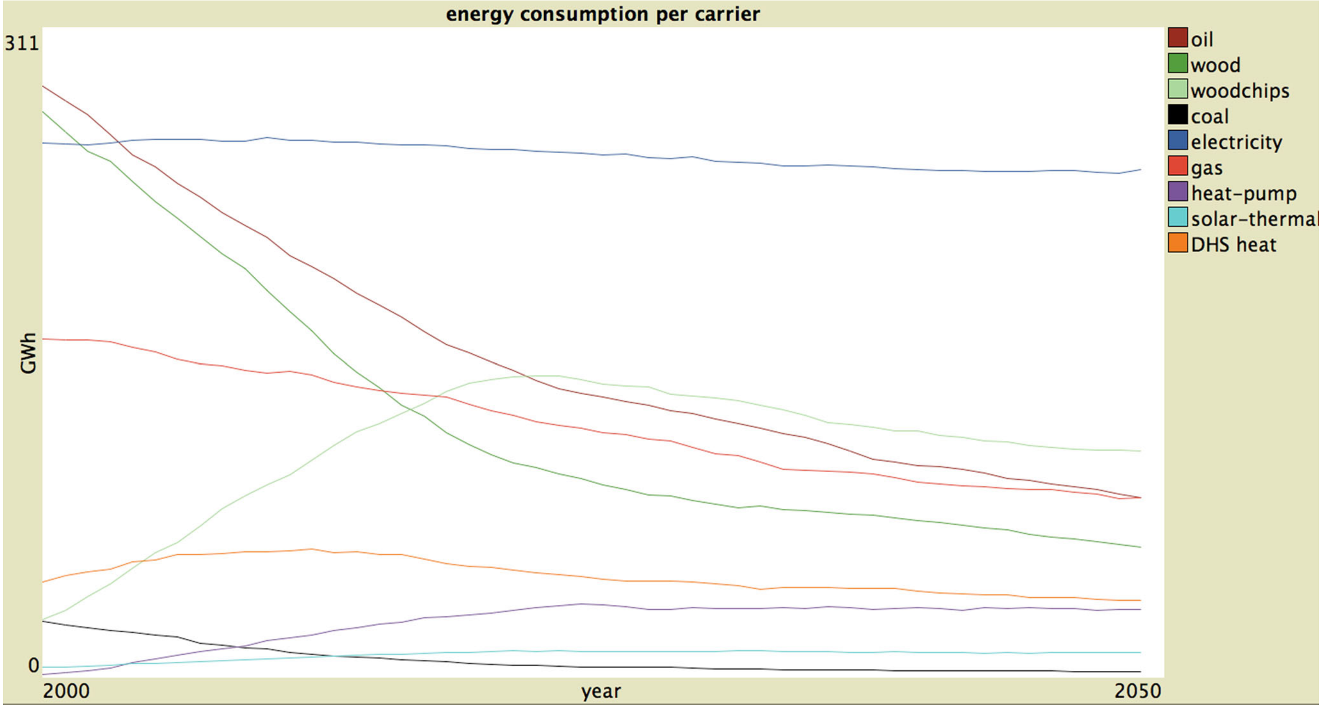

Fig. 3 Development of energy consumption per carrier in EWG in the BAUxBAU scenario (own investigation)

BAUxBIO scenario, the heating energy gained from wood and woodchips would amount to 264 GWh/a.

It is striking that even in the BAUxBAU scenario, where current envelope renovation rates, legislation standards and changes in heating systems stay constant over time, the overall energy demand will significantly decrease (by almost 50 %). However, complete self-sufficiency regarding the use of renewables in heating will not be possible in any of the scenarios. Even in the most energy-efficient scenario (TRANSxBIO), around 60 GWh/a (about 15 % of the amount in 2000) of the heating demand will still be covered by oil and gas. That is, to achieve complete independence from non-renewable energy sources for heating by the year 2050, the envelope renovation rate would have to be further increased. In addition, the preferences for new heating systems would have to favor wood and woodchips or solar-thermal and heat pump systems, and abandon fossil fuel systems.

Regarding overall energy demand, alternative heating (ALT) and biomass (BIO) scenarios show a tendency towards slightly higher energy demands than the BAU scenarios. Nevertheless, they do achieve a drastic reduction in fossil fuel heating systems. The biomass scenarios (BIO) show similar total demand levels to those seen in the BAU scenarios, but their reduction of fossil fuel based heating is higher than in the ALT scenarios.

Although electric main heating systems are no longer installed, electricity consumption only decreases slightly throughout the simulation, as electricity demand in the buildings stays the same. Thus, electricity will become the most important energy carrier in the region in most scenarios. The importance of electricity in the future is further demonstrated in the alternative heating scenarios (TRANS): even with tightened legislation and increased renovation rates, electricity demand is as high as in other scenarios (Fig. 2). Furthermore, in all alternative heating scenarios (ALT), electricity demand is higher due to the increased installation of heat pumps.

Fig. 3 illustrates the dynamics in the demand of energy carriers over time for the BAUxBAU scenario. We see that the initially dominant energy carriers (i. e. oil and wood) quickly drop and have much less importance in 2050 than in 2000. The heating systems based on woodchips, gas, heat pumps and solar-thermal systems initially see an increasing demand. However, their overall demand starts to decrease in about 2025 when regional energy heating demand decreases, as more and more buildings are retrofitted (see also Schubert 2016 this issue). This has significant implications for the design of new heating infrastructure. The infrastructure should be flexible enough to adapt to first an increasing and then a decreasing demand for energy.

4.2 Regional potential for supply of renewable energy

Fig. 4 illustrates the potential of renewable energy in EWG including the heat potential of renewable energy carriers (i. e. wood and solar-thermal), renewable heat potential for DHS (i. e. wood and energy/diverse crops), and renew-

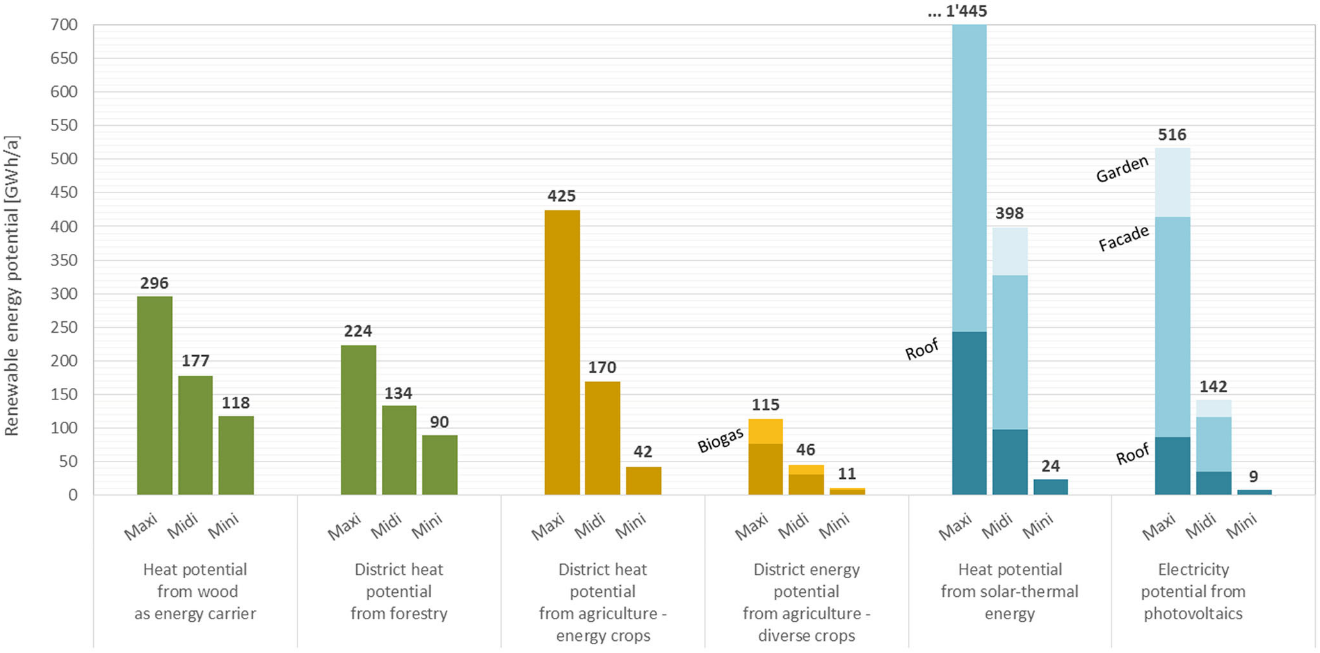

Fig. 4 Potential regional energy supply of renewable energy in EWG in different scenarios (own investigation)

able electricity potential (i. e. PV) for each scenario (Maxi, Midi, Mini). Results show that the technical heat potential from wood as an energy carrier accounts for 296 GWh/a (Maxi) and decreases to 118 GWh/a if only 40 % of the forest area is used (Mini). In the case where biomass resources from forestry are used for heat generation in large-scale energy plants, the numbers decrease to 224 GWh/a in the Maxi and 90 GWh/a in the Mini scenario, as the energy conversion takes place outside buildings and is delivered through a DHS.

For biomass gained from agriculture, only large-scale energy generation is feasible. The DHS potential from energy crops (425 GWh/a in the Maxi to 42 GWh/a in the Mini scenario) is higher than the potential from forestry, but far lower if the energy is generated based on the crops most commonly cultivated in the region (115 GWh/a in the Maxi to 11 GWh/a in the Mini scenario). In fact, the district heat potential of the most common crops cultivated in the region is about 70 % lower than for energy crops. This implies that if biomass produced on agricultural areas is to be used for energy purposes, production should shift towards energy crops.

Besides the regional supply potential from forestry and agriculture, Fig. 4 illustrates the solar energy potential. The heat potential from solar-thermal energy accounts for 1,445 GWh/a in the Maxi scenario, where the total suitable roof, façade, and garden area is used for energy generation. This potential shrinks dramatically to 24 GWh/a in the Mini scenario where only 10 % of the suitable roof area is used. If the total suitable area is used to apply PV cells the electricity potential drops from 516 GWh/a in the Maxi to 9 GWh/a in the Mini scenario. In the Maxi and Midi scenario of both cases (solar-thermal and PV), the highest share for generating solar energy can be attributed to the façade of buildings (Maxi 64 % and Midi 58 %), followed by the roof areas (17 % and 25 %), and the garden areas (20 % and 18 %) (for details see EA, Tab. E9, E10 and E11).

4.3 Aligning future energy demand and the supply potential of renewable energies

Having outlined the energy demand from buildings and potential supply of renewable energies in the region, we now compare the two and analyze how much of the future energy demand could be covered with regional renewables. Tab. 4 shows the regional demand for renewable energy carriers for 2050 (i. e. wood and woodchips, and solar-thermal), the demand for heat from DHS, and the electricity demand from buildings compared to their corresponding supply potentials. As a first step, we compare potential renewable energy supply from forests to demand for wood and woodchips; solar-thermal potential to its own demand; PV potential to electricity demand; and the agriculture biomass potential to heat demand from DHS.

As shown in Fig. 2 and EA, Tab. E14, for all scenarios, except the STAG scenarios, the final demand for renewables in 2050 can easily be covered with the renewable energies already supplied in the year 2000. Tab. 4, however, indicates that this does not necessarily correspond to

Tab. 4 Potential regional supply (Mini, Midi, and Maxi) compared to the regional energy demand in 2050 for renewable energy in different scenarios (see EA, Tab. E14 for details)

	Demand scenarios									**Potential supply**		
Demand scenarios	**BAU**			**STAG**			**TRANS**			**Mini**	**Midi**	**Maxi**
Heating systems scenarios	**BAU**	**ALT**	**BIO**	**BAU**	**ALT**	**BIO**	**BAU**	**ALT**	**BIO**			
Wood & Woodchips (2050) [GWh/a][a]	161	105	264	173	118	292	94	64	155	118	177	296
Solar-thermal (2050) [GWh/a][b]	11	24	6	12	26	6	7	15	5	24	398	1445
Heat from DHS (2050) [GWh/a][c]	29	30	27	32	37	36	17	17	18	42 (11)	170 (46)	425 (114)
Electricity (2050) [GWh/a][d]	206	229	196	201	231	199	206	218	197	9	142	516

[a] Supply potential from forest
[b] Supply potential from solar-thermal energy
[c] District heat potential from agriculture (diverse crops in parenthesis)
[d] Electricity potential from photovoltaics

the regional supply potential. This becomes clear when analyzing the regional wood supply: for most of the BAU and BIO heating system scenarios modeled, the wood and woodchips produced regionally in the Mini scenario would not be sufficient to cover the total demand in 2050. The Midi or even the Maxi supply would be required to cover the demand in 2050 with regional supply. For the Maxi supply, then, the whole forest area would have to be used for producing wood and woodchips for energy production. In the EWG, however, currently only about 34 % of the forest area is cultivated for energetic purposes. Increasing this area would result in conflicts with other uses, e. g. saw wood using 50 % of the products from the forest, or industrial timber using 16 % of the forest products (BMLFUW 2012).

The potential supply of agricultural biomass from energy crops in the Mini scenario would be sufficient to cover the demand for heat from DHS in all energy demand scenarios. However, in EWG currently not even 1 % of the total agricultural area is cultivated with energy crops, while 5–10 % would be necessary to meet the demand for heat from DHS (Statistics Austria 2010b). It should be evaluated, though, to what extent marginal lands could be allocated for producing energy crops. If the most common crops cultivated in the region were used for energy generation, the demand for heat from DHS would be more difficult to supply and would lead to significant land use conflicts regarding food versus energy production. Another aspect in this context is that in the EWG, currently the heat demand from DHS is mainly supplied by biomass from forestry; this in turn diminishes the calculated wood and woodchips potential for central and room heating systems (by about 30 GWh).

The final demand for solar-thermal in 2050, though, could be covered with the Mini supply for almost all scenarios. As mentioned above, however, electricity will become the dominant energy carrier in 2050, and can hardly be supplied regionally with PV considering the current implementation rates. Far more suitable roof, façade, and garden areas than those calculated in the Midi supply would be required for PV electricity generation (which competes with the area used for solar-thermal installations). This will be difficult to achieve, although the province of Styria (Weiz-Gleisdorf) is the leading province in Austria regarding PV installation. In Styria about 3.3 % of all buildings were equipped with PV in 2012; of these, 85 % of the newly installed PV plants are installed on roof areas, 15 % are ground installations, and only 0.2 % of the newly installed PV plants are façade-integrated (Biermayr/Eberl/Ehrig et al. 2013). Thus, a good option for policy-makers might be to combine PV and solar-thermal installations. It would further be beneficial to consider supporting research and development on PV façade technologies, and to provide subsidies for the implementation of PV on façades.

5 Conclusions and outlook

This paper presents an approach for: (i) analyzing the development of the demand for renewable energies in buildings taking into consideration envelope renovation rates, legislative standards and preferences in the heating systems; and (ii) relating demand to the potential regional supply, taking into account potential land use conflicts. In the following section, we conclude with our key results, present policy implications, and address the need for further research.

In the year 2050 the energy demand from buildings will decrease by 40–55 % depending on the envelope renovation rate and legislative scenario chosen. In all scenarios, the transition phase presents an increasing demand for specific energy carriers before envelope renovation and legislation affect and reduce the overall demand. Consequently, when planning energy supply from renewables, it is important to take into account that the demand for all energy carriers, except electricity, decreases over time. This suggests that we should aim for and foster flexible energy infrastructures.

The final demand of energy for heating per year is lower if legislation is tightened than if the envelope renovation rate is doubled. However, if cumulative energy savings are considered, doubling the renovation rate would save three times more energy (about 3 TWh, compared to the business as usual scenario) by 2050 than strengthened legislation for envelope renovations would do (about 1 TWh). Policymakers should consider this fact when designing their policies.

Although the choice of heating system technology has a very small effect on overall energy demand from buildings, it determines the demand for renewable energy carriers. We found that regionally available energy sources have to be further developed in order to supply the regional energy demand from buildings. In doing so, three issues have to be considered. First, a balance between fostering alternative and wood-based biomass heating systems is necessary, as the demand for wood for regional energy competes with the demand for wood for construction. Second, 5–10 % of agricultural areas should be used to produce energy crops in order to supply DHS with biomass. Third, to produce a sufficient amount of electricity, PV should be subsidized not only for roofs, but also for façades and freestanding installations.

Further research should focus on three issues. The first concerns spatially explicit analyses: How can conflicts at a land-use level (i. e. marginal areas, food, energy production,) be aligned and optimized? In exploring this question, it is important to consider that the demand from buildings accounts for only 35 % of total energy demand. If the other 65 % of energy demand has to be covered through renewable energy carriers, land-use conflicts are likely to increase. Second, what is the relationship between the distribution of future energy carriers under different scenarios and the net environmental benefits? Third, what are the parameters that influence the decision on when to renovate, how energy efficient the renovation should be, and which heating system to choose? It should further be investigated whether increasing standards for envelope renovation could lead to a decrease in the renovation rate. This information would allow new types of bundled policy measures to be designed.

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