2000-Watt Switzerland: Modelling spatial impacts of energy consumption

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Modelling spatial impacts of energy consumption

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Cover page: Visualisation of energy use based on FaLC output, by author.

Abstract

An increasing level of wealth and economic production is recognised to have an impact on resource depletion, greenhouse gas emissions or energy use. Several reduction targets have been introduced in Switzerland to mitigate negative effects of future development, one being the 2000-Watt Society ("2000-Watt-Gesellschaft", 2000WS). It is known that meeting these goals can only be achieved through a stringent set of reduction measures. However, the consequences on our spatial environments of pursuing such reduction measures have largely remained unexplored.

The principal goal of this master thesis is modelling and describing the spatial effects of energy reduction measures, which would help meet the 2000WS targets. A method allowing for energy estimation from spatial data was developed and a set of scenarios devised to test economic, regulatory and behavioural components of energy reduction measures. Household space heating and commuting energy demand were chosen as energy use estimators, due to their large share in total Swiss energy use and their manifold long-term spatial implications.

An agent-based, land-use transport interaction model was used in the form of the Facility Location Choice Simulation Tool (FaLC). This tool allows for the simulation within Switzerland on the level of 2949 National Passenger Traffic Model zones and the time span 2015-2040 was chosen for the model runs.

The scenario implementations could not be fully assessed due to an unintended decline in the modelled population. The energy estimation method however, delivers plausible results for the correctly calibrated start year. A reduction in population can bring about a reduction in space heating demand, but may have reciprocal effects on commuting energy with an increase in trip relations. Although rural municipalities have a higher per capita energy consumption, metropolitan regions are the dominant consumers of energy in the household sector.

The key conclusion reached is that no single reduction measure can achieve a significant reduction to reach 2000WS goals. The most substantial impacts can be reached by focusing on measures, which target cities and their agglomerations in Switzerland. Furthermore mobility and settlement development have to be a coordinated effort, so as not to counteract each other in the final outcome.

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List of abbreviations

2000WS – 2000-Watt Society

ARE – Federal Office for Spatial Development (“Bundesamt für Raumentwicklung”)

CHF – Swiss franc

CO_2 – Carbon dioxide

E – Energy

E.g. – for example (“exempli gratia”)

EnG – Energy Bill (“Energiegesetz”)

ETH – Swiss Federal Institute of Technology Zürich

FaLC – Facility Location Choice Simulation Tool

GDP – Gross Domestic Product

GHG – Greenhouse gas

GWh – Gigawatt-hour

GWS – Building and dwelling register (“Gebäude- und Wohnungsstatistik”)

IVT – Institute for Transport Planning and Systems

J – Joule, unit of energy

kWh – Kilowatt-hour

MZMV – Mobility and Transport Microcensus (“Mikrozensus Mobilität und Verkehr”)

NPVM – National Passenger Traffic Model (“Nationales Personenverkehrsmodell”)

Pkm – person-kilometre

SIA – Association of Swiss Engineers and Architects (“Schweizerischer Ingenieur- und Architektenverein”)

TWh – Terrawatt-hour

W – Watt, unit of power

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1 Introduction

1.1 2000-Watt Society: an overview

Generating economic growth and ever-improving standards of living are often associated with environmental impacts, such as increased energy consumption (mostly in the form of fossil fuels) as well as an increase in CO_2 emissions (Notter 2013). In order to mitigate such impacts and be able to assess the differences between industrialised and developing nations (Figure 1), the concept of the "2000-Watt Society" was presented in 1998 by a group of researchers at the ETH Zürich (Novatlantis 2005).

The main goal of the 2000-Watt Society (2000WS) is a sustainable use of resources and energy, motivated in part to secure a fair distribution of resources on a global scale (Novatlantis 2005). Additionally it aims to limit CO_2 production at a level where the effects of global warming can be kept below an average temperature increase of 2°C (Fachstelle 2000-Watt-Gesellschaft 2017). Consequently, the 2000WS concept stipulates a reduction of primary energy consumption to an average total value of 2000 Watts per person and a total yearly production of 1 tonne of CO_2 per person by the year 2100 (Table 1).

Most fundamentally, the 2000WS is a framework, which defines clear end-goals with only a handful of intermediary goals. The broad and non-prescriptive nature of the 2000WS provides enough flexibility to

Figure 1: Global power and energy consumption (Novatlantis 2005, own formatting of colours for legibility).

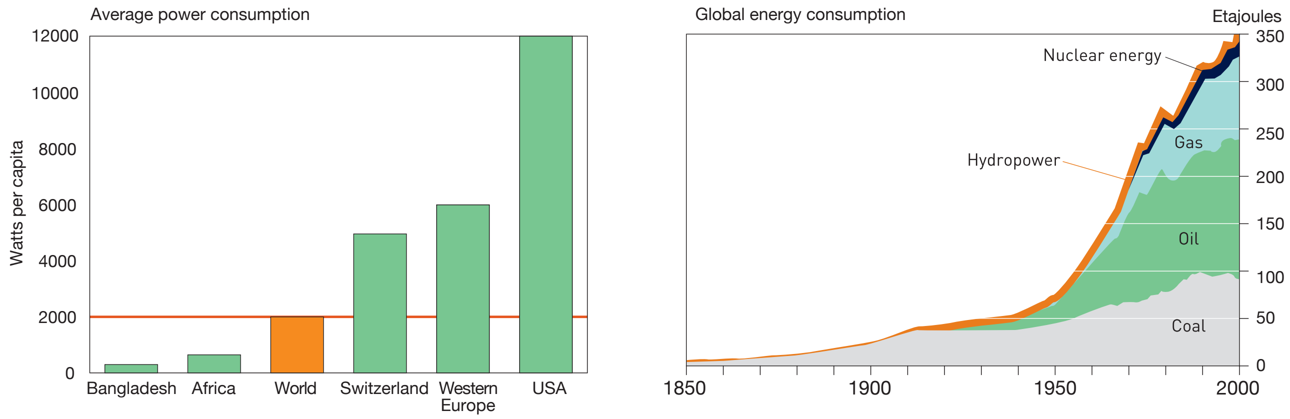


Table 1: Reduction goals 2000WS (Fachstelle 2000-Watt-Gesellschaft 2014, own translation and formatting).

Year	2005	2050	2100	**Reduction factors by 2050**
Average total power consumption [Watt/person]	6300	3500	2000	**1.8**
Yearly total CO_2 emissions [tonnes/person]	8.6	2.0	1.0	**4.3**

impact a wide range of institutions, industries and individuals.

In implementing the 2000-Watt goals, the two focal tenants are defined as efficiency and sufficiency. Efficiency is defined as a reduction of resource and energy consumption in current processes, as well as transfer to renewable sources of energy in place of non-renewables. Sufficiency on the other hand, pertains to choices taken towards a frugal way of life and economic development. These two concepts align with (and represent) the scope of choices available for top-down, as well as bottom-up processes. Whereas governmental institutions can set forth new emission standards or industries develop more efficient production processes; individuals can choose to consume or travel less. It is explicitly understood and stated that in achieving the 2000-Watt goals, both tenants have to be considered (Fachstelle 2000-Watt-Gesellschaft 2014: 28).

These principles are carried forward in the most concrete implementation concept of the 2000WS, the “Bilanzierungskonzept 2000-Watt-Gesellschaft” (Fachstelle 2000-Watt-Gesellschaft 2014). This document is meant to act as an aid in establishing energy reduction goals, as well as a method to assess and monitor whether developments or policies are compatible with the 2000WS. The “Bilanzierungskonzept” explains and defines the overall goals, from which the total reduction on a national level is derived (see Table 1). These reduction factors can be used on a cantonal (or municipal) level to derive more relative goals for the different territories of Switzerland. This approach is meant to help in setting absolute targets, which would reflect the present energy consumption within Switzerland. Municipalities which consume more energy (such as urbanised areas), would reduce their consumption in greater total amounts, but in many cases remaining above the national average. These national level goals would still be achieved, through an averaging out (or balancing out) with areas consuming less energy (below the national average consumption) (Fachstelle 2000-Watt-Gesellschaft 2014).

The “Bilanzierungskonzept” further suggest that measures can be assessed at any level: on that of urban developments (“Arealentwicklungen”), buildings, as well as on an household (or person) level. The concept even suggests that through answering a series of consumption related questions, individuals are able to quantify their energy consumption and therfore their 2000WS compatibility and personal reduction goals (Fachstelle 2000-Watt-Gesellschaft 2014: 16).

1.2 Fundamental definitions of energy consumption

Within the context of this research, energy can be defined as a property associated with an energy source or carrier. Primary energy is defined as a raw state of an energy source, which has not undergone any transformation, current examples being: crude oil, coal, uranium, solar or wind energy. Only a small proportion of current energy consumption is satisfied by primary energy sources directly, which dictates the requirement for transformation processes (BFE 2017a: 6).

In its generation, transformation and delivery, an energy source undergoes various losses (due to inefficiencies inherent to multiple processes). Therefore, the final energy consumption is defined by the energy delivered to and required by the end users. These transformation processes, as well as the delivery to end-customers, are the defining tasks of the so-called energy industry (BFE 2017a: 6, 9). Since this thesis project studies energy consumption (as opposed to energy production), the values used herein pertain to final energy use, unless otherwise stated.

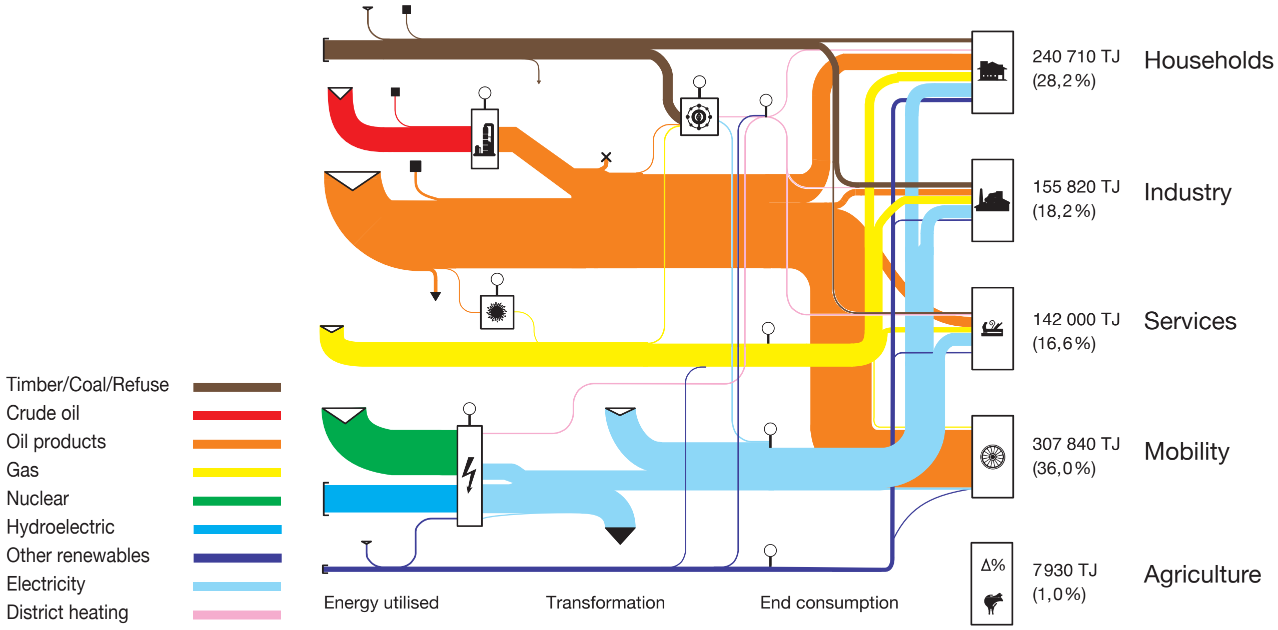
Energy as a physical quantity of work is measured in Joules (J), whereas the rate of work (power) is measured in Watts (W or Joules per second). An associated measure used in energy estimation is the kilowatt-hour (kWh) (Prognos 2012: LVII). The following conversion factors and decimal prefixes used in this thesis are summarised as follows:

1 J = 1 Ws	Giga (G) = 10^6
1 J = 2.78 * 10^7 kWh	Mega (M) = 10^9
1 kWh = 3.6 MJ	Terra (M) = 10^{12}
1 TWh = 3.6 PJ	Peta (P) = 10^{15}

1.3 Current Swiss energy consumption

The current energy consumption in Switzerland is dominated by the mobility and household sectors (Figure 2).

Figure 2: Swiss energy flow diagram (Gesamtenergiestatistik 2016, Bundesamt für Energie 2017, own translation and formatting of text and legend for legibility).



Together, they make up almost two thirds of all energy consumption (64.2%). The mobility sector (36.0%) is heavily reliant on oil and crude oil products, while the household sector (28.2%) is adapted to use a wider range of primary and final energy sources (BFE 2017a).

In the years 2000 to 2015 there has been a marginal decrease in household consumption and a marginal increase in the mobility sector (Table 2). The most recent trends in the Swiss energy market can be characterised by an overall increase in end-consumers (defined in terms of population, as well as housing floor area or number of vehicles). Coupled with increasing efficiency in transformation and end use, the national consumption was able to remain on a stable level. The most change has been experienced in agriculture (-14.7%) and industry (-3.7%), driven mostly by an overall decrease in actual production output within these sectors inside of Switzerland (Prognos 2016a).

Table 2: Change in energy consumption by sector 2000-2015 in PJ (Prognos 2015, Schweizerische Gesamtenergiestatistik 2015, BFE 2015, own translation and formatting).

Sector	**2000**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**Δ '00 – '15**
Households	236.3	264.9	225.7	244.3	258.9	218.9	232.4	-1.6%
Industry	160.7	168.6	162.3	163.2	164.5	157.0	154.7	-3.7%
Services	137.6	151.9	135.5	143.5	149.8	130.8	138.2	0.4%
Mobility	303.3	308.4	309.6	313.0	312.7	311.7	305.3	0.7%
statistical diff. (incl. Agriculture)	9.2	8.9	9.4	9.3	9.0	7.4	7.8	-14.7%
Total consumption	**847.0**	**902.7**	**842.5**	**873.3**	**895.0**	**825.8**	**838.4**	**-1.0%**

1.4 Swiss energy planning frameworks

1.4.1 Federal legislation – Energy Strategy 2050

The federal energy legislation has undergone substantial shifts in the last decade, culminating in the Swiss population voting to accept the revised Energy Bill (EnG) on 21. May 2017. The new EnG can be considered part of the Energy Strategy 2050 ("Energiestrategie 2050"), set forward to replace the previous Energy Strategy 2007 in wake of the Fukushima disaster (BFE 2017b). The EnG is a response to Switzerland's shift away from nuclear power and defines its primary goals as increasing efficiency in energy consumption and a trend towards renewable resources (Federal Council 2013, Federal Assembly 2016). Energy consumption is thus dictated a reduction of 16% until the year 2020, 43% by 2035 and 54% by 2050 (measured in relation to the consumption in 2000). This represents a total energy consumption of 125 TWh by 2050. Interesting to note is that the reduction set forth by the EnG is close to the factor of 1.8 (56%) defined by the 2000WS (compare Table 1). Furthermore, the mandatory power output through hydroelectricity and from renewable energy sources is also defined (Appendix A1), to form viable substitutes to the future reduction of nuclear power (Federal Assembly 2016).

The EnG also defines the responsibility on a federal level to decide on and control the standards for products (such as consumer appliances or cars). The requirements for buildings are left in the responsibility of cantons, whereas businesses and industry lies in both federal and cantonal authority. Measures for implementing and supporting renewable energy production are also described. These measures fall into categories of information, education, research and development, with accompanying rules regarding the financing of such measures. Regular investments in the energy production infrastructure are also supported, with hydroelectric and renewable energy sources being financed nationally up to 40-60% of their investment costs (Federal Assembly 2016).

1.4.2 Federal legislation – CO_2-Bill

Another major pillar of Swiss energy policy, is the bill on reducing CO_2-emissions (CO_2-Bill or "CO_2-Gesetz"). The CO_2-Bill is a set of laws put in place in order to reduce greenhouse gas emissions below a level that would mitigate the effects of global warming below 2°C (Federal Assembly 2012a). Even though no direct reference is established, the goals of the CO_2-Bill nevertheless match those of the 2000WS (see Section 1.1).

The major reduction goal defined by the CO_2-Bill is a reduction of GHG emissions by 20% until 2020 (measured in relation emission levels in 1990). Reduction measures in the building sector are defined to be the responsibility of the cantons, but 300 million CHF are allocated yearly by the federal government for their implementation. One concrete regulation in the mobility sector limits the emission levels of all production cars to a level below 130g CO_2/km (Federal Assembly 2012a).

The CO_2-Bill also introduces a legal framework for a CO_2 emissions trading scheme, stating that enterprises with medium to high emission levels can participate in such a trading scheme. The bill further leaves the option of mandatory participation for certain types of enterprises (but does not specifically define these enterprise types) and defines fines for failure to obtain sufficient trading certificates (Federal Assembly 2012a). However, the actual implementation of the emissions trading scheme is defined by the CO_2-Regulation ("CO_2-Verordnung"), with annual updates concerning the trading volume or which enterprises are required to participate (Federal Assembly 2012b).

1.4.3 Local regulations and policies

Despite not being legally binding and without presenting definite implementation strategies, the principles of the 2000WS have been adopted (directly or in congruence) by all cantons as part of their energy strategy and policy development (Fachstelle 2000-Watt-Gesellschaft 2018a). Such policy development is furthermore in accordance with the regulations set forth by the EnG, which requires the cantons to secure renewable energy interests in their strategic development plans ("Kantonale Richtplanung") (Federal Assembly 2016: Art. 10).

1.4.4 Building standards

Since almost half of the total energy consumption can be attributed to the construction, maintenance and use of buildings, the Association of Swiss Architects and Engineers (SIA) has published standards of practice ("Merkblatt SIA-Effizienzpfad Energie"). These standards of practice are meant to help achieve energy consumption and GHG emissions reduction goals congruent with those of the 2000WS. The guidelines and calculation tools consider the whole building lifecycle, as well as location dependent consumption values due to mobility. Furthermore, the guidelines are set up in a manner, which allows their application during all early design phases, construction or renovation (SIA 2017). However, these building standards are not mandatory and are yet to be adopted by the building industry as a whole (Fachstelle 2000-Watt-Gesellschaft 2018b).

Perhaps a more widely adopted set of building standards, are the Minergie certifications. A range of different certifications are in place to drive the energy efficiency of buildings and reduce the environmental impact of construction, in a similar manner to the SIA guidelines. By the year 2016, just over 40'000 buildings have been constructed or renovated according to Minergie standards (Verein Minergie 2017). Although the rate of adoption has been increasing since its inception in 1998, with over 1.7 million residential buildings in Switzerland (BFS 2017a) the Minergie projects represent only a fraction of the total building stock.

1.5 Future energy perspectives

A comprehensive study on the future development of energy consumption was published in order to aid in policy decisions such as the EnG or the CO_2-Bill. The study entitled "Die Energieperspektiven für die Schweiz bis 2050" (Prognos 2012) is comprised of three scenarios: Status Quo ("Weiter wie bisher"), New Energy Policy ("Neue Energiepolitik") and Political Measures ("Politische Massnahmen"). These scenarios represent a wide range of possible outcomes and are modelled bottom-up from a set of key indicators in all areas covering the national energy consumption (households, industry, mobility, services and agriculture, energy supply) (Prognos 2012).

To illustrate the used estimation methodology further, the average energy consumption for housing is derived from the total floor area and the measured energy supplied to households. This value is then modelled in a future projection with a number of assumptions determining the development of energy consumed (e.g. technical efficiency, changes in floor area per person, substitution rate of housing stock, etc.). The scenario Status Quo assumes the continuation of current drivers and standards (such as the "Klimarappen" on fuel). The second scenario New Energy Policy is defined by an assumption of increasing technological efficiency (especially in the area of building standards and technical installations). The scenario Political Measures assumes a more proactive engagement in measures and policies towards lowering energy consumption (by increasing incentives and regulatory measures) (Prognos 2012).

The evaluated models found that only the scenario Political Measures would achieve a per capita energy reduction on the level of -53% (see Figure 3), representing the a reduction factor of 1.8 required for the

2000WS goal in 2050 (Prognos 2012). The modelling process of this study allows to measure the impact of each policy instrument on the whole consumption, therefore producing a set of measures and targets which can ascribed to potentially achieving the 2000WS goals. The comprehensive nature of the study effectively provides one with an answer as to whether it is possible and in which way a 2000WS can be reached in Switzerland.

1.6 Spatial development and energy consumption

Considering energy consumption from the perspective of spatial development, it cannot be overlooked that mobility and households (the two largest consumers of energy) are connected in a complex relationship to each other (Figure 4). There are numerous examples of new transport infrastructure measures generating a local population increase and vice versa; locations with dense settlement structures manifest a wide range of transport services (ARE 2013).

There are many steps in this feedback process, ranging in scale from individual mobility or relocation decisions, to decisions undertaken by investors in developing a certain location. Consequently there is a temporal variation with steps ranging from short to mid-term in their effects (ARE 2013). Considered as a whole however, mobility and households constitute a significant, long-term spatial determinant of energy consumption.

Figure 3: Scenario comparison from "Energieperspektiven für die Schweiz bis 2050" (Prognos 2012, own translation and formating for legibility).

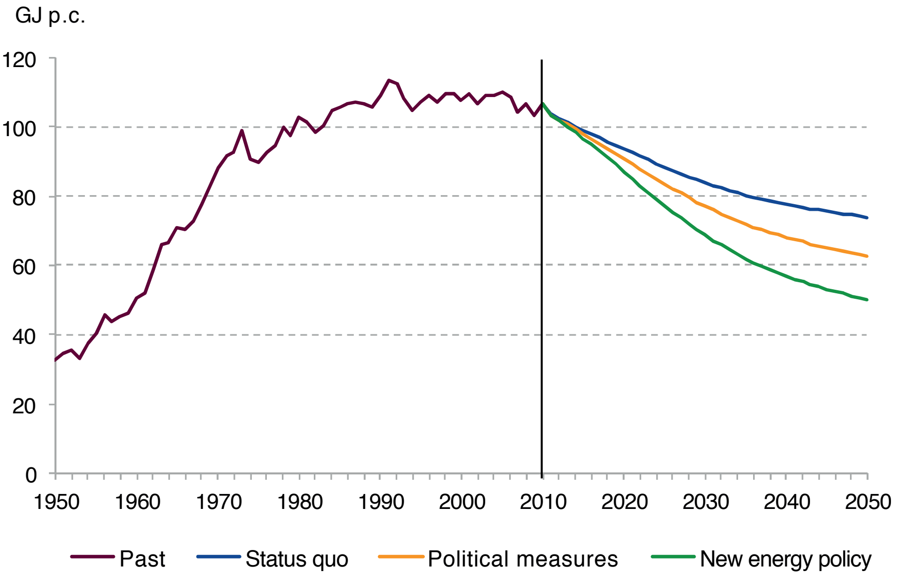
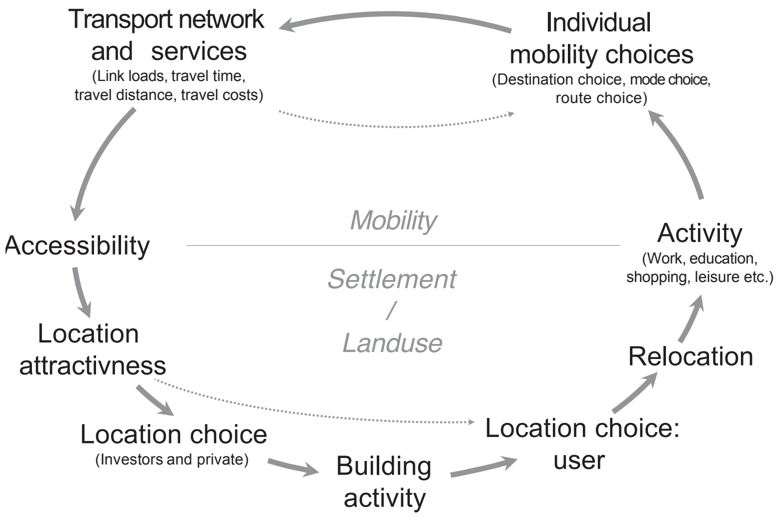


Figure 4: Feedback process between land-use and mobility (Wegener & Fürst in ARE 2013, own translation).



Most research on Swiss energy consumption approached the subject from either an energy accounting or market economy standpoint (BFE 2015). However two recent projects in particular studied the spatial components of energy consumption and which contributions can be made by spatial planning in reducing energy use.

The first reduction measure suggested, recommends applying more compact building forms, for example by encouraging the construction of multi-family dwelling (as opposed to single family homes). Secondly, increasing the permitted building zone densities would also bring about a reduction in energy use (Hollenstein 2012). Moving the focus to mobility, a polycentric settlement structure could lead to a decrease in average travel distances. Another measure put forward is the densification and concentration of settlement development around railway stations (Von Moos 2015).

Both studies conclude that no single measure can bring about a reduction of energy use sufficient to reach 2000WS goals. In order to make a significant contribution from a spatial perspective, various approaches need to be pursued in coordination with each other. Potential measures could be implemented in the form of top-down instruments (e.g. spatial regulation, economic measures) or bottom-up effects (e.g. behavioural or socio-demographic changes) (Hollenstein 2012).

2 Research goals

The required reduction in resources, consumption and emissions to achieve the 2000-Watt Society (2000WS) goals are substantial. Despite the long-term time frame for reaching those goals, it remains uncertain at best, whether they can be achieved. Even with an understanding of how a certain measure can contribute to the 2000WS, there is no clear vision of how a complete reduction in energy consumption will shape our environment.

Comprehensive research undertaken as part of the Energy Strategy 2050 has found however, that continuing with current standards of life (and including currently planed future policy measures aimed at energy reduction) will not be enough to reach 2000WS goals (Prognos 2012). In light of the current energy use context, the following research goals have been defined and pursued as part of this thesis project.

I. Model interactions between long term location choice, mobility and energy use

Although measures to reduce energy consumption have been developed by various research fields, their actual spatial consequences remain largely unstudied. Location decisions are long-term determinants of mobility and vice versa, forming complex systems (Section 1.6). Therefore understanding the effects of energy consumption on our future spatial development requires a model able to capture the interaction between location choice, mobility and the drivers of household energy consumption.

II. Derive estimation methods for household energy consumption and mobility from spatial data

Numerous studies on energy consumption have been carried out, varying in the researched aspects, temporal and spatial scales. Furthermore, each study uses a different estimation methodology and there is no single established method (BFE 2015). Accordingly for this research project, an energy estimation method needs to be developed, appropriate for the chosen modelling approach and further research goals.

III. Visualise and compare the spatial consequences in energy consumption

Complementary to the two previous goals is the need to evaluate and compare spatial effects and interactions of energy consumption. A recent research project has demonstrated the possibilities and importance of displaying spatial components of energy use in Switzerland (Schneider 2017). However, the interactions between spatial determinants (e.g. location typologies) has been explored to a lesser degree. Visualising energy consumption and spatial characteristics in tandem, is therefore an important goal in understanding future development possibilities.

IV. Simulate how energy consumption can be influenced by economic, regulatory and behavioural aspects

A set of appropriately constructed scenarios for energy reduction measures forms a crucial part of this thesis project, firstly aiding to verify the energy estimation methods (Goal II). Furthermore, meaningful ways for analysing and comparing wide-ranging spatial data (Goal III) can be devised in light of contrasting scenario measures. The aforementioned interaction between spatial development and energy use (Goal I) can be better understood and explored. Finally, the effects of the scenarios can be evaluated and recommendations for spatial reduction measures formulated.

3 Method

3.1 FaLC

The principal tool used to model the spatial effects of energy consumption is the Facility Location Choice Simulation Tool (FaLC) – an agent-based, land-use and transport interaction modelling tool. The development of FaLC was initiated in 2012 by regioConcept and the Institute for Transport Planning and Systems (IVT) at the ETH. In its current state, FaLC offers the possibility to simulate a synthetic population of Switzerland, with over 8 million agents on the level of 2949 National Passenger Traffic Model (NPVM) zones (Appendix A2)(Bodenmann 2013).

In its simulation workflow, FaLC uses a set of input and attribute tables (see Appendix A3), to firstly generate agents and then populate each zone. An agent is assigned a household and may belong to business (as an employee or an owner). Each simulation run goes through yearly cycles, in which a sequence of calculation steps (modules) determines changes in population at the end of each cycle (e.g. whether new households are formed, agents change their place of employment or businesses are closed). These modules comprise a mixture of probabilistic and discrete choice models. The discrete choice models determine mostly the relocation of households and business location choices (Appendix A4)(ARE 2017).

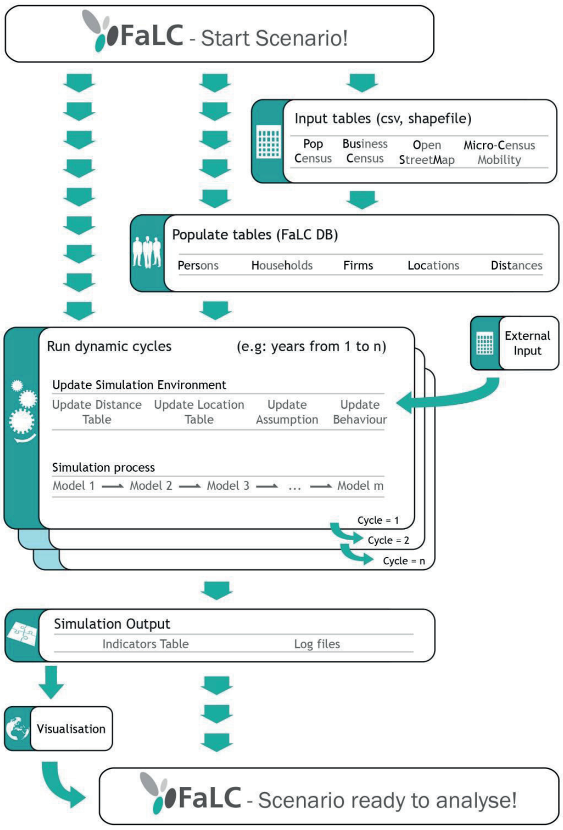
A completed simulation run generates a series of demographic, commuting and spatial indicators, which can be used for further analysis, comparison and visualisation. This way, a range of summary statistics and maps can be created for each simulation run.

3.2 Energy estimation from spatial data

3.2.1 Overview of modelling techniques

Since FaLC does not produce energy indicators, the actual household energy consumption has to be

Figure 5: FaLC simulation workflow (Bodenmann 2016).



modelled using existing FaLC outputs. A number of estimation approaches are used for household energy consumption, which can be classified into two principal groups. The choice between these two approaches is determined by the data used, as well as the type of effects to be represented (Swan 2008).

The first group of top-down (or econometric) approaches, use values of total energy consumption of a group (for example the household sector), which is represented by a number of attributes (macroeconomic indicators such as GDP or number of appliances sold). The top-down approach relies on aggregated historical data and its simplicity in application is counterbalanced by a loss of more complex consumption interactions (Swan 2008).

Bottom-up (or property based) models, extrapolate the characteristics of a selection within a group (such as individual houses), as a way to represent a sector as a whole. This group of models typically uses physical attributes (building shape, heating method, built year). Bottom-up models either infer relationships through statistical methods (e.g. regression models) or engineering methods, which measure the actual power ratings or thermodynamic relationships within buildings. A particular advantage of this approach is the possibility of modelling technological or environmental changes, but it requires an appropriate extrapolation methodology to represent a sector as a whole (Swan 2008).

3.2.2 Household energy consumption estimation

A bottom-up modelling approach was chosen, as FaLC is based on individual agents and produces spatial output data (as opposed aggregated macroeconomic data). The modelling workflow is based on a methodology used by the canton of Luzern, which uses the cantonal building and dwelling register ("Kantonale GWS") to estimate household energy consumption (UWE 2013, UWE 2015). An overview of the estimation workflow used in this study is outlined in Figure 6 and described in further detail.

With space heating comprising 67.4% of all household energy consumption (Appendix A5), a representative estimate of energy consumption can be obtained by considering space heating alone. Furthermore, the determinant factors are spatially explicit and dynamic in the case of space heating, whereas the consumption due to remaining uses is primarily determined by individual usage patterns and behaviour (Prognos 2016b).

Narrowing down the estimation methodology to space heating, the following bottom-up model requires two inputs: the specific heat energy demand and the floor area of a given building or building group. The

Figure 6: Household space heating energy consumption: estimation workflow.

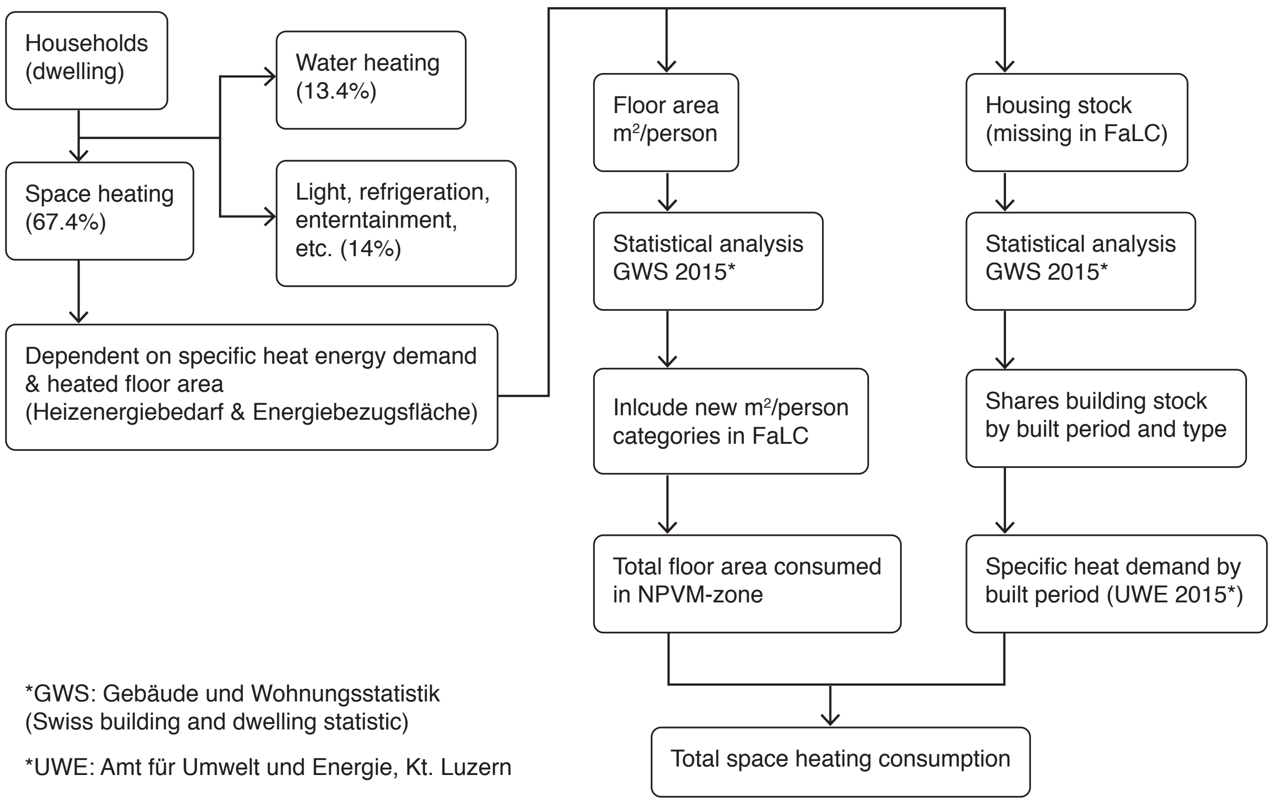


Table 3: Left: Floor area per person categoris in FaLC (Bodenmann 2016). Right: Refinement through additional categories (GWS 2015: BFS 2017a).

FaLC floor area consumption categories [m²/person]

	2015	2040
residents in large city	45.3	56.1
residents in agglomeration and small cities	50.3	54.9
residents countryside	55.3	52.5

Updated floor area consumption categories [m²/person]

	2015	2040
1: Urban	41.8	48.1
2: Suburban	43.9	50.2
3: Regional cen.	51.2	57.5
4: Periurban	49.9	56.2
5: Touristic	44.4	50.7
6: Industrial	47.2	53.5
7: Rural commuting	49.8	56.1
8: Rural mixed	48.6	54.9
9: Agricultural	46.2	52.5

classification of building groups is chosen, in order to match that of the GWS 2015 (BFS 2017a), whereas the associated heat demand is based on observed consumption of a sample of 245 buildings in the year 2015 (UWE 2015).

The total heated floor area is obtained from FaLC output data, which in turn is based on an assumptions table defining a per capita consumption according to three location types. In order to obtain a more representative and spatially variant floor area consumption, the three categories were replaced with 9 new categories, based on the ARE municipality typologies (ARE 2017a). The floor area per person was then assigned values obtained from the GWS 2015 for each municipality type and referenced back through modified FaLC input tables (see Table 3). The resulting difference in total floor area between GWS 2015 and the FaLC base scenario in 2015 is 1.13%, giving a representative global value for the FaLC floor area outputs.

The building type shares necessary for the specific heat demand are not contained in FaLC and need to be extrapolated from the total floor area of a given NPVM-zone. These shares are obtained again from GWS 2015 data and are calculated in the form of mean shares for all 9 of the ARE municipality types (Appendix A7).

Combining the total floor area by building type of each municipality and the specific heat demand values, the total energy demand for household space heating of a given NPVM-zone can be obtained with the following formula (UWE, 2015):

$$E_{household} = \sum_{i}^{n} A_{h\,j}\, E_{h\,j}\, E_{s\,j}$$

$E_{household}$ = total annual space heating demand of NPVM-zone/municipality [kWh]

$A_{h\,j}$ = energy relevant floor area of building period j [m2]

$E_{h\,j}$ = annual specific heating demand of building period j [kWh/m2]

$E_{s\,j}$ = renovation factor for building period j [-]

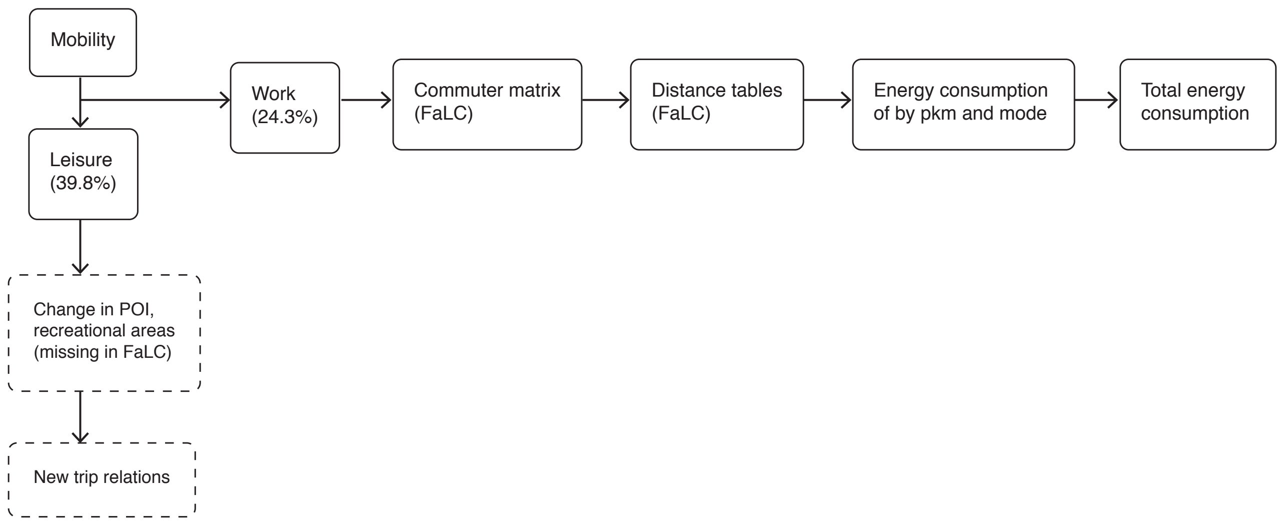
The renovation effect was chosen to affect 1% of the existing building stock per year, representing the total building replacement rate in Switzerland over the last 100 years (SIA 2017b).

3.2.3 Commuting energy consumption estimation

In estimating the energy use due to mobility, a similar bottom-up technique (as with the household energy estimation) was used (see Figure 7). Work-based trips were chosen as determinant of energy consumption, comprising the second largest share of 23.4% in terms of total energy consumption in the mobility sector (Appendix A6, Prognos 2016a). In addition, the distance to work is dominant in dictating long-term location choice (ARE 2017b) and therefore more appropriate for the study of the interaction between location choice, mobility and energy consumption.

Technological changes (and the associated fleet characteristics) are assumed for the purposes of this research

Figure 7: Commuting energy consumption: estimation workflow.



to remain constant, leaving the modal split and total person-kilometre travelled as the relevant values in estimating energy consumption (Infras 2007). While the person-kilometre can be retrieved from the FaLC commuter matrix (and its associated distance table), the modal split was obtained from the total distances by mode of the Swiss population, based on the Mobility and Transport Microcensus (MZMV, BFS 2017b).

By combining the primary energy factors to each corresponding mode group (Frischknecht 2017), the total energy due to commuting was estimated with the following formula:

$$E_{commuting} = \sum_{i}^{n} D\, M_j\, E_{h\,j}$$

$E_{commuting}$= total annual commuting energy [MJ]

D = total person-kilometre travelled [km]

M_j = mode share for mode j [-]

$E_{h\,j}$ = primary energy factor for mode j [MJ/km]

However, the commuting output in FaLC does not represent total commuting distances (e.g. ignoring intra-zonal trips) and is only calibrated to reproduce shares of distances in its commuting relations (ARE 2017b). Therefore, the estimated commuting energy consumption can only be used in comparative analysis of relative changes between scenarios.

3.3 FaLC specifications, evaluation and visualisation of results

All the simulation runs were performed for the years 2015-2040, with FaLC build 1.2.0-1938. The FaLC-specific implementation of the scenario measures is described in detail in the following chapter.

In order to reduce white noise effects within the simulation, each yearly cycle was repeated 20 times and the average values for the indicators calculated (ARE 2017b). The evaluation of the indicators was carried out using the statistical software R (R Core Team 2017), while the visualisation of spatial data was done using the “tmap” package (Tennekes 2017) and the commuter flows were implemented spatially with the “statplanr” package (Lovelace 2017).

4 Scenarios

4.1 Scenario purpose and definition

The scenarios developed as part of the thesis project focus foremost on testing the research goals (Chapter 2) and do not represent scenario formation in the sense of strategic decision making or dealing with future uncertainties (Meinart 2014).

The defined scenarios are firstly intended to examine spatially determined drivers of energy reduction (Section 1.6). Hence, these spatial scenarios also allow to verify the energy estimation methodology from spatial data applied in this project. Lastly, there is an opportunity to study how FaLC handles a range of unique scenarios, which would otherwise require different modelling techniques for each scenario.

The scenarios were chosen in a way, which would allow representing a wide range of spatial instruments and measures (Schönwandt 2006). Therefore they include top-down (economical and regulatory) instruments, as well as bottom-up scenarios representative of demographic or behavioural changes.

4.2 Scenario 0: 2015-2040

The following scenario represents the expected development of Switzerland, according to current national trends and predictions (Bodenmann 2016). The results for the year 2015 are used to verify the energy estimation methodology and describe the current energy use in relation to spatial patterns. Additionally, it serves as a base scenario for comparisons between the final simulation year 2040, as well as the remaining scenarios.

4.3 Scenario 1: Land tax

The first scenario addresses the assumption that households in urban environments consume more energy than in periurban or rural municipalities (Hollenstein 2012). This scenario is based on a theoretical model for a land-use tax which is dependent on the building zone consumption per person (Gmünder 2012). The idea is to decelerate urban sprawl by discouraging the creation of new building zones, but also encouraging the building in already urbanised areas. Although the principal motivation is the preservation of agricultural land and natural resources (Gmünder 2012), an effect of such a sprawl-tax can also be examined in the context of energy use.

The land tax model chosen, represents a one time payment made upon purchasing building land and can be implemented within FaLC by adjusting the existing land price of a municipality by applying the following formula (Gmünder 2012):

$$L_{new\ j} = L_j + L_j \times T \times Z_{Gmünder\ j}$$

$L_{new\ j}$ = Sprawl-adjusted land price in zone j [CHF]

L_j = Existing land price in zone j [CHF]

T = Tax rate valuation (set at 2CHF) [CHF]

$Z_{Gmünder\ j}$ = Weighting factor: sprawl index of zone j [-]

$$Z_{Gmünder\ j} = \frac{F_{BZ\ j} / E_{BZ\ j}}{F_{BZ\ CH} / E_{BZ\ CH}}$$

FBZ_j = total building-zone area in zone j [m2]

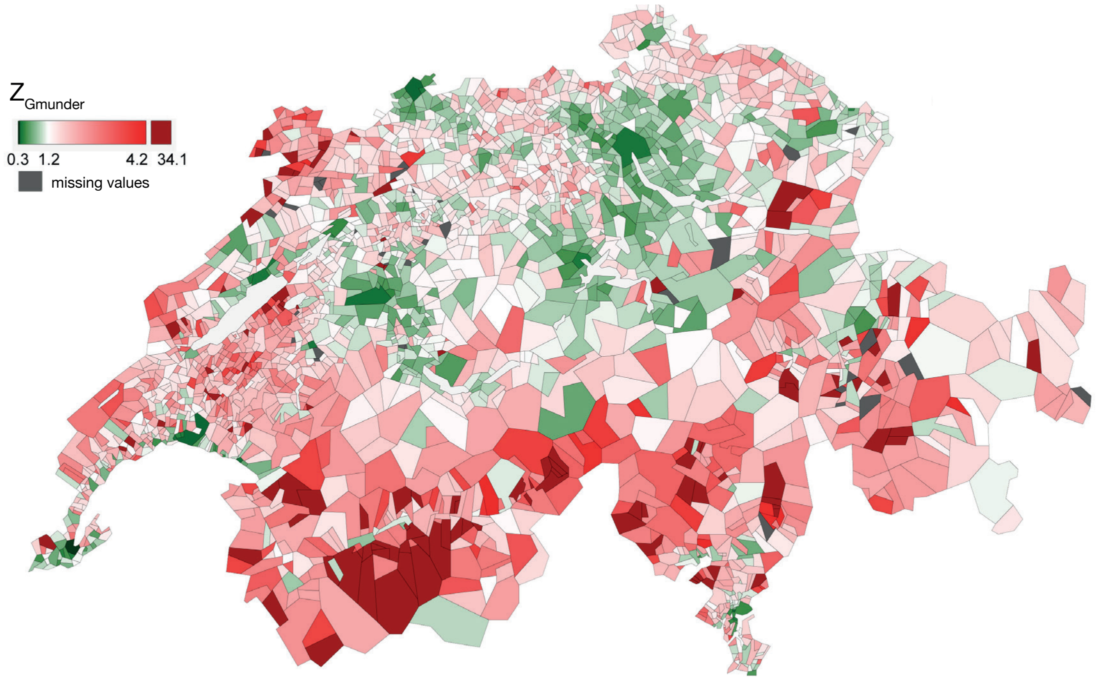
EBZ_j = total population within building zone in zone j [-]

FBZ_{CH} = total building-zone area of Switzerland [m2]

EBZ_{CH} = total population within all building zones in Switzerland [-]

The weighting factor $Z_{Gmünder}$ is here the key attribute which allows a spatial differentiation of the tax impact. It is expected that a land price increase (and therefore a decrease in utility) will generate household relocations from rural to urban municipalities (Figure 8).

Figure 8: Weighting factor $Z_{Gmünder}$ for Swiss municipalities (Gmünder 2012, own translation).



4.4 Scenario 2: Floor area consumption

The second scenario considers the effects of strict regulatory measures. Whereas the previous scenario looked at overall relationship between land use and settlements, the following case moves down in scale to how building zones are used. One recommendation for energy use reduction stipulates a more dense utilisation of existing building zones. A more dense of usage of building zones can lead to more compact building forms in two ways in particular: firstly by increasing the average occupancy per building, secondly be reducing the building envelope (and the associated heat demand). This regulation can come either in the form of increasing utilisation factors ("Ausnützungsziffer") or by introducing a maximum allowed share of single family homes in a given residential zone (Hollenstein 2012).

The intended final outcome would be a decrease in floor area per person consumption in the periurban and rural zones. This effect is implemented in FaLC by letting the values in the floor area input table for the municipality types 3 to 9 (ARE 2017a) converge to those of the suburban areas (municipality type 2). This convergence would occur linearly until the year 2030, after which the development in floor area consumption for the municipality types 3 to 9 matches that of municipality type 2 (Table 4).

Table 4: Adjusted floor area consumption per person in m² for Scenario 2: Floor area consumption.

	2015	2030	2040
1: Urban	41.8	45.6	48.1
2: Suburban	43.9	47.7	50.2
3: Regional cen.	51.2	47.7	50.2
4: Periurban	49.9	47.7	50.2
5: Touristic	44.4	47.7	50.2
6: Industrial	47.2	47.7	50.2
7: Rural commuting	49.8	47.7	50.2
8: Rural mixed	48.6	47.7	50.2
9: Agricultural	46.2	47.7	50.2

4.5 Scenario 3: Local lifestyle

The last scenario tests the influence of behavioural change on energy use. The scenario attempts to answer what spatial effects would occur if households would choose to live closer to their workplace and would prefer zones with better public transport accessibility. Therefore it verifies whether a more decentralised settlement pattern, with shorter commuting distances can contribute to energy reduction (Von Moos 2015). This is further developed by considering the difference between homeowners and tenants, as homeowners tend to live further from their workplace (Appendix A8), have a higher share of motorised vehicle ownership and consume on average more floor area (ARE 2017b).

The scenario is implemented within FaLC through the household-relocation utility functions (Appendix A4). Although the utility function is identical for all households, there is a differentiation between household types through different parameter values. A comparison of the β-values for the homeowner classes with those for tenants, shows a greater sensitivity to relocation distance or public transport accessibility versus accessibility by car for the tenant classes (ARE 2017b). Therefore the β-values for distance to workplace, previous location, accessibility by car and public transport are replaced for the homeowners to match those of the tenants.

5 Results

5.1 FaLC model outputs

Upon evaluating the final outputs of the modelled scenarios, the results obtained were unexpected and difficult to explain in relation to the supposed hypothetical outcomes. However, all the output data (including the reference scenarios) was very consistent. Analysing the results further, it was found that all scenarios displayed a decreasing population trend and linear decline in yearly births (Figure 9). Both of these fundamental trends contradict all current population projections (BFS 2016) and can therefore be considered as being unrealistic. Even more surprising is the fact that this population decline occurs principally in the urban municipality types (Figure 10).

These results were thus reported to the software developer and further attempts at correcting the model runs were made. Over 10 combinations of base input tables, with 5 software versions produced the same effects. The conclusion at the time of writing is that there is an error within a FaLC module and this error could not be rectified over the course of this thesis project.

Figure 9: FaLC population effects 2015-2040. Left: total population, right: yearly births.

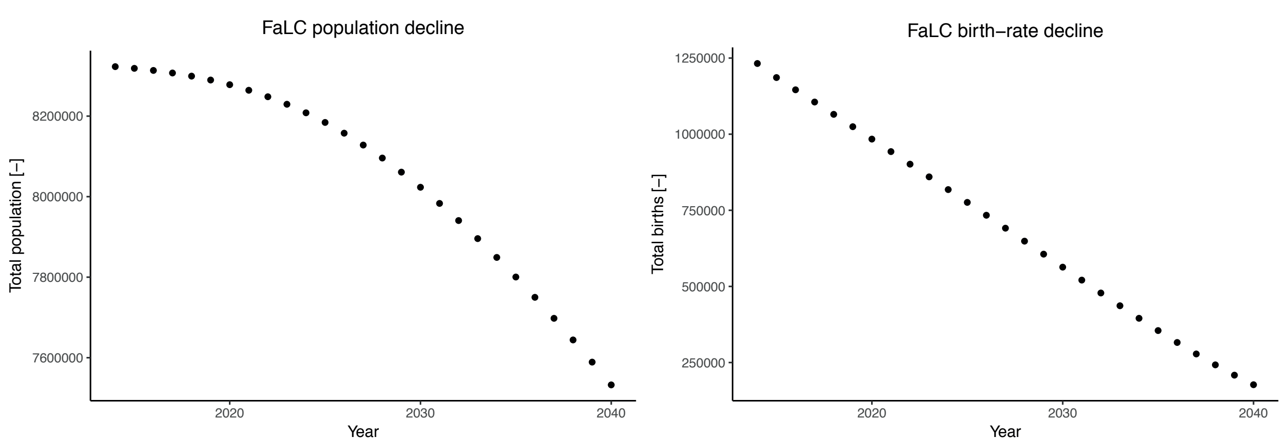
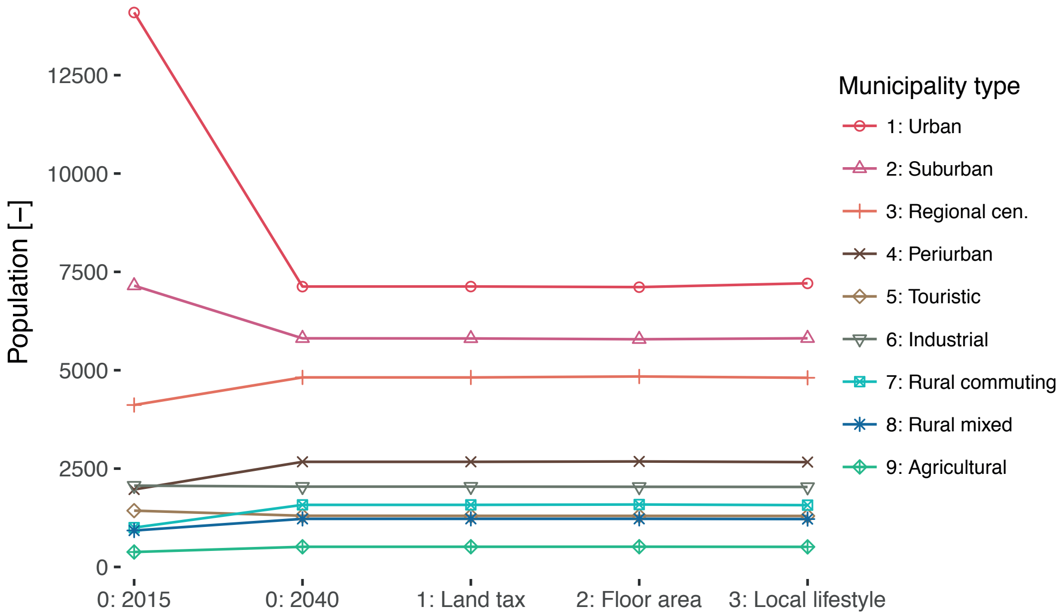


Figure 10: Average population by municipality type and scenario.



This consequently implies that the intended scenario effects cannot be separated in their evaluation from the unintended effect of an urban population decrease caused by FaLC itself. Nevertheless, the remaining aspects of this study, in particular the energy estimation and spatial visualisation methodologies, can still be described and assessed. Since the projected model runs for the years 2040 are not reliable, the focus of the results will be on the start year analysis, with the other scenarios providing a supplementary role.

5.2 Overall results (Scenario 0: 2015)

The year 2015 shows the calibrated starting state of the FaLC run for Switzerland (Figure 11). Clearly visible are the population centres around the Zurich, Berne, Geneva and Lugano agglomerations. These zones are characterised by the largest settlement areas, but also a high population density. The alpine regions have also localised settlement centres in terms of built areas; however, they are also more sparsely populated.

This overall spatial structure of Switzerland is also reflected in the resulting commuter flows. The hierarchy between the principal urban or regional centres and their associated agglomeration is depicted through the relative commuter volume. However, it is important to note that absolute commuter values do not represent the actual observed commuter flows in Switzerland (ARE 2016, ARE 2017b).

Figure 11: Population and commuter flows Scenario 0: 2015.

5.3 Household energy use

The energy estimated of the base run and scenarios lie in the range of ca. 145-160 PJ (Table 5). Most important for the purposes of this thesis is that the estimated values lie within previous estimates of household energy consumption (139.7-192.0 PJ, Prognos 2016). These results show that national-level estimates on energy consumption can be made from basic spatial data, as long as the model assumptions are correct and further refined with reliable building stock data (in this case the GWS 2015).

Visualising the energy data for the base year 2015, plausible results can be observed (Figure 12). The largest share of energy consumed is in the populated metropolitan zones, yet these zones show a more efficient per capita usage (compare Figure 13 and Figure 14). These results are further consistent with other spatial assessments of energy use (Hollenstein 2012). One conclusion that can be drawn, is that although rural households are less efficient in their energy consumption than their more urban counterparts, the most impact in energy reduction can still be made in the major agglomerations.

When comparing the energy reduction impact of the different scenario measures, the unintended effect generated by the modelling tool has to be kept in mind. This can be formulated as the energy reduction effect of a population decrease of around 400'000 urban inhabitants (a 5% decrease of the Swiss population, BFS 2016). Phrased more evocatively: what are the effects on energy use if the population of Zurich would disappear by the year 2040?

This effect is captured by the results for the year 2040 of the reference scenario, which shows a 9% reduction in household energy use, compared with the starting year 2015 (Table 5). Scenarios 1 and 3 do not show

Table 5: Total space heating household energy estimation.

	0: 2015	0: 2040	1: Land tax	2: Floor area	3: Local lifestyle
Average power [W/ person]	1'624	1'443	1'443	1'380	1'444
Total energy [PJ]	166	150	150	145	150
Δ in average power Scenario 0:2015:		**-11%**	**-11%**	**-15%**	**-11%**
Δ in total energy Scenario 0:2015:		**-9%**	**-9%**	**-12%**	**-9%**

Current average power consumption Switzerland: ca. 6800 W/person
(Fachstelle 2000-Watt Gesellschaft 2017, Bundesamt für Energie 2016).

Figure 12: Household space heating energy consumption and commuter flows Scenario 0: 2015.

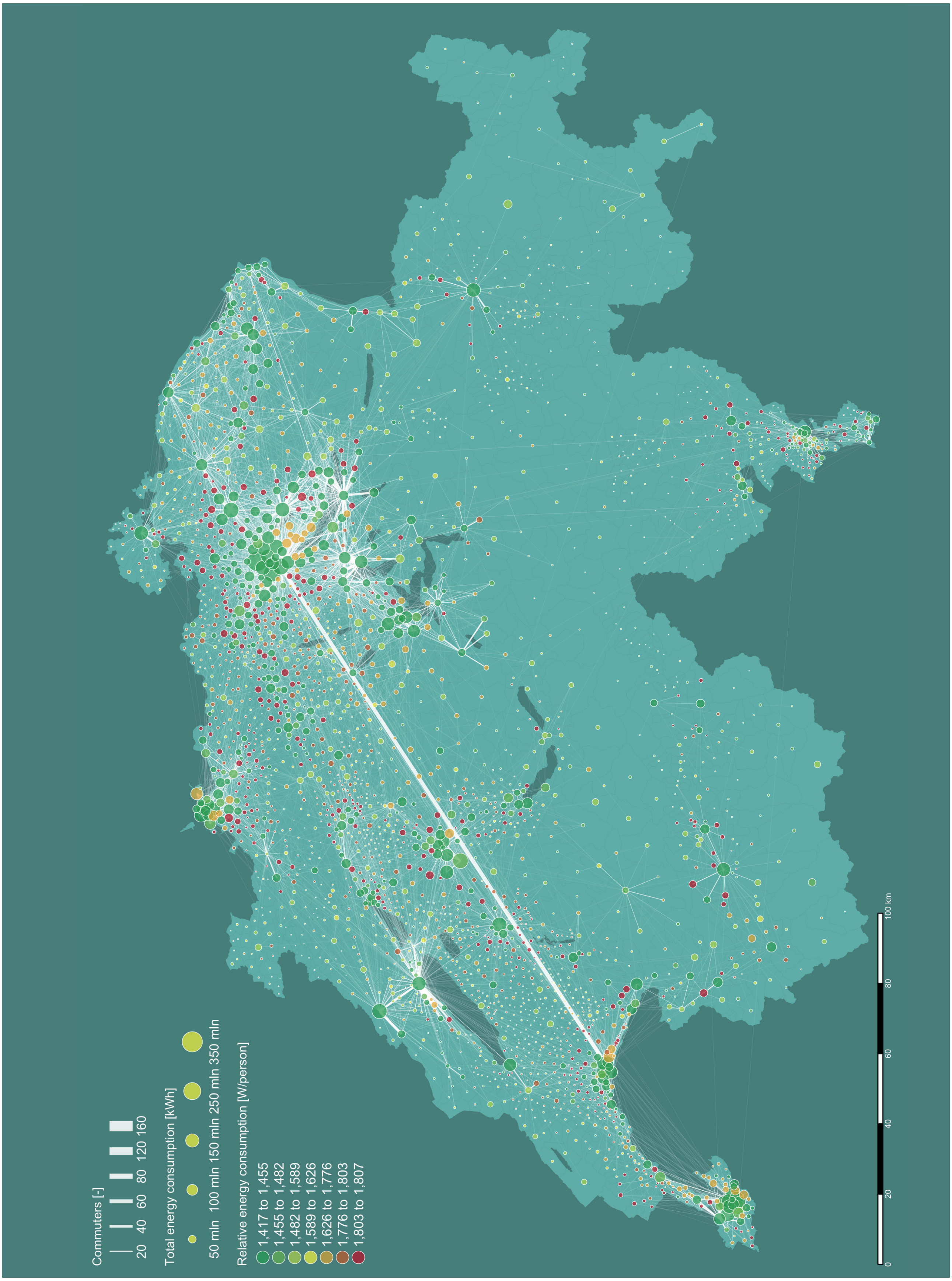
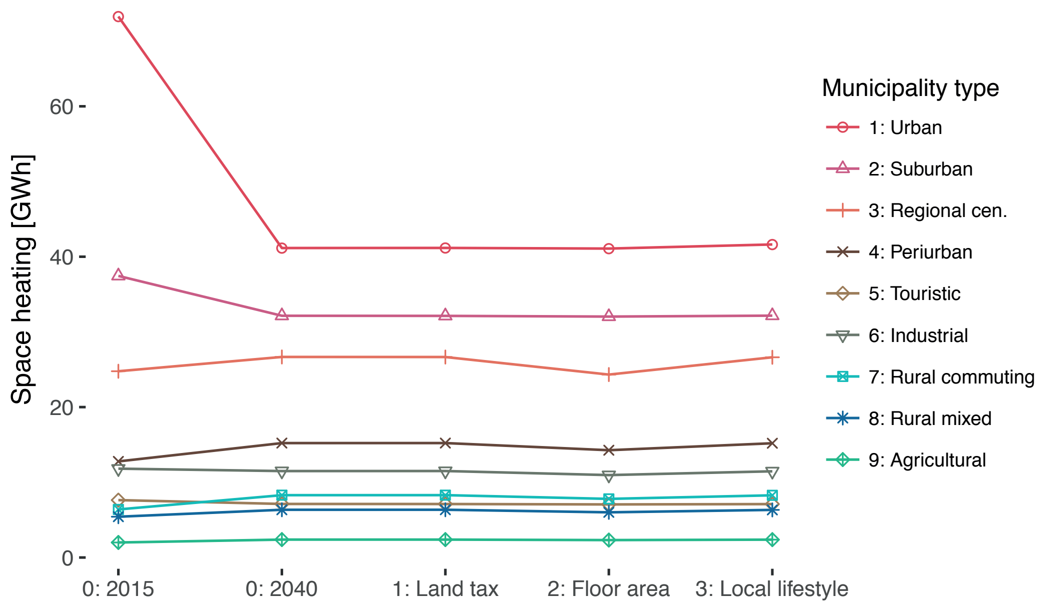
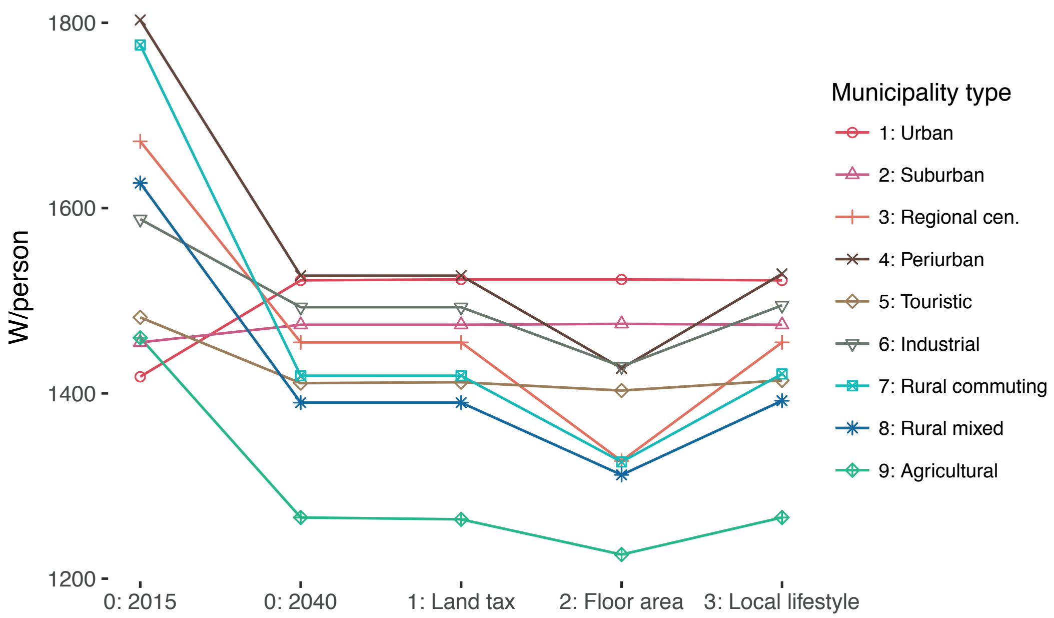


Figure 13: Total household space heating energy by municipality type.



differences in total energy used, in comparison to the reference scenario. This could be firstly due to the intended scenarios not being capable of producing actual significant effects. Alternatively this could be explained by the fact, that the necessary interaction between urban and rural zones in the above scenarios cannot be captured in the model (due to an already diminishing urban population). Scenario 2 however, brings about a decrease of 12% in total energy compared to 2015. This result is consistent with the estimation methodology and shows that the floor area consumption per person is a major driver of energy use.

Figure 14: Average per capita power consumption by municipality type.



Differentiating the household consumption by municipality types, shows an average decrease in the rural consumption driven by a more energy efficient new building stock. The previously most efficient urban zones experience a per capita increase in energy consumption (Figure 14). It has to be noted however, that the absolute decrease in urban population (and therefore heated floor area) is the main driver of energy reduction in all scenarios.

The linear relationship of the applied estimation method is illustrated by Figure 15, by analysing the relationship between municipality size and energy consumption. Comparing the gradients of the modelled scenarios, shows a higher rate in energy use to that of Scenario 0: 2015. Therefore, despite the aforementioned absolute reduction in energy use, a general decrease in overall energy efficiency can be observed.

Analysing the energy in its spatial dimension, the most striking change is the reduced energy efficiency of cities (Figure 16). The general situation of metropolitan areas being the main energy consumer, is as expected still the case. The above results are consistent between all scenarios (Appendix A13 - Appendix A15). An analysis of variance was carried out to be able to discern significant differences in distribution (Montgomery 2012) of the household space heating consumption per municipality and scenario. The results showed that the scenario types indeed produced differences in distribution. To analyse where the differences between scenarios occur, a pair-wise compairson of sample was carried out using Tukey's Honest Significant Difference method (Montgomery 2012). Scenario 2: Floor area is the only scenario producing

Figure 15: Household space heating consumption by municipality size.

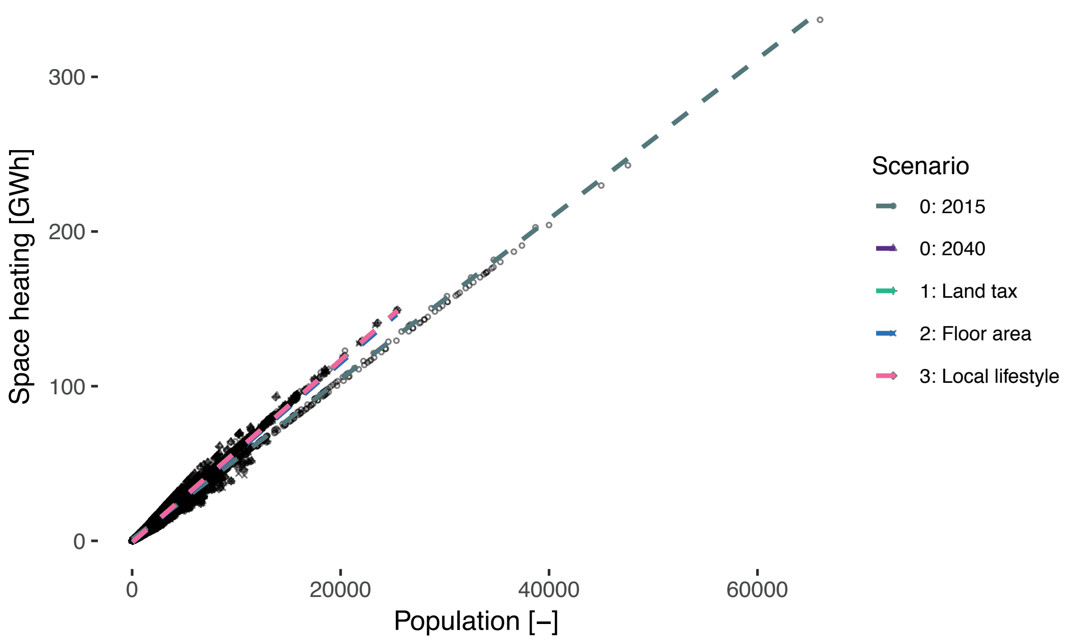


Figure 16: Household space heating energy consumption and commuter flows Scenario 0: 2040.

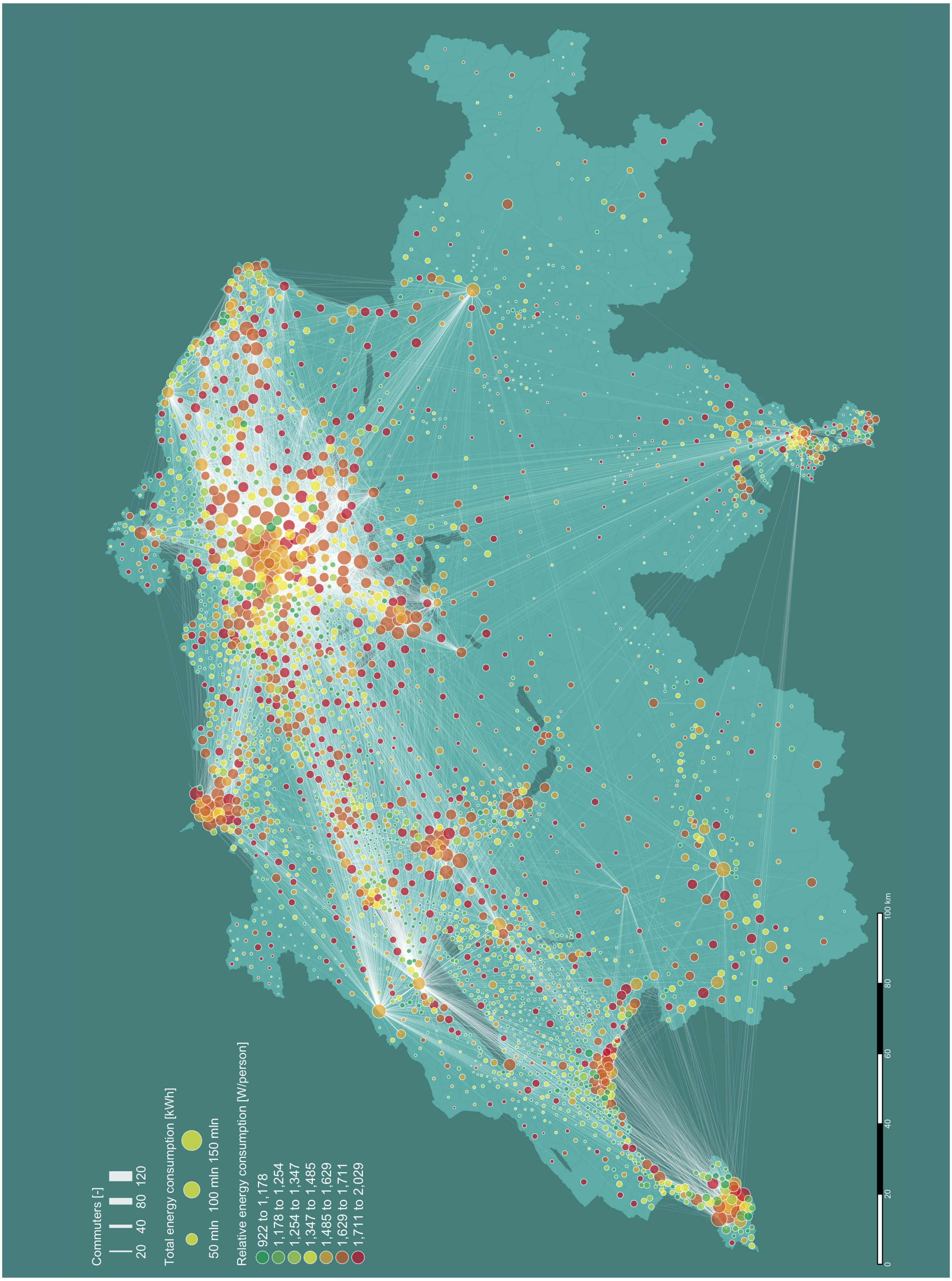


Table 6: Total energy consumption of NPVM-zones [kWh]: Tukey multiple comparison of means, 95% family-wise confidence level.

Scenario A	-	Scenario B	difference	lower interval	upper interval	p-value adjusted	
1: Land tax	-	0: 2040	-398.21	-28166.44	27370.01	1.00	
2: Floor area	-	0: 2040	-471961.02	-499729.24	-444192.79	6.56E-12	***
3: Local lifestyle	-	1.42	11503.07	-16265.15	39271.30	0.71	
2: Floor area	-	1: Land tax	-471562.81	-499331.03	-443794.58	6.56E-12	***
3: Local lifestyle	-	1: Land tax	11901.29	-15866.94	39669.51	0.69	
3: Local lifestyle	-	2: Floor area	483464.09	455695.87	511232.32	6.56E-12	***

significantly different results within the set of modelled scenarios, confirming the overall results (compare Table 5). The slight differences between the remaining three scenarios can most probably be attributed to white-noise effects whithin FaLC (Bodenmann 2016).

In summarising the effects of the presented reduction scenarios, it can be concluded that no single spatial measure can achieve the 2000WS goals. This can be perhaps explained by the fact that so far, any long-term development brings about an increase in the consumption of resources (Notter 2013). Therefore singular reduction measures can at the most limit the negative impacts of future development on energy use.

5.4 Commuting energy

The total estimated energy use due to commuting does not produce reliable results, which constitute around 2% of the actual values for the reference year 2015 (Prognos 2016). This is explained by the FaLC commuter outputs themselves, which do not represent absolute total distances, but relative distance distributions (ARE 2017b). Consequently, the estimated values can be used mostly for comparative analysis between scenarios. More importantly for the purposes of this thesis project, a lack of reliable commuting energy estimates does not allow for a total energy appraisal of each scenario. In other words, a scenario measure for reduction in household consumption can have a reciprocal increase in commuting energy and such outcomes cannot be fully appraised by using FaLC as the principal modelling tool.

With these conditions in mind, the main resulting trend is a doubling of total commuting distances and therefore a doubling in overall energy consumption across all scenarios (Table 7). The average commuting distance however, decreases in relation to the year 2015 (Figure 17). These results are explained by an

Table 7: Total commuting energy estimation.

Primary energy consumption commuting

Commuting mode	Primary energy factor [MJ/pkm]	Mode share commuting [-]	0: 2015 [MJ]	0: 2040 [MJ]	1: Land tax [MJ]	2: Floor area [MJ]	3: Local lifestyle [MJ]
Human powered	0.00	0.05	0	0	0	0	0
Motorcar	3.31	0.62	651'383'532	1'221'221'442	1'260'833'729	1'275'939'423	1'275'939'423
Bus	1.66	0.04	19'006'588	35'633'773	36'789'611	37'230'377	37'230'377
Tram	1.21	0.01	5'195'325	9'740'256	10'056'197	10'176'677	10'176'677
Train	0.97	0.27	82'867'578	155'361'102	160'400'490	162'322'203	162'322'203
Other	1.47	0.00	2'103'892	3'944'401	4'072'344	4'121'134	4'121'134
	Total:	**1.00**	**760'556'914**	**1'425'900'973**	**1'472'152'371**	**1'489'789'814**	**1'489'789'814**
		Total [PJ]:	**0.76**	**1.43**	**1.47**	**1.49**	**1.49**
		Δ in energy consumption Scenario 0:2015:		**87%**	**94%**	**96%**	**96%**

Results 1/50th of 42.6 PJ energy consumption for work trips (Prognos 2016).

increase in new agents commuting, with the new commutes occuring between more proximate zones.

This is further demonstrated by the energy maps (Figure 16), in which a dense commuting network replaces the more hierarchical structure of the start year (Figure 12). This change is particularly visible in the case of commuting relations between the largest Swiss cities. Analysing the zone types of the trip origins, this effect however is certain to have been caused by the unintended population decline in urban zones.

Analogous to the household energy efficiency is the relationship between person-kilometres travelled and municipality size (compare Figure 19 and Figure 15). The final model model outputs show a steep

Figure 17: Boxplot of person-kilometre travelled by NPVM-zone.

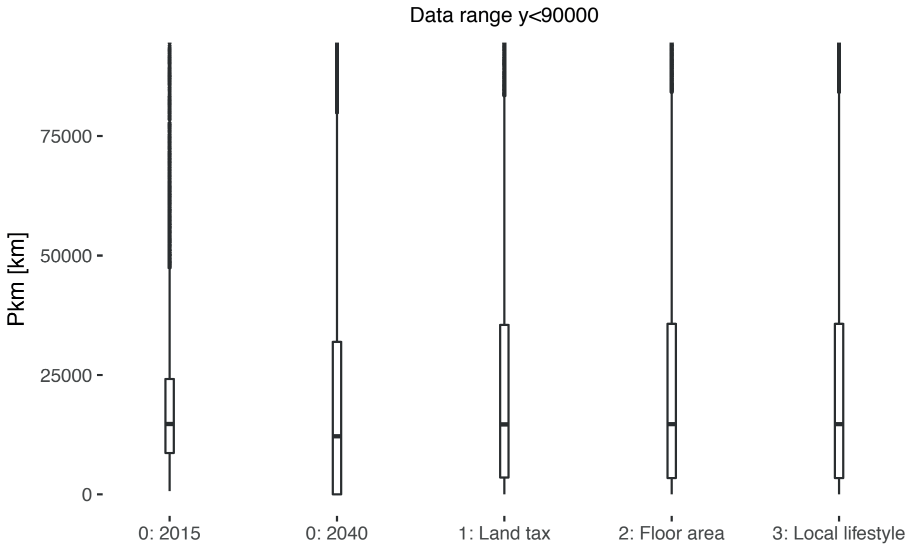


Figure 18: Difference in population, housing floor area and commuter flows to start year 2015 and Scenario 0: 2040.

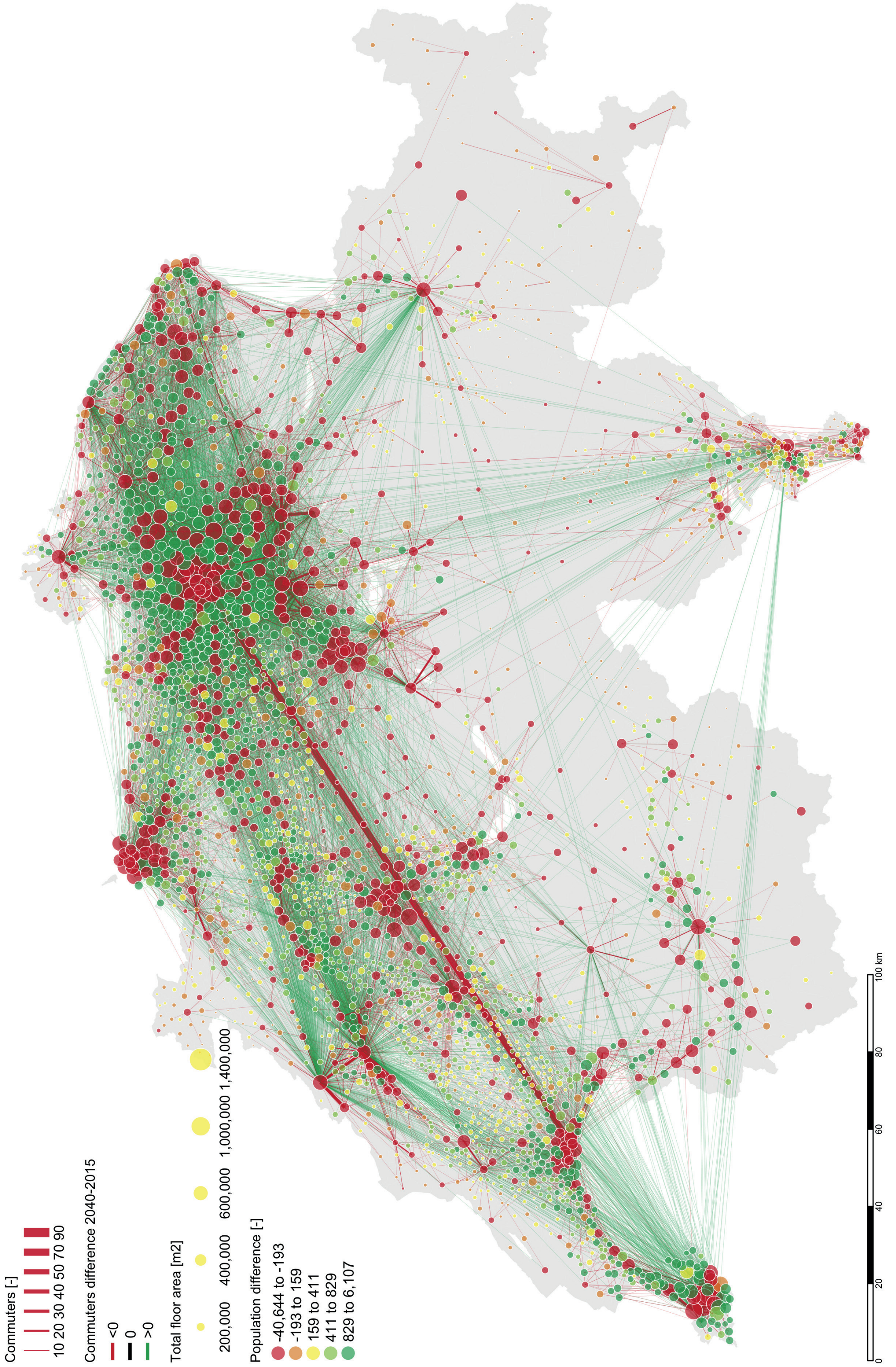
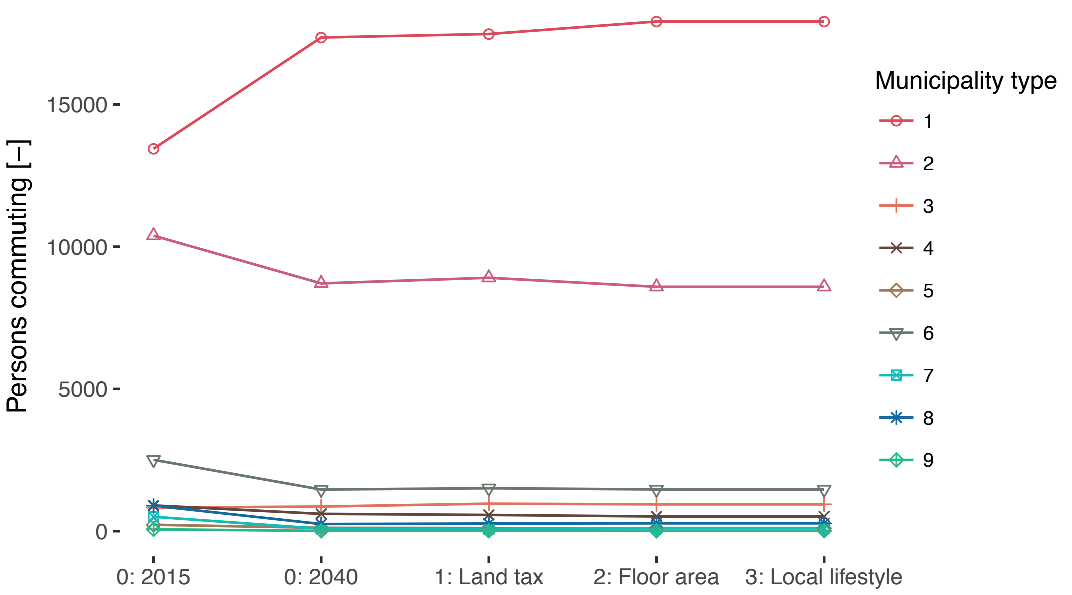


Figure 19: Number of commuters by municipality type of trip origin.



increase in the rate of kilometres travelled, compared to Scenario 0: 2015. This illustrates (in tandem with the doubling of total distance travelled) that an increase in households commuting can have a significant impact on energy use - even if the commutes are across short distances.

Similarly to the household energy estimation, the effects of the scenarios cannot be fully assessed. Nevertheless, the model outputs show that removing the most dense centres of population and activity,

Figure 20: Person-kilometre travelled by municipality size of trip origin.

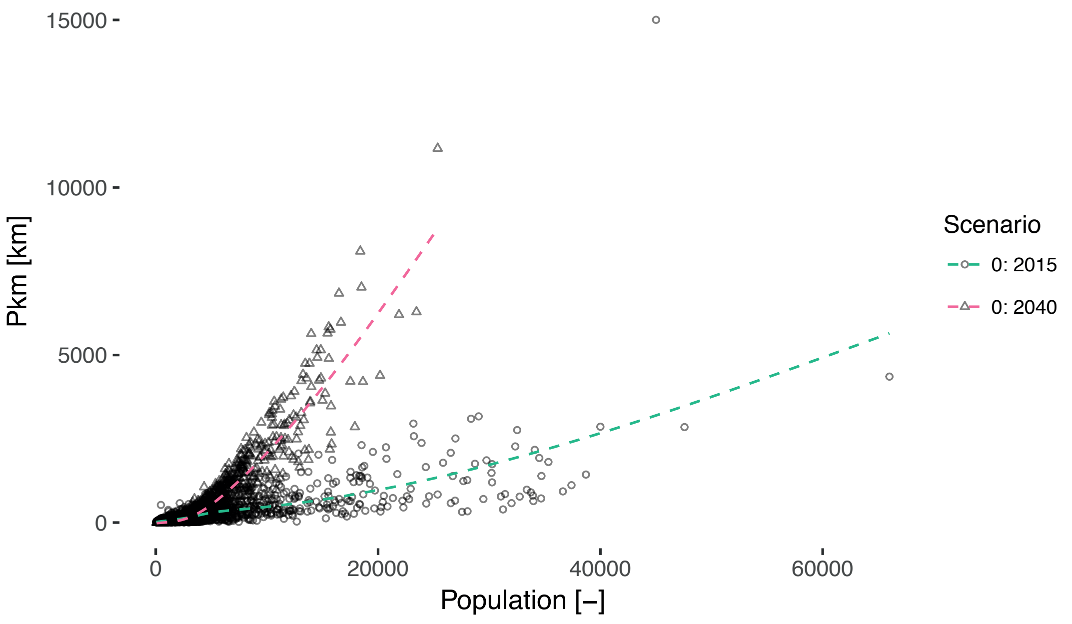
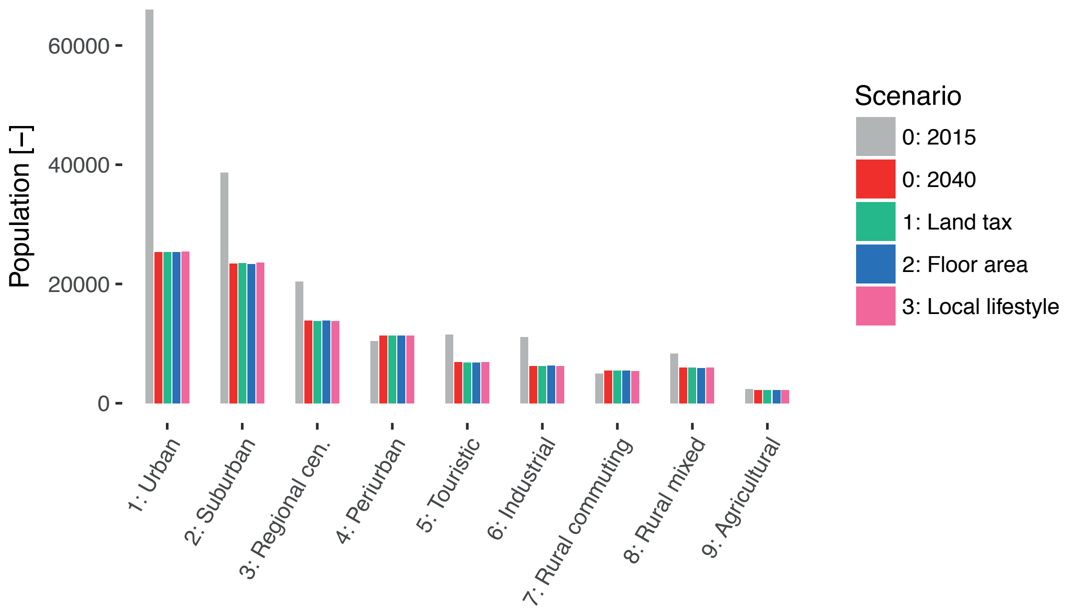


Figure 21: Total population by municipality type.



leads to an increase in commuting trips. The main recommendations that can be formulated with the obtained results are that reaching the 2000WS goals requires spatial planning decisions, which strengthen urban centres and create regional hubs in less populated areas of Switzerland.

Figure 22: Population density for municipalities between 10'000 and 30'000 inhabitants.

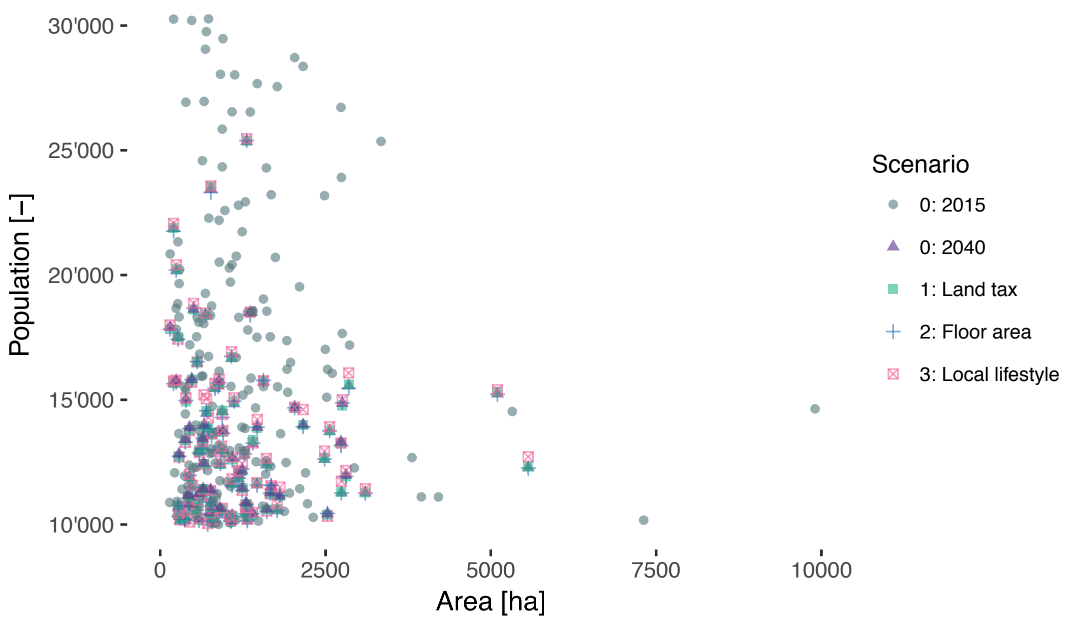
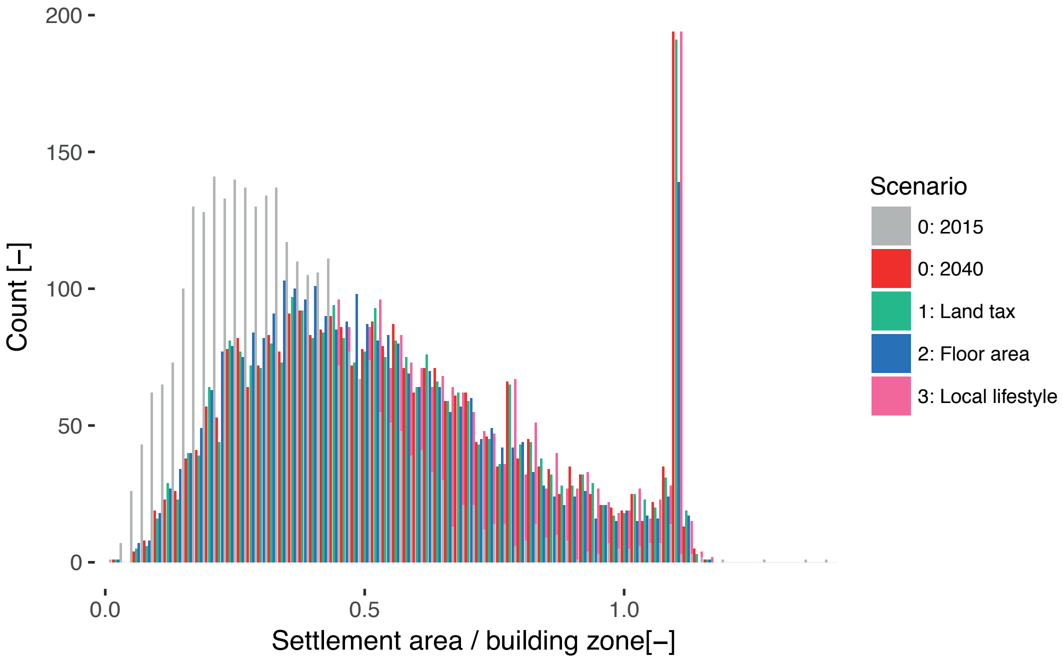


Figure 23: Distribution of building zone utilisation.



5.5 Land use and settlement structure

All scenarios show the same pattern in terms of changes in land use and population distribution. The urban zones are accompanied in their population decrease by the other municipality types – with the exception of periurban, rural commuting and agricultural zones (Figure 18, Figure 21).

Unsurprisingly, the medium sized municipalities become less dense in terms of population size (Figure 22), yet an increase in building zone usage can be shown (Figure 23). Conforming to the model specifications is the observed increase in average occupied floor area per person (Appendix A11). The exception in this case is Scenario 2, which assumes that most households will experience a decrease in floor area consumption.

The relocation outputs offered by FaLC did not uncover any additional or interpretable results. The relocations between the NPVM-zones conform to population changes illustrated by Figure 18; namely no relocations to most zones (but the urban types in particular). Only marginal net increases are visible in some rural zones, but nearly not enough to explain the overall population drain.

Even with the skew introduced by the FaLC population loss, some spatial conclusions can be drawn. A projected population growth in rural and periurban municipalities, coupled with the trend for an increasing floor area per person increase, will require the use of additional land for settlements. These questions of land use will therefore have to be answered in the near future and will certainly leave an impact on our environments across all spatial types and regions. Furthermore, this aspect will occur regardless of whether the energy use components will be explicitly adressed in future development. However, the priniciples of sustainable land-use and the act of reducing urban sprawl are not only compatible with household energy reduction measures: one can be achieved by pursuing the other.

6 Discussion and conclusions

6.1 Research goal summary

6.1.1 Modelling long-term spatial interactions

This research project demonstrated the need and possibilities to model interactions between long-term location choice, mobility and energy use. The Facility Location Choice simulation tool (FaLC) used in this thesis shows the potential to model these complex interactions and effects of location choice on the scale of a whole country. The wide range of input data and development assumptions provide a powerful framework for modelling tasks. The similarly expansive data outputs enable a multi-faceted analysis necessary for spatial planning tasks. Furthermore, it was shown that this data can be expanded upon, beyond the actual intended purposes of FaLC. Nevertheless, it became apparent over the course of this thesis that this simulation tool needs further development.

6.1.2 Spatial energy estimation

The energy estimation methods applied in this project showed varied outcomes. It could be shown that bottom-up estimation models for the household sector (UWE 2015) deliver plausible results from basic spatial data. The quality of such estimates is dependent on further data refinement (e.g. with the GWS 2015) and the quality of the output data. This last aspect is illustrated by the commuting energy estimates. Since commuter output data is not able to adequately represent actual trips, only relative changes could be assessed.

The obtained results showed that energy reduction measures can have positive effects in terms of household consumption, but negative impacts in the area of mobility. This insight firstly illustrates the complexity of spatial interactions. Secondly, this implies the need for estimation outputs to be complementary and comparable for a total energy assessment, which is able to weigh the benefits in one area against the costs in another.

6.1.3 Spatial visualisation of energy use

Spatial data offers the possibility of uncovering numerous effects and interactions. This thesis has shown the potential for comparing typical spatial data (e.g. population density) with less analysed, but nevertheless relevant components (energy use). In order to compare different outputs or scenarios systematically, visual data needs to be supplemented by descriptive statistics. This holds especially true if the differences are difficult to discern due to minor effect sizes or large-scale depictions. Nevertheless, such visualisations can be used as a basis for overview plans, formulating development goals and coordinate spatially relevant activities and sectors (ARE 2018) with the interests of energy reduction.

6.1.4 Influencing energy use

The possibility to derive and implement in FaLC distinct measures influencing energy consumption could be demonstrated. Since their intended hypothetical reduction effects could not be discerned nor assessed, this research aspect remains mostly unresolved. Although some effects could be described, in order to uncover new spatial interactions or make energy reduction recommendations, more work needs to be invested. The main conclusion made herein, is that the added value of a simulation tool such as FaLC to test a set of disparate instruments, has to be weighed against applying ground-up models developed for a specific research aspect.

6.2 Future research and improvements

The complexity of spatial interactions illustrated by this thesis project confirms the importance of land-use transport interaction models (ARE 2013). Alternative modelling approaches could be used in their place, but a tool such as FaLC can potentially provide a wealth of output data with shorter development and setup time. It was however also shown, that adequately capturing spatial phenomena and incorporating them into planning decisions, requires that the reliability of such modelling tools be further improved.

Although the household energy estimation showed some promising capabilities, this type of bottom-up model offers the advantage of expanding and adding further detail. One such addition could be in the form of a more representative building stock model. A time-series analysis could provide the renewal or decay rate of the different dwelling categories. A more complex mode refinement could be in devising household consumption based on socio-economic characteristics. This could be carried out with a likelihood model, obtaining floor area consumption and dwelling type (single family home or flat) based on attributes such as household size, composition or location type. Since a dataset such as the GWS also contains building age, there is a possibility to directly link energy demand with the obtained household dwelling profile.

The mobility energy estimation is an aspect that was shown to need significant further development. The commuter data obtained was too incomplete to be representative. An alternative approach worth pursuing would be to apply demographic data from the scenario outputs and apply them in a four-step transport planning model for trip estimation (Ortuzar 1995). Such an approach would also take into account (and allow to modify) the assumptions determining future mode choice.

The refinement of mobility outputs is especially pertinent in light of a total energy assessment of scenario measures. This research project showed spatial interactions causing potentially reciprocal effects in response to a given intervention. Therefore, perhaps the most crucial future improvement should be in producing a more comprehensive total energy assessment.

6.3 2000-Watt Switzerland: recommendations

No single spatial measure can achieve reductions significant enough to meet 2000-Watt Society (2000WS) goals. Furthermore, reductions goals need be pursued through all possible instrument types and no overwhelming advantage of a given approach could be identified. Thus one returns to the main tenants of sufficiency and efficiency set forward by the 2000WS framework.

Floor area consumption and heat demand are the main drivers in household energy consumption. Even if households could be made to live in more dense environments, the current quality of the housing stock will remain a hurdle in achieving significant reduction goals. The same holds true for the mobility side of energy use. Even with a reduction in trip distance and relations, the reduction impact will remain limited without a change to more efficient mode choices.

Based on the spatial distribution of energy use, urban agglomerations will play a major role in achieving 2000WS reduction goals. The potential certainly exists, as cities have been hotspots for the kind of innovation

(O'Sullivan 2012), necessary in achieving such ambitious goals. Notwithstanding is the role of the peri-urban areas, which will need to be accommodated in their future expansion. Spatial development can therefore be approached not only from the point of view of sustainable building land usage. Densification measures and creation of regional hierarchies can furthermore contribute to long-term reductions in energy use.

Lastly it was shown that reductions in one spatial aspect can be nullified through energy increases in that of another area. Thus the principal conclusion and recommendation for achieving a 2000-Watt Switzerland is the necessity for an intersectoral approach. Such an approach would allow to coordinate different development interests and increase the effectivness of implementated measures. In conclusion, this thesis hopefully demonstrated not only the relevance of energy use in its spatial dimension, but also its compatibility with sustainable planning principles, so that it can be embraced in the years to come.

7 Literature

ARE (2006) *Erstellung des nationalen Personenverkehrsmodell für den öffentlichen und privaten Verkehr – Modellbeschreibung*, Bundesamt für Raumentwicklung, Bern.

ARE (2010) *Nationales Personenverkehrsmodell des UVEK, Basis Modell*, Bundesamt für Raumentwicklung, Bern.

ARE (2013) *Abstimmung von Siedlung und Verkehr; Diskussionsbeitrag zur künftigen Entwicklung von Siedlung und Verkehr in der Schweiz – Schlussbericht,* Bundesamt für Raumentwicklung, Bern.

ARE (2016) *Perspektiven des Schweizerischen Personen- und Güterverkehrs bis 2040 – Hauptbericht*, Bundesamt für Raumentwicklung, Bern.

ARE (2017a) Gemeindetypologie und Stadt/Land-Typologie, https://www.bfs.admin.ch/bfs/de/home/statistiken/raum-umwelt/nomenklaturen/gemtyp.html, Bundesamt für Raumentwicklung, November 2017.

ARE (2017b) *Weiterentwicklung Flächennutzungsmodellierung: Wohnstandortwahl Erweiterung des Modells FaLC: Verhaltensmodelle und synthetische Population*, Bundesamt für Raumentwicklung, unpublished.

ARE (2018) Kantonale Richtpläne, https://www.are.admin.ch/are/de/home/raumentwicklung-und-raumplanung/strategie-und-planung/kantonale-richtplaene.html, Bundesamt für Raumentwicklung, January 2018.

BFE (2015) *Annahmen und Methoden diverser Studien zu Energieperspektiven, Bericht zuhanden der UREK-S*, Bundesamt für Energie, Bern.

BFE (2017a) *Schweizerische Elektrizitätsstatistik 2016*, Bundesamt für Energie, Bern.

BFE (2017b) Was ist die Energiestrategie 2050?, http://www.bfe.admin.ch/energiestrategie2050/06445/index.html?lang=de#, Bundesamt für Energie, Bern, August 2017.

BFS (2016) *Szenarien zur Bevölkerungsentwicklung der Kantone 2015-2045*, Bundesamt für Statistik, Bern.

BFS (2017a) Einzeldaten aus der Gebäude- und Wohnungsstatistik GWS 2015, Bundesamt für Statistik, Bern.

BFS (2017b) *Verkehrsverhalten der Bevölkerung 2015*, Bundesamt für Statistik, Bern.

Bodenmann, BR, BJ Vitins, I Vecchi, A Zeiler, J Hackney, and KW Axhausen (2013) *FaLC: Implementation of a Land-Use Transport Interaction Model for Switzerland*, regioConcept and IVT, Herisau/Zurich.

Bodenmann BR, I Vecchi, B Sanchez, J Bode, A Zeiler and KW Axhausen (2014a) *Implementation of a Synthetic Population for Switzerland, FaLC Working Paper, 01*, regioConcept and IVT, Herisau/Zürich.

Bodenmann BR, J Bode, B Sanchez, A Zeiler, P Furták, M Kuljovsky, I Vecchi and KW Axhausen (2014b) *An Integrated Land Use Model for Switzerland Detailed Description of the FaLC Template, FaLC Working Paper, 02*, regioConcept and IVT, Herisau/Zürich.

Bodenmann BR, J Bode, B Sanchez, A Zeiler, P Furták, M Kuljovsky, I Vecchi and KW Axhausen (2016) *An Integrated Land Use Model for Switzerland Detailed Description of the FaLC Template 2016, FaLC Working Paper, 03*, regioConcept and IVT, Herisau/Zürich.

Fachstelle 2000-Watt-Gesellschaft (2014) Bilanzierungskonzept 2000-Watt-Gesellschaft, http://www.2000watt.ch/fileadmin/user_upload/2000Watt-Gesellschaft/de/Dateien/2000-Watt-Gesellschaft/Bilanzierungskonzept_2000-Watt-Gesellschaft.pdf, Fachstelle 2000-Watt-Gesellschaft, Zurich, September 2017.

Fachstelle 2000-Watt-Gesellschaft (2017) Ein Konzept mit zwei gleichwertigen Zielen: Synthesepapier mit Argumentationshilfen für Energiestadtberater/innen und angehende 2000-Watt-Berater/innen, http://www.2000watt.ch/fileadmin/user_upload/2000Watt-Gesellschaft/de/Dateien/2000-Watt-Gesellschaft/FAQ/2000-Watt-Gesellschaft-Synthesepapier.pdf, Fachstelle 2000-Watt-Gesellschaft, Zurich, September 2017.

Fachstelle 2000-Watt-Gesellschaft (2018a) Bauen in der 2000-Watt-Gesellschaft, http://www.2000watt.ch/fuer-kantone/diese-machen-mit/, Fachstelle 2000-Watt-Gesellschaft, January 2018.

Fachstelle 2000-Watt-Gesellschaft (2018b) Kantone unterstützen die Vision der 2000-Watt-Gesellschaft, http://www.2000watt.ch/alte-seite/quartiere-und-areale/effizienzpfad-energie/, Fachstelle 2000-Watt-Gesellschaft, January 2018.

Federal Assembly (2012a) *Bundesgesetz über die Reduktion der CO_2-Emissionen (CO_2-Gesetz)*, BBl 2012 113, Bern.

Federal Assembly (2012b) *Verordnung über die Reduktion der CO_2-Emissionen (CO_2-Verordnung)*, AS 2012 7005, Bern.

Federal Assembly (2016) *Energiegesetz (EnG)*, BBl 2016 7683, Bern.

Frischkencht R (2017) *Umweltkennwerte und Primärenergiefaktoren von Transportsystemen, KBOB-Ökobilanzdatenbestand v.2.2:2016, Stand 2016*, Uster.

Federal Council (2013) *Botschaft zum ersten Massnahmenpaket der Energiestrategie 2050 (Revision des Energierechts) und zur Volksinitiative "Für den geordneten Ausstieg aus der Atomenergie (Atomausstiegsinitiative)"*, BBl 2013 7561, Bern.

Gmünder M (2012) *Abgaben für eine ökologische und haushälterische Flächennutzung*, Bundesamt für Umwelt, Bern.

Hollenstein K (2012) *Welchen Beitrag kann die Umsetzung der räumlichen Mindeststrategie «Innen- vor Aussenentwicklung» zur Senkung des Energieverbrauchs leisten?* Master thesis, Chair of Spatial Development, ETH Zürich, March 2012.

Infras (2007) *Der Energieverbrauch des Verkehrs 1990 – 2035, Ergebnisse der Szenarien I bis IV und der zuge- hörigen Sensitivitäten „BIP hoch", „Preise hoch" und „Klima wärmer"*, Bundesamt für Energie, Bern.

IWSB (2016) *Analyse von Instrumenten zur Steuerung des Wohnflächenkonsums,* Bundesamt für Wohnungswesen, Grenchen.

Jakob M, J Eberhard (2014) Erneuerungsverhalten im Bereich Wohngebäude, https://www.researchgate.net/publication/242240858_Erneuerungsverhalten_im_Bereich_Wohngebaude, May 2014.

Kavgic M, A. Mavrogianni, D Mumovic, A Summerfield, Z Stevanovic, M Djurovic-Petrovic (2010) A review of bottom-up building stock models for energy consumption in the residential sector, *Building and Environment*, vol. 45, 1683–1697.

Lovelace R (2017) Package 'stplanr' documentation, https://github.com/ropensci/stplanr/blob/master/vignettes/stplanr-paper.Rmd, November 2017.

Novatlantis (2005) *Smarter living: Generating a new understanding for natural resources as the key to sustainable development – the 2000-watt society*, Bundesamt für Energie, Bern.

Notter DA, R Meyer, JH Althaus (2013) The Western Lifestyle and Its Long Way to Sustainability, *Environmental Science and Technology*, vol. 47, 4014-21.

Meinart S (2014) *Field manual – scenario building*, European Trade Union Institute, Brussels.

Montgomery DC (2012) *Design and Analysis of Experiments, Eight edition*, John Wiley & Sons, Inc.

O'Sullivan A (2012) *Urban Economics, Eighth edition*, McGraw Hill, New York.

Ortuzar J. de D., LG Willumsen (1995) *Modelling Transport,* Wiley, Chichester.

Prognos (2012) *Die Energieperspektiven für die Schweiz bis 2050: Energienachfrage und Elektrizitätsangebot in der Schweiz 2000 – 2050, Ergebnisse der Modellrechnungen für das Energiesystem*, Bundesamt für Energie, Bern.

Prognos (2016a) *Ex-Post-Analyse des schweizerischen Energieverbrauchs 2000 bis 2015*, Bundesamt für Energie, Bern.

Prognos (2016b) *Der Energieverbrauch der Privaten Haushalte 2000 – 2015: Ex-Post-Analyse nach Verwendungszwecken und Ursachen der Veränderungen*, Bundesamt für Energie, Bern.

R Core Team (2017) *R: A language and environment for statistical computing*, R Foundation for Statistical Computing, Vienna, Austria.

Rey E, S Lufkin, P Renaud, L Perret (2013) The influence of centrality on the global energy consumption in Swiss neighborhoods, *Energy and Building*, vol. 60, 75-82.

Schneider S, P Hollmuller, P Le Strat, J Khoury, M. Patel, B Lachal (2017) Spatial-temporal analysis of the heat and electricity demand of the Swiss Building stock, *Frontiers in Built Environment*, vol. 3-53.

Schönwandt W, W Jung (2006) *Ausgewählte Methoden und Instrumente in der räumlichen Planung: kritische Sondierung als Beitrag zur Diskussion zwischen Planungswissenschaft und –praxis*, Akademie für Raumforschung und Landesplanung, Hannover.

Schwartz P (1991) *The art of the long view,* Doubleday, New York.

SIA (2017a) *Merkblatt SIA-Effizienzpfad Energie (SIA 2040)*, Schweizerischer Ingenieur- und Architektenverein, Zürich.

SIA (2017b) Modernisierung des Gebäudeparks Schweiz, http://www.sia.ch/de/themen/energie/modernisierung-gebaeudepark, Schweizer Ingenieur- und Architektenverein, November 2017.

Tennekes M (2017) Package 'tmap' documentation, https://cran.r-project.org/web/packages/tmap/tmap.pdf, November 2017.

UWE (2013) *Gebäude-Heizenergiebedarf, Methodik zur Schätzung des Heizenergiebedarfs mittels kantonalem Gebäude- und Wohnungsregister*, Kanton Luzern, Bau Umwelt- und Wirtschaftsdepartament, Luzern.

UWE (2015) *Energiespiegel Methodik und Diskussion*, Kanton Luzern, Bau Umwelt- und Wirtschaftsdepartament, Luzern.

Verein Minergie (2017) *Geschäftsbericht 2016*, Verein Minergie, Basel.

Von Moos L (2015) *Einfluss verschiedener Raumentwicklungsstrategien auf den Energieverbrauch durch Mobilität,* Master thesis, Chair of Spatial Development, ETH Zürich, June 2015.

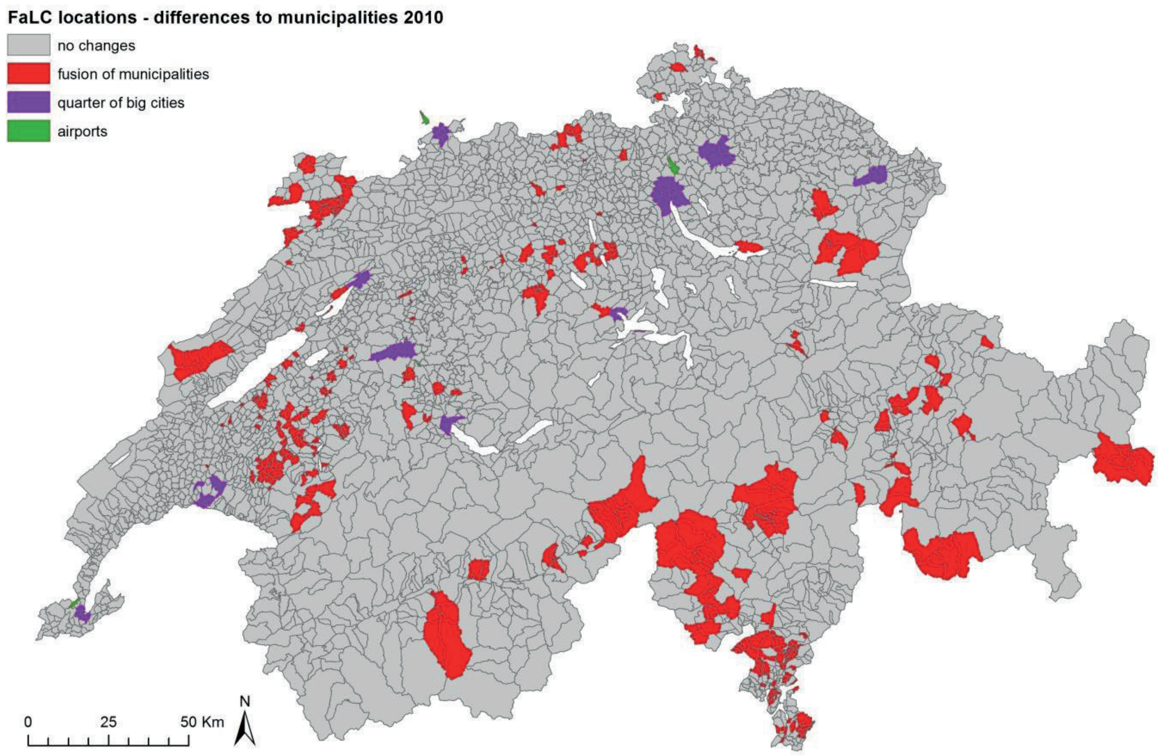
WSL (2010) *Fiskalische Instrumente und Flächeninspruchnahme*, Eidg. Forschungsanstalt WSL, Birmensdorf.

Appendix

Appendix A1 Current electricity production in Switzerland by type and federal requirements (BFE 2016, Federal Assembly 2016, own translation and formatting).

Year	2016 [TWh]	2020 [TWh]	2035 [TWh]	Minimum increase by the year 2035 [%]
Hydroelectricity	36.3	-	37.4	3
Nuclear power	20.2	-	-	-
Conventional central station power plants (non-renewable)	1.9	-	-	-
Conventional central station power plants (renewable)	1.2	4.4	11.4	360
Various renewable energy sources	2.0			

Appendix A2 FaLC spatial resolution and differences (Bodenmann 2013).



Appendix A3 Excerpt from FaLC location attribute table specification (Bodenmann 2016).

Attribute	Description	Entities
locid	ID location	[integer]
Denot	Location name	[character]
Canton_nr	Number of canton	[integer]
run	Number of cycles (years) passed	[integer]
Pop_tot	Census: total number of population	[integer]
Emp_tot	Census: total number of employess	[integer]
fl_sdl	Area of building zone	[integer]
mia_4	Yearly rent for 4-room-flats	[integer]
gt_gmz	Municipality is a large or medium centre	[integer]
bst_dbr	Diversity of sectors	[double]
se_aansl	Access to highway (0/1)	[integer]
se_bahn	Access to railway (0/1)	[integer]
lp_wohn_norm	Land prices for residential use (normalized)	[double]
bz_totnd_norm	Density in Building Zones (normalized)	[double]
wb_hsabs_q_norm	Quote of persons with university degree	[integer]
bst_dbr_norm	Diversity of sectors (normalized)	[double]
st_hg_k_norm	Tax rate for holding companies (normalized)	[double]
st_pg_e_norm	Tax rate for partnerships (normalized)	[double]
st_kg_g_norm	Tax rate for private coorporations (normalized)	[double]
se_ac_at_norm	Accessibility (total, normalized)	[double]
se_wfk_norm	Cantonal business development (normalized)	[double]
se_ac_wt*	Accessibility of residents (normalized)	[integer]
se_wfr_vf_norm	Promotion as business location (normalized)	[double]
pop_1	Not used (replaced by pop_tot)	[integer]
pop_2	Not used (replaced by emp_tot)	[integer]
av_1	Accessibility value: car, residents	[numeric]
av_2	Accessibility value: car, employees	[numeric]
av_3	Accessibility value: public transport, residents	[numeric]
av_4	Accessibility value: public transport, employees	[numeric]
av_5*	Accessibility value: bicycle, residents	[numeric]

Appendix A4 FaLC agent utility functions (ARE 2017b).

$$\textbf{Utility}_{\textbf{household base}} = \text{built year}_{\text{post 1980}} \times \beta_{\text{built-post 1980}} + \text{built year}_{\text{homogeneity}} \times \beta_{\text{built-homogeneity}} +$$
$$\text{lake access} \times \beta_{\text{lake access}} + \text{lake view} \times \beta_{\text{lake view}} + \text{distance nature} \times \beta_{\text{distance nature}} +$$
$$\text{aircraft noise} \times \beta_{\text{aircraft noise}} + \text{municipality type} \times \beta_{\text{municipality type}} + \text{built year}_{\text{post 1980}} \times \beta_{\text{built-post 1980}} +$$
$$\text{tavel time urban centre} \times \beta_{\text{tavel time urban centre}} + \text{public transport quality} \times \beta_{\text{pt quality}} +$$
$$\text{motorway access} \times \beta_{\text{motorway access}} + \text{railway access} \times \beta_{\text{railway access}} + \text{leisure density} \times \beta_{\text{leisure density}} +$$
$$\text{population density} \times \beta_{\text{population density}} + \text{retail density} \times \beta_{\text{retail density}} + \text{services density} \times \beta_{\text{services density}}$$

$$\textbf{Utility}_{\textbf{household moving}} = \log(1 + \text{distance}_{\text{moving}} + 0.0001) \times \beta_{\text{dstiance-moving}} +$$
$$\log(1 + \text{distance}_{\text{workpalce}} + 0.0001) \times \beta_{\text{dstiance-workplace}} + \text{accessibility}_{\text{car}} \times \beta_{\text{accessibility-car}} +$$
$$\text{accessbility}_{\text{public transport}} \times \beta_{\text{accessbility-PT}} + \text{foreigners} \times \beta_{\text{foreigners}} + \text{language} \times \beta_{\text{language}} +$$
$$\text{relative price} \times \beta_{\text{relative price}}$$

$$\textbf{Utility}_{\textbf{business}} = \text{land price} \times \beta_{\text{land price}} + \text{landuse density} \times \beta_{\text{landuse density}} +$$
$$\text{university degree} \times \beta_{\text{university degree}} + \text{tax partnership} \times \beta_{\text{tax partnership}} + \text{motorway access} \times \beta_{\text{motorway access}} +$$
$$\text{railway access} \times \beta_{\text{railway access}} +$$
$$(\text{accessbility car}_{\text{employees}} + \text{accessbility public transport}_{\text{employees}} - 11929/10972) \times \beta_{\text{accessibility}} +$$
$$\text{business promotion}_{\text{canton}} \times \beta_{\text{business promotion-canton}}$$

Appendix A5 Swiss household energy consumption 2015 in PJ (Prognos 2016b, own translation and formatting).

Household energy consumption in PJ (Prognos 2016)

	2000	2010	2011	2012	2013	2014	2015	Δ'00-'15
Space heating	167.5	192.2	149.0	168.1	185.5	139.7	154.4	-7.8%
Water heating	32.3	32.2	31.6	31.9	32.2	31.7	31.9	-1.2%
A/C, ventilation	3.6	4.4	3.8	4.2	4.7	3.9	4.4	21.9%
Entertainment, IT	5.4	5.5	5.3	5.1	5.0	4.8	4.6	-13.2%
Cooking, cleaning	8.8	9.3	9.3	9.3	9.4	9.5	9.6	8.8%
Light	5.7	5.7	5.4	5.1	4.9	4.5	4.1	-28.9%
Washing, drying	2.6	4.9	5.0	5.1	5.1	5.1	5.0	93.1%
Refrigeration	7.1	6.9	6.8	6.7	6.6	6.5	6.4	-10.2%
Other appliances	4.6	7.1	7.3	7.7	8.0	8.3	8.6	86.8%
Total	**237.7**	**268.2**	**223.4**	**243.4**	**261.3**	**214.2**	**229.1**	**-3.6%**

Appendix A6 Swiss energy consumption, mobility sector in 2015 in PJ (Prognos 2016a, based on BFS 2012, ARE 2012, own translation and formatting).

Energy consumption mobility 2015, by mode and trip purpose in PJ

Trip purpose	**Road**	**Rail**	**Air**	**Total**
in PJ				
Work	40.0	2.5	0.0	42.6
School	4.3	1.1	0.0	5.4
Shopping	23.2	0.8	0.1	24.1
Business	22.4	0.6	0.9	23.8
Leisure	66.4	2.8	0.6	69.8
Other	8.9	0.6	0.0	9.5
Total	**165.3**	**8.4**	**1.5**	**175.2**
Share in %				
Work	24.2%	29.7%	2.0%	24.3%
School	2.6%	13.2%	0.0%	3.1%
Shopping	14.1%	9.5%	5.0%	13.8%
Business	13.5%	6.7%	56.0%	13.6%
Leisure	40.2%	33.3%	37.0%	39.8%
Other	5.4%	7.6%	0.0%	5.4%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**
Energy share by Mode	94.3%	4.8%	0.9%	100.0%

Appendix A7 Specific heat demand by built period and dwelling type (GWS 2015: BFS 2017a).

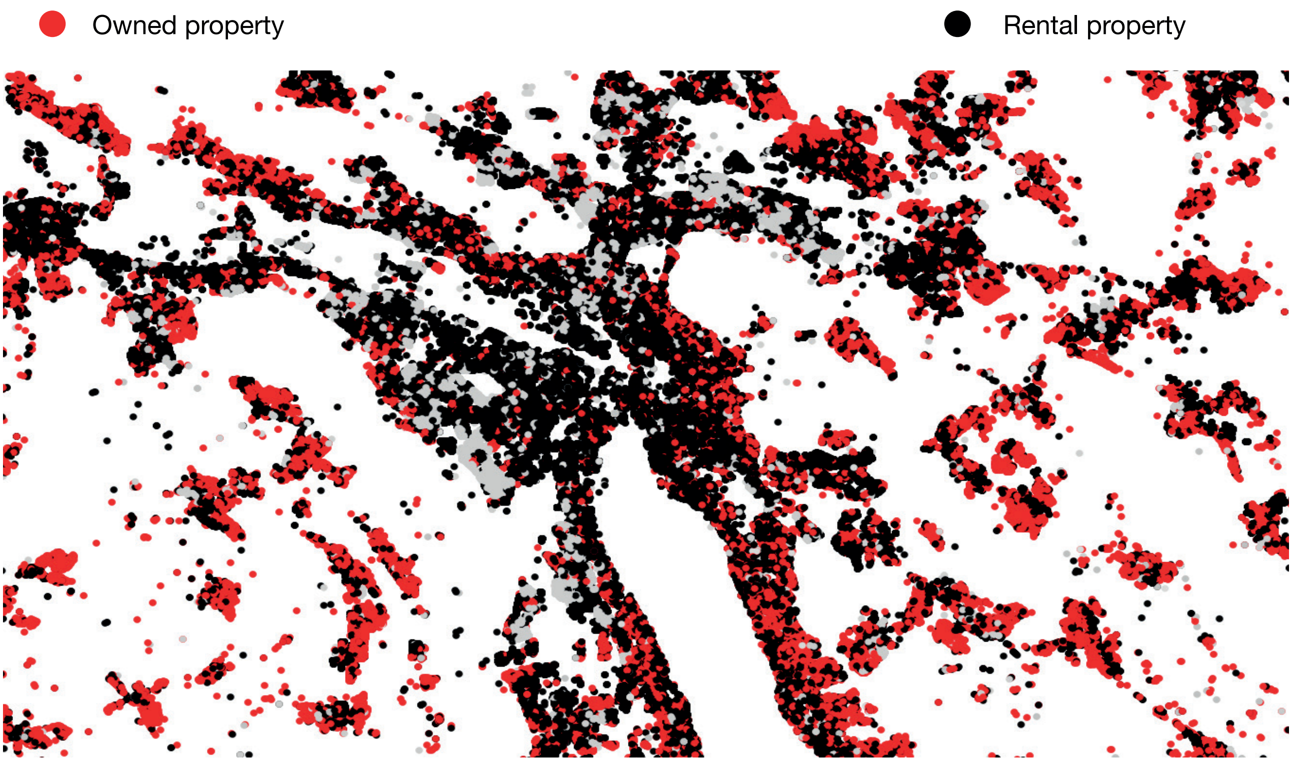
Energy values for space heating E_h in kWh/m² (UWE 2015)

Built period	Single family home (GWS: 1021)	Multiple flat dwelling (GWS: 1025)	Dwelling with additional functions (GWS: 1030)	Non-dwelling unit with flats (GWS: 1040)	Renovation effect E_s
Pre 1919	150	140	140	150	1.00
1919-1945	175	155	155	175	1.00
1946-1960	150	140	140	150	1.00
1961-1970	150	135	135	150	1.00
1971-1980	140	130	130	140	1.00
1981-1985	125	115	115	125	1.00
1986-1990	120	110	110	120	1.00
1991-1995	115	95	95	115	0.95
1996-2000	110	80	80	110	0.90
2001-2005	105	80	80	105	0.80

Share of building category in total building stock [-] (GWS 2015)

Built period	Single family home (GWS: 1021)	Multiple flat dwelling (GWS: 1025)	Dwelling with additional functions (GWS: 1030)	Non-dwelling unit with flats (GWS: 1040)
Pre 1919	0.0354	0.0562	0.0469	0.0077
1919-1945	0.0294	0.0365	0.0161	0.0030
1946-1960	0.0305	0.0520	0.0146	0.0024
1961-1970	0.0276	0.0704	0.0180	0.0028
1971-1980	0.0424	0.0644	0.0150	0.0027
1981-1985	0.0229	0.0243	0.0059	0.0011
1986-1990	0.0277	0.0284	0.0082	0.0019
1991-1995	0.0200	0.0282	0.0067	0.0014
1996-2000	0.0281	0.0258	0.0058	0.0009
2001-2005	0.0261	0.0261	0.0029	0.0005
2006-2010	0.0253	0.0397	0.0039	0.0006
2011-2015	0.0182	0.0390	0.0057	0.0008

Appendix A8 Spatial distribution of homeowners in the Zürich region (ARE 2017b, own translation).



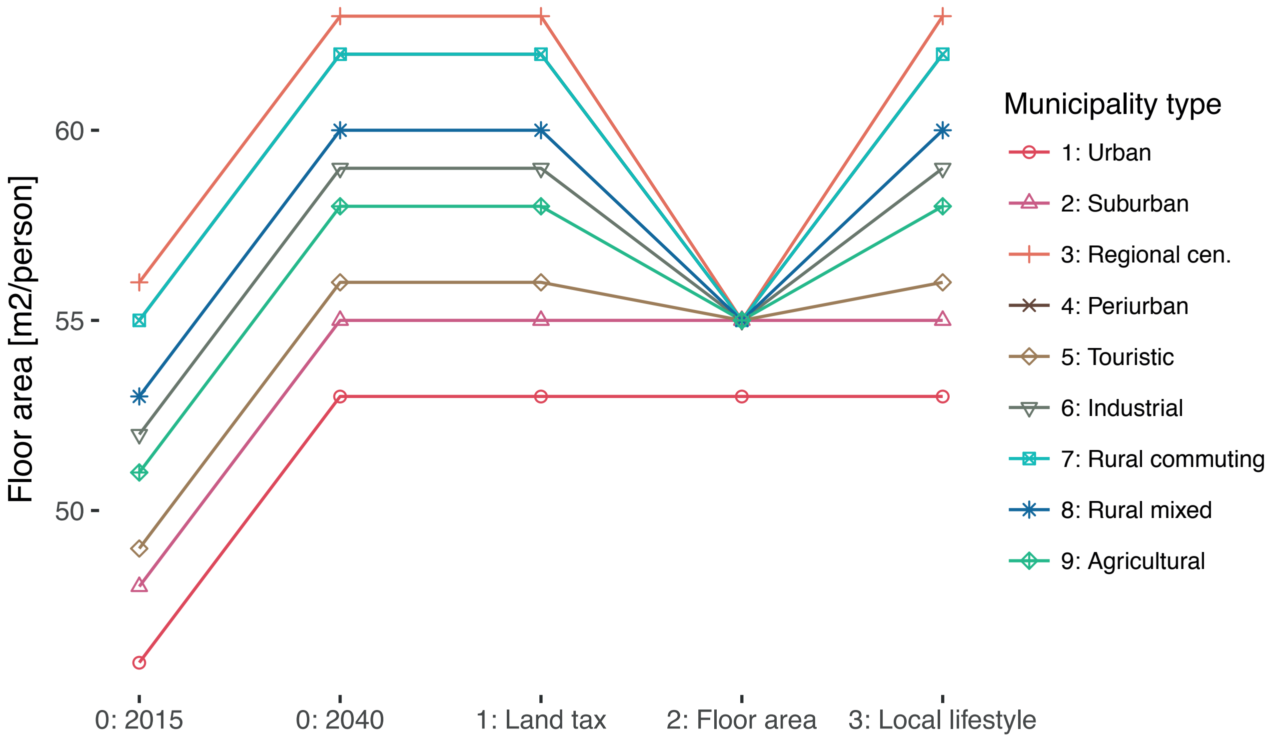
Appendix A9 Analysis of variance of household space heating by municipality and scenario, 0.95 confidence interval.

	Degrees of freedom	Sum squared	Mean squared	F-value	Pr(>F)	
Scenario	3	5.00E+14	1.67E+14	969.19	2.2E-16	***
NPVM-Zone	2943	3.30E+18	1.12E+15	6520.79	2.2E-16	***
Residuals	8829	1.52E+15	1.72E+11			

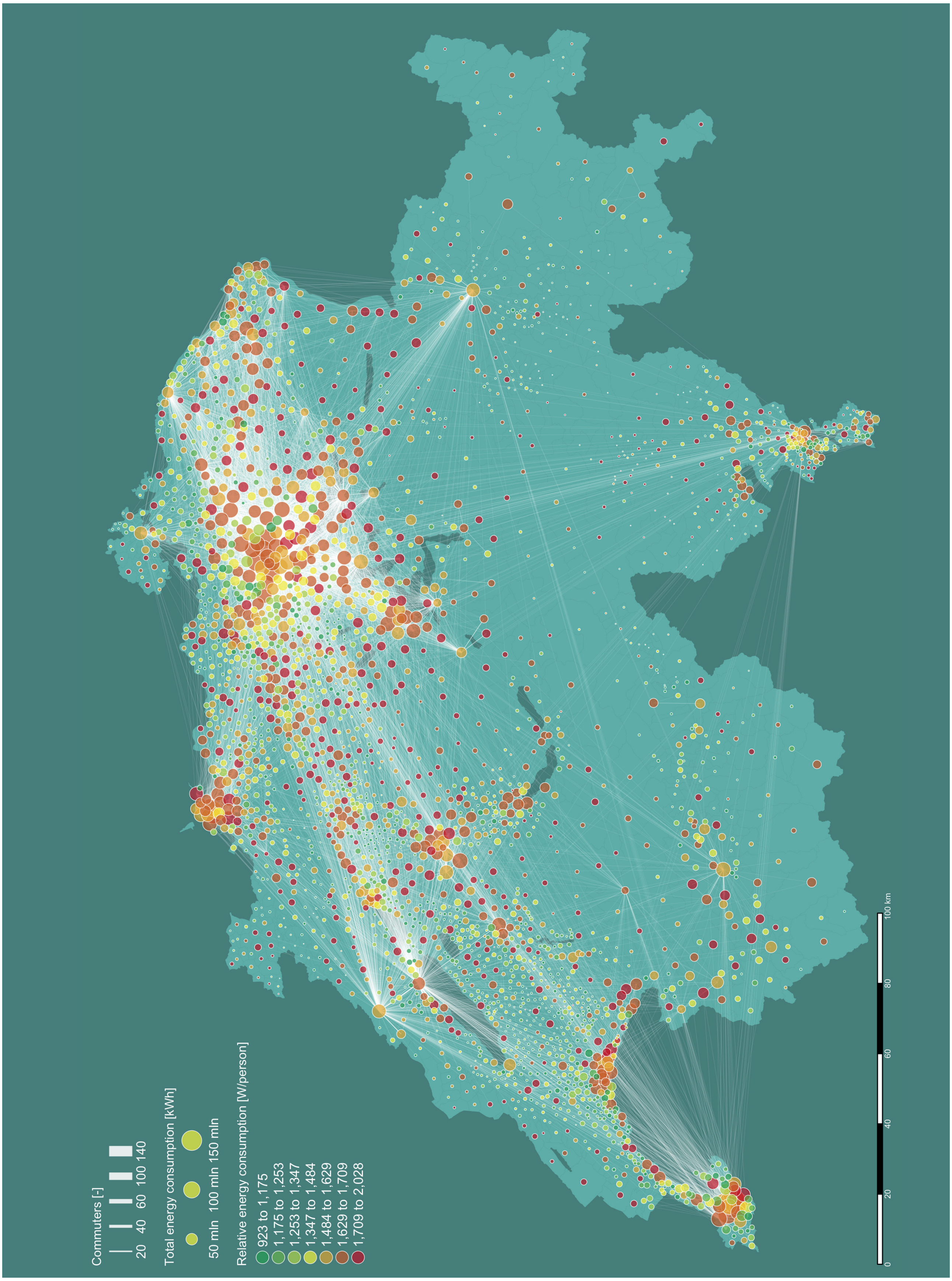
Appendix A10 Total person-kilometre travelled in modelled scenarios.

Commuting mode	Primary energy factor [MJ/pkm]	Mode share commuting [-]	0: 2015 [pkm]	0: 2040 [pkm]	1: Land tax [pkm]	2: Floor area [pkm]	3: Local lifestyle [pkm]
Human powered	0.00	0.05	17'174'628	32'199'192	33'243'625	33'641'907	33'641'907
Motorcar	3.31	0.62	196'792'608	368'949'076	380'916'535	385'480'188	385'480'188
Bus	1.66	0.04	11'449'752	21'466'128	22'162'417	22'427'938	22'427'938
Tram	1.21	0.01	4'293'657	8'049'798	8'310'906	8'410'477	8'410'477
Train	0.97	0.27	85'873'138	160'995'961	166'218'124	168'209'537	168'209'537
Other	1.47	0.00	1'431'219	2'683'266	2'770'302	2'803'492	2'803'492
	Total:	**1.00**	**317'015'001**	**594'343'421**	**613'621'908**	**620'973'539**	**620'973'539**
			Δ in pkm Scenario 0:2015:	**87%**	**94%**	**96%**	**96%**

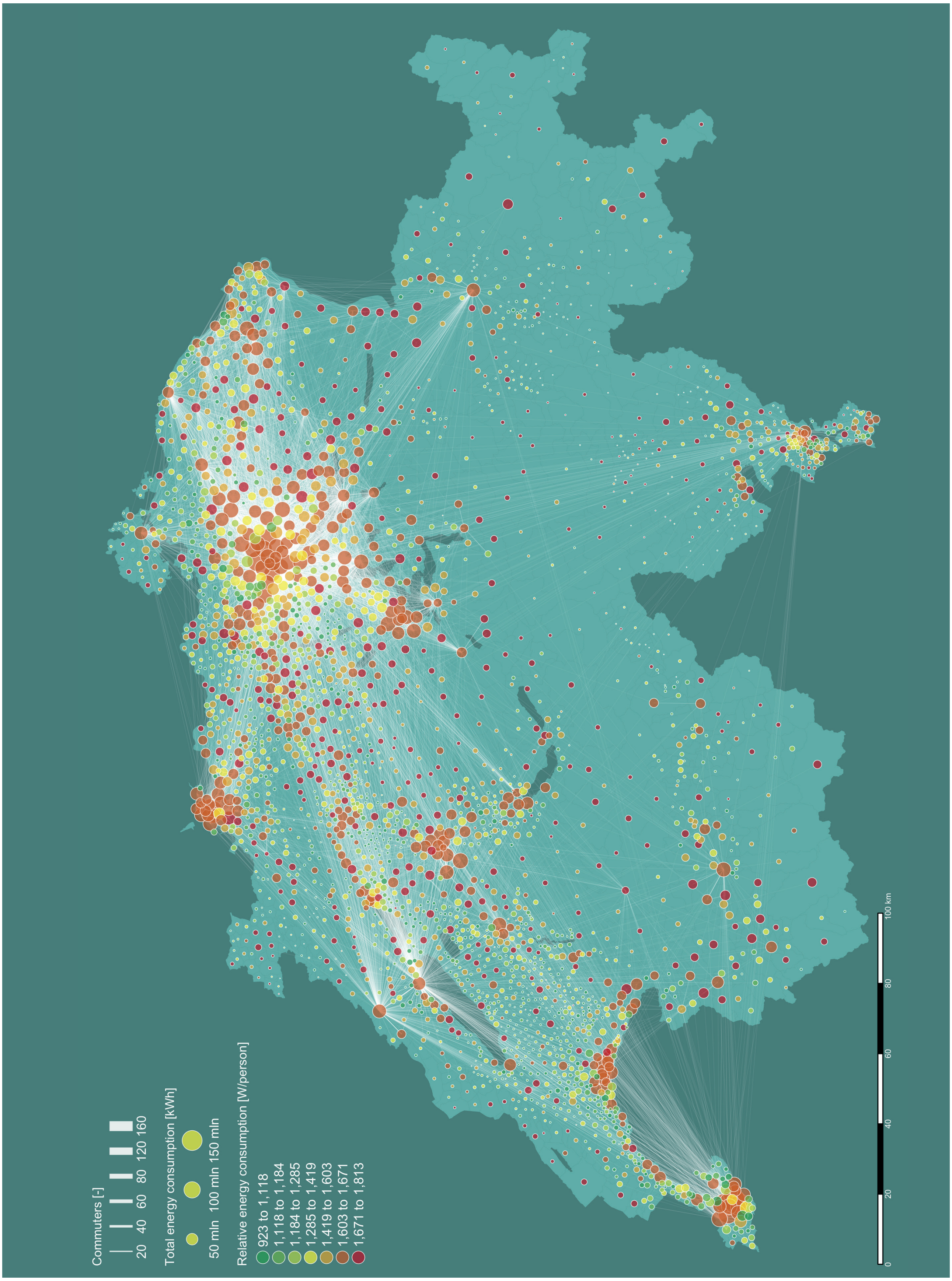
Appendix A11 Average floor area consumption by municipality type.



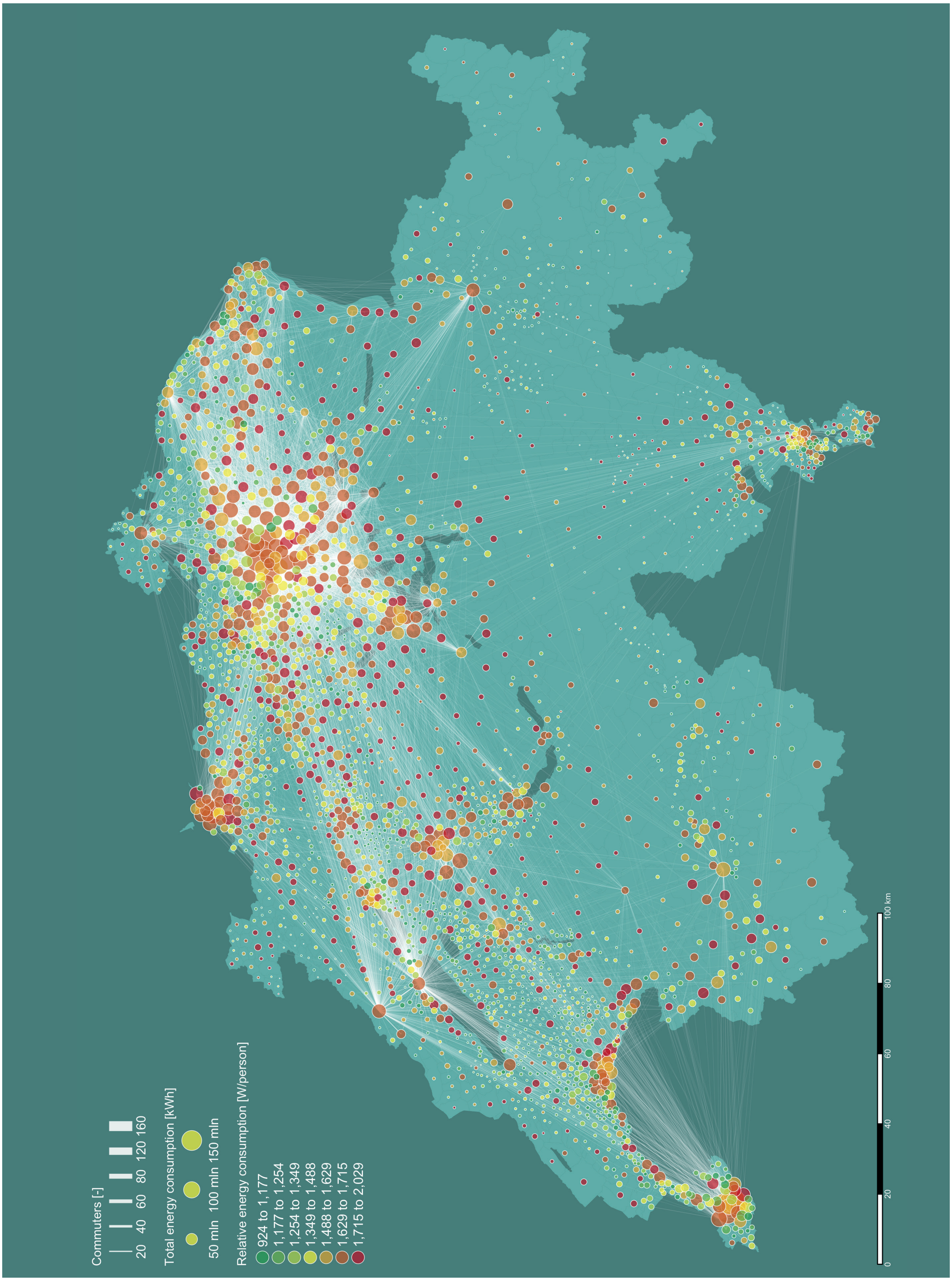
Appendix A12 Household space heating energy consumption and commuter flows Scenario 1: Land tax.



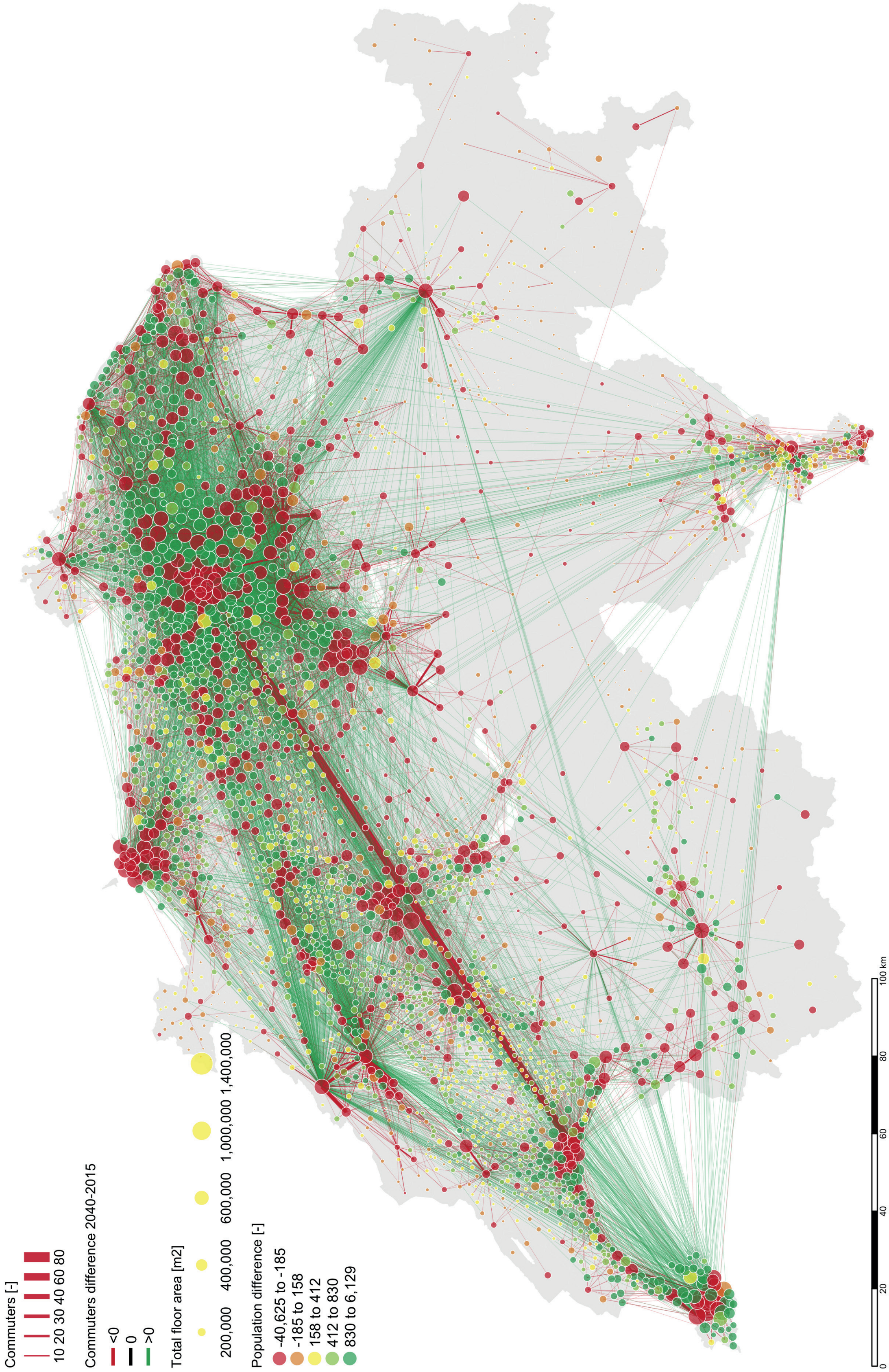
Appendix A13 Household space heating energy consumption and commuter flows Scenario 2: Floor area.



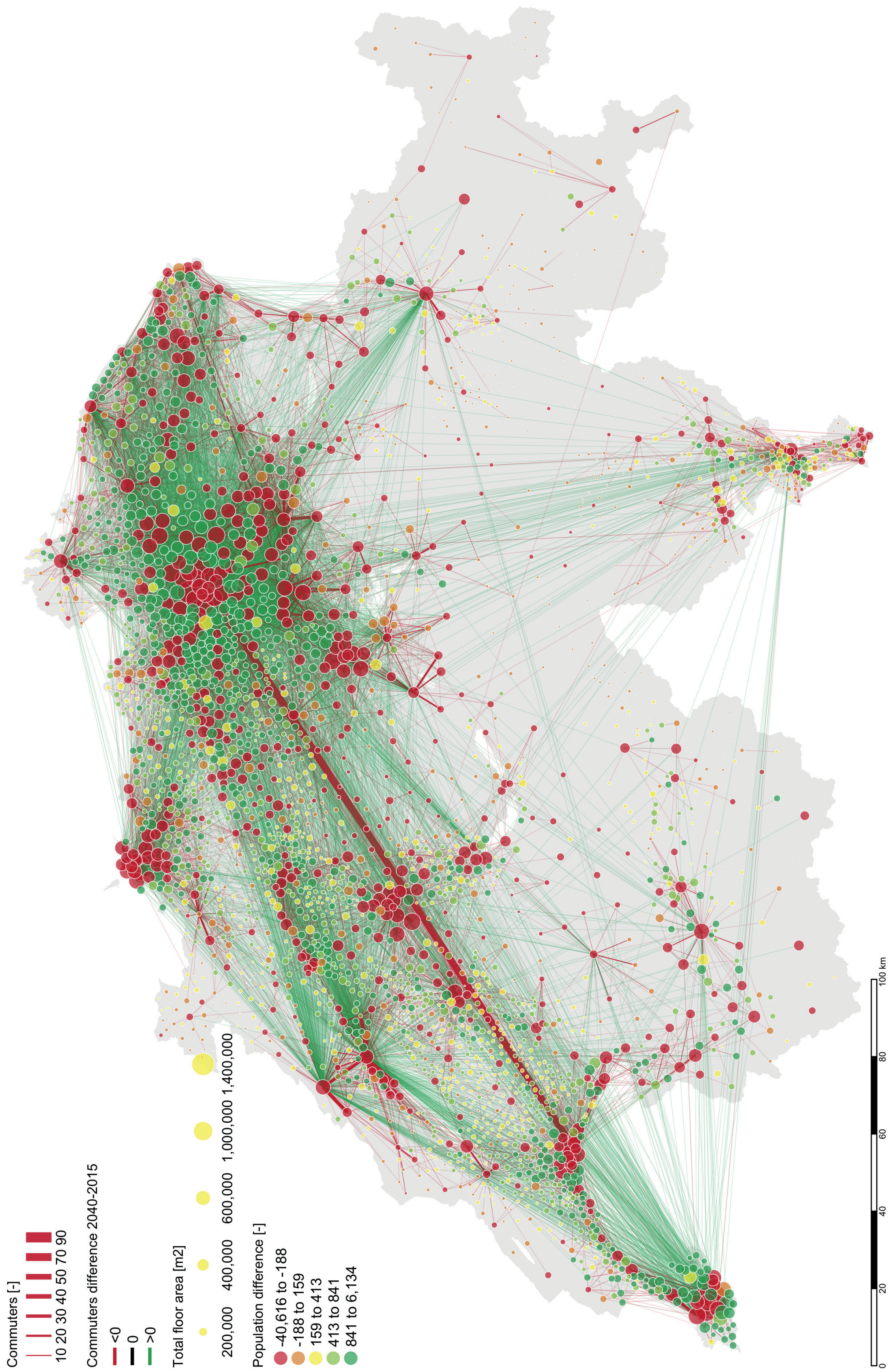
Appendix A14 Household space heating energy consumption and commuter flows Scenario 3: Local lifestyle.



Appendix A15 Difference in population, housing floor area and commuter flows to start year 2015 and Scenario 1: Land tax.



Appendix A16 Difference in population, housing floor area and commuter flows to start year 2015 and Scenario 2: Floor area.



Appendix A17 Difference in population, housing floor area and commuter flows to start year 2015 and Scenario 3: Local lifestyle.