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Long-term energy savings and greenhouse gas emission reductions in the Swiss residential sector

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Abstract

The aim of this paper is to explore the possibilities to reach two long-term targets regarding energy consumption and greenhouse gas emissions of the Swiss residential building stock: a reduction of the final energy consumption by a factor of 3 and of CO_2 emissions by a factor of 5 until 2050. A model is constructed to describe the dynamics of the energy-relevant properties of the residential building stock. Appropriate scenarios are discussed in terms of decisions made during construction or renovation of residential buildings which affect heat demand and determine the energy carriers used for heating and hot water generation. We show that both targets could be reached, although ambitious efforts are necessary. The central element of a successful strategy is to reduce the specific heat demand of existing buildings during renovation and to substitute the heating and hot water systems by less carbon intensive ones. Our results suggest that there is more flexibility to reach the emission target than the energy reduction target.

Keywords: Energy consumption; CO_2 emissions; Residential building stock

1. Introduction

The energy requirements of present civilizations are a key issue for sustainable development. Regarding the limited supply of non-renewable energy resources (especially fossil fuels) and the emission of greenhouse gases (GHG) affecting global climate (IPCC, 2001), it had been postulated that a sustainable energy system cannot be reached merely by substituting less sustainable resources by more sustainable ones, but also requires an overall reduction of present energy consumption levels, primarily in industrialized countries (Imboden, 2000; Imboden and Jaeger, 1999; Steger et al., 2002). In Switzerland as well as in many other countries, the operation of buildings (heating, cooling, hot water generation, lighting) consumes about half of the total national energy supply. In this study, we look at the Swiss residential building sector (key figures are presented in Table 1). We ask the question under which conditions two specific long-term targets could be reached, both of which are relevant for a sustainable energy future.

The first target addresses the sustainability of the present level of energy consumption and its variation between different countries. Presently, the average global consumption of primary energy is 2100 W/capita.[1] This figure varies between about 300 W/capita (e.g. in Bangladesh) and more than 10,000 W/capita (USA, Canada). It includes non-commercial energy, which amounts to about 10% of the global energy consumption. It has been suggested that an industrialized country like Switzerland could cover all its needs with 2000 W/capita instead of its present 6000 W/capita[2] (Imboden and Roggo, 2000; Jochem, 2004; Spreng, 2005; Steger et al., 2002). The concept of the '2000 Watt Society', promoted by the Board of the Swiss Federal Institutes of Technology in 1998 (ETH-Rat, 1998), has found its way into the 'Sustainable Development Strategy' of the Swiss Federal Council (2002) as a conception guiding

[1]The 2100 W corresponds to 66 GJ/yr or 18,400 kW h/yr (note: 1 W = 1 J/s).

[2]This number includes the net grey energy import of imported or exported goods; grey energy is the energy needed for the production of goods.

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Table 1
Key figures of the Swiss residential sector in the year 2000

Number of residential buildings	1.4 million	
Number of dwellings	3.6 million	
Permanently inhabited	3.1 million	
Temporarily inhabited	0.4 million	
Not inhabited	0.1 million	
Living space see Fig. 4 (year 2000)		
Share of heating systems see Fig. 1 (year 2000)		
Ownership of dwellings		
Tenant		59%
Homeowner		35%
Member of a co-operative		4%
Other		2%
Final energy consumption of Switzerland by sector (PJ/yr)		
Total		855
Residential sector		231
Heating and hot water (by fuel see Fig. 7a (year 2000))		194
Lights, appliances, cooking[a]		37
Industrial sector		168
Service sector		140
Transport sector		302
Agriculture sector		14
CO_2 emissions see Fig. 7b (year 2000)		

Nearly a fourth of the final energy consumption in Switzerland is due to heating and hot water generation in the residential sector. Switzerland has the smallest share of home owner households in Western Europe. Most people live in tenant households (BFE, 2005; BFS, 2004a,b).

[a]Assuming 65% of electricity is used for lighting, appliances and cooking (Jochem and Jakob, 2004).

energy and climate protection policy and was set as strategic goal for 2050 in the master plan of the Federal Energy Research Commission (CORE, 2004). This would mean a reduction of Switzerland's present per capita consumption by a factor of 3 in the next 45 years.

The second target is related to the goal put forward by a number of governments and organizations, such as the European Union, to limit the global warming due to GHG emissions to 2 °C above pre-industrial temperatures (European Council, 1996, 2005). According to Meinshausen (2005) and Den Elzen and Meinshausen (2005) the translation of this goal would result in a GHG emission reduction for industrialized countries of approximately 80% compared to the 1990 emissions. Regarding the uncertainties of present climate models this reduction would allow to reach the 2 °C target with a probability of 75%. A larger certainty would require an even greater emission reduction. For the case of Switzerland, the Federal Energy Research Commission (CORE, 2004) has set as target 1 ton of CO_2 per capita and year by 2050 which means a reduction by a factor of 6, which is even more than the mentioned 80% reduction. Other European countries have defined similar long-term targets for GHG emission reductions ranging from 50% to 80% (Kawase et al., 2006). Studies discussing the possibilities of reaching these targets were conducted, for example, for the Dutch energy system (Treffers et al., 2005) and for the UK building sector (Johnston et al., 2005).

For both, the 2000 W/capita target and the 2 °C target, we analyse the conditions under which the energy demand and the CO_2 emissions of the residential building sector could be reduced by the required amount, i.e. by a factor of 3 for the energy demand and to 20% of 1990 emissions for CO_2.

For our investigation the residential building sector was chosen due to four reasons: Firstly, in Switzerland the current energy demand for heating and hot water generation in the residential sector amounts to a fourth of the total final energy demand (Table 1). Secondly, the technologies for improving the energy efficiency of new and refurbished buildings and the potentials to switch to less carbon intensive or carbon free energy resources are well known. Thirdly, the development of the residential building stock follows certain rules which are driven by the conservation of investments, the demand for living space, and the operating costs due to energy consumption. It can be assumed that these driving mechanisms do not change drastically over time. Therefore, the dynamic behaviour of the residential building stock can be modelled fairly easily. Fourthly, buildings together with the infrastructure (roads and railways, water supply and waste water disposal, supply of electricity, gas, etc.) represent the most important 'memory' of the anthroposphere and thus determine the speed at which the constructed world can be transformed (Steger et al., 2002). Given the present investment into the building and infrastructure it would take about 60 years to rebuild Switzerland. In contrast, the Swiss car pool is completely exchanged once every 11 years. Thus, changes of the present energy system have first to be focussed on the building sector.

In this paper, it is shown how the mentioned targets could be reached until 2050. Appropriate scenarios are discussed in terms of decisions made during construction or renovation affecting heat demand and determining the energy carriers used for heating and hot water generation. In order to describe the energy demand and the CO_2 emissions of the Swiss residential building stock, a simulation model was developed by extending the residential building stock model of Wüest & Partner (1994). This model has been designed to predict the construction activity due to renovation or construction of residential buildings according to the supply and demand of living space. In addition to the evolution of the living space, the model accounts for changes in the heat demand per area and the energy resources used for heating and hot water generation.

The outline of this paper is as follows. The method and the simulation procedure is presented in Sections 2 and 3; in Section 4, the origin of the input data are presented and discussed in Section 5. Finally, the results are evaluated in terms of the goals of energy and climate policy discussed above.

2. Method

To show under which circumstances the mentioned targets can be reached until 2050, the energy demand and the CO_2 emissions are computed according to different 'forced action scenarios' and compared with the reference scenario (business as usual). A scenario is defined by a specific set of input parameters, which is relevant for the energy demand and the mix of energy resources by which the demand is covered. The values for the input parameters are presented in Section 4. The reference scenario is constructed by extrapolating present trends into the future. In the forced action scenarios a limited number of parameters is altered relative to the reference case.

If a new building is constructed, the owner has to decide on the energetic quality of the building structure (energy standard) and choose the energy source for heating and hot water generation. Thus the heat demand and the corresponding CO_2 emissions of the building are defined during construction. These parameters are only changed during renovation when energy standard as well as energy carrier are altered. Renovations regularly occur after a certain time period. It is a common concept in Switzerland to renovate buildings periodically in order to conserve their value. This concept is also applied by planners and owners of buildings to schedule the maintenance of the buildings (see e.g. Christen and Meyer-Meierling, 1999). Renovation cycles are not prescribed by law but are common practice of reinvestment.

All simulations start from the existing building stock in 2000 (the initial state). The heat demand per area (HDA) of the stock is assumed to depend only on the year of construction or last renovation of the buildings. The energy carriers of these buildings for heating and hot water generation are determined according to the data of the Swiss Census 2000.

In the reference scenario, the HDA of new buildings depends on the year of construction and corresponds to the current SIA[3] standard by 2013. The HDA of buildings undergoing renovation is reduced by a few percent depending on the year of construction (see Section 4). Heating systems are implemented in new buildings according to the relative shares shown in Fig. 1a and altered during renovation according to the substitution matrices of Fig. 1b. Corresponding rules for new construction and renovation are defined for hot water generation.

In the forced action scenarios, new buildings are constructed and existing buildings are renovated according to alternative energy standards, but the renovation interval remains the same as in the reference scenario. The alternative energy standards, labelled as A to F, are defined relative to the HDA of new buildings of reference standard R (Fig. 2). Note that R is the same as the standard E. As a consequence of technological improvements the heat demand decreases with time for all energy standards including the reference standard.

Some of the chosen energy standards correspond to established norms. Standard D and F are defined according to the MINERGIE[4] standard for new and refurbished buildings, respectively. Standard A is comparable to the MINERGIE-P[5] standard, to the German Passive House[6] standard and to the target standard A of buildings compatible with the 2000 Watt society (Preisig and Pfäffli, 2004).

Compared to the reference scenario, the forced action scenarios are characterized by less carbon intensive systems for heating and hot water generation (gas or renewable energy). The corresponding shares and substitution matrices for heating systems are shown in Fig. 1c–f for single family houses.

An overview of the discussed scenarios is given in Table 2. The scenarios branch off from the reference case in 2006. They have in common that the action taken remains constant over time. For example, in scenario DF1 the energy standard of all buildings undergoing renovation is changed from R (reference) to F while the heating and hot water systems are substituted according to the matrices of forced action 1 (e.g. Fig. 1d for single family houses). Furthermore, buildings constructed after 2006 have energy standard D and heating and hot water systems according to forced action 1 shown in Fig. 1c for single family houses.

The scenarios listed in Table 2 are used to calculate energy demand and CO_2 emissions for well defined forced action scenarios. Obviously, in the real world energy related measures would not remain constant with time as in these scenarios. The scenarios are not constructed as potential real paths into the future but rather span the space of possible developments, that is, indicate lower and upper limits for future energy needs and CO_2 emissions of the Swiss residential building sector.

3. Model

The model describes the temporal development of the Swiss building stock and its energy demand due to heating and hot water generation. The building stock is characterized by the energy reference area (ERA), which is a measure for the effective heated area according to the definition by the Swiss Society of Engineers and Architects

[3]The SIA 380/1 standard of the Swiss Society of Engineers and Architects (SIA, 2001) is widely used in Switzerland as regulatory law. It defines a target value for the allowed heat demand (upper bound) and the rules to calculate the heat demand for different buildings. The target value depends on the ratio of building envelope and Energy Reference Area (ERA, 'Energiebezugsfläche') (see Jakob et al. (2002) for specific values) and hence depends on the building type. The specific heat demand is 240 and 200 $MJ/(m^2\,yr)$ for typical single family and multifamily houses, respectively.

[4]The registered trademark MINERGIE is a quality label for new and refurbished buildings with low-energy demand. See www.minergie.com for details.

[5]The MINERIGE-P standard is an advanced MINERGIE standard.

[6]The German Passive House standard is widely comparable to the Swiss MINERGIE-P standard. See www.passivhaus-institut.de for details.

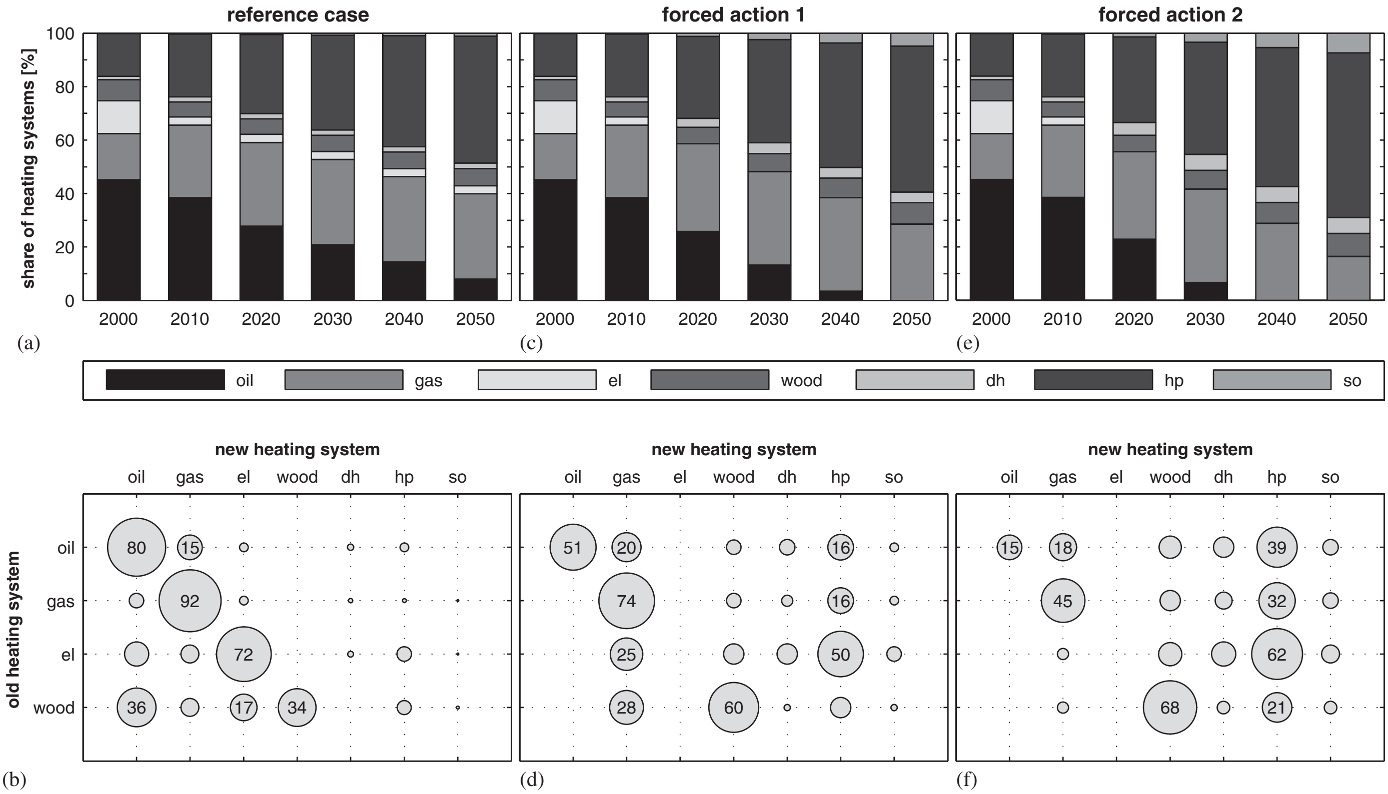

Fig. 1. Assumed dynamics of heating systems (HS) in single family houses (SFH) for the reference case (a) and (b), the forced action 1 (c) and (d) and the forced action 2 (e) and (f). Upper row: Relative share of systems installed in new buildings. Lower row: Substitution matrices for heating systems (HS) during renovation. The area of the circles is proportional to the probability (percentage) of the new HS for a given old HS. The systems are oil, gas, electricity (el), wood, district heating (dh), heat pump (hp), solar (so). Note that no substitutions of existing dh-, hp- and so-systems are assumed. Forced actions differ from reference mainly by higher substitution of oil supplied systems by renewable energies. Forced action 2 assumes a higher substitution of gas. In both forced action electrical heating is always replaced, but not by oil or gas.

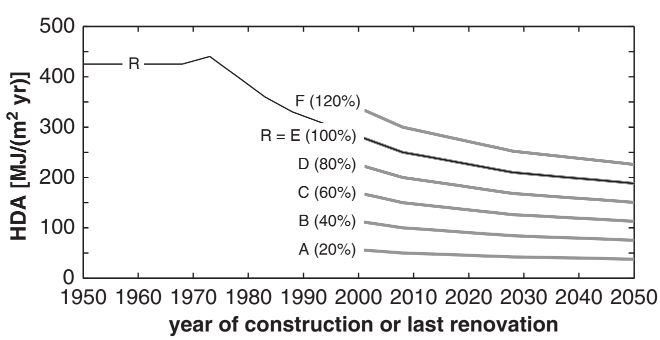

Fig. 2. Heat demand per area (HDA) for new single family houses (SFH) by year of construction for the reference energy standard R and the alternative standards A, B ... F defined as 20%, 40% ... 120% of the HDA of the reference standard of new buildings. Similar curves are defined for small and large multiple dwellings (not shown here). HDA for buildings constructed before 1950 is the same as in 1950.

(SIA, 1982).[7] We classify the ERA according to building type (BT), energy standard (ES), construction year, type and time of renovation, and the implemented heating and hot water systems (HS and WS). The meanings of these parameters are explained below. The future building stock is calculated from the existing one, represented by a list of ERA classified by the parameters above, by successively applying updating rules for each year, which take into

Table 2
Scenarios characterized by the energy standard of new and refurbished buildings (see Fig. 2) and systems for heating and hot water generation (reference, forced actions 1 and 2, see Fig. 1)

Label	Energy standard		Heating and hot water systems (forced action)
	New	Refurbished	
RRr	R	R	Reference
RR1	R	R	1
DF1	D	F	1
DF2	D	F	2
AF1	A	F	1
AC1	A	C	1
AC2	A	C	2
AA1	A	A	1
AA2	A	A	2
ZZ1	Z	Z	1
ZZ2	Z	Z	2

Z = energy standard of buildings with no heat demand (“zero energy house”).

[7]ERA corresponds to “Energiebezugsfläche” (EBF) in the referenced German publication.

account the changes due to renovations and demolition as well as the demand for new buildings.

3.1. Renovation submodel

Every building (represented by the corresponding ERA) is subject to a sequence of renovations, which are determined by the renovation period (RP) and the fraction of realized renovations f_r. The renovation period gives the time between construction (or renovation) and subsequent renovation. The parameter f_r defines the fraction of these buildings which really undergo renovation when RP is reached. The two parameters, RP and f_r, determine the regularly occurring renovations of buildings. For both the renovated as well as the not renovated buildings, the next option for renovation is given after another RP, see Fig. 3.

We distinguish between two types of renovations: partial renovation (PREN) and total renovation (TREN) which alternate, starting with PREN one RP after construction. Partial renovation includes replacement of service units such as kitchen, bath and heating. In addition to PREN, TREN includes the building structure (e.g. insulation of facade, replacement of windows). By upgrading still unused space (e.g. attic) TREN can also cause ERA to increase. In the model this is described by the retrofit gain, i.e. the relative gain of ERA. Buildings (or ERA) skipping a renovation undergo a TREN after the next RP.

The model describes also the loss of ERA by demolition. Demolition is described by a probability function which increases with the elapsed time since the last renovation (PREN or TREN). Since for the actual model runs described below the probability is zero for elapsed times smaller than RP, only these building which have skipped a renovation are subject to demolition.

Up to here the procedure closely follows the one used by Wüest & Partner (1994). These authors modelled the evolution of ERA in Switzerland without looking at energy standards and energy carriers. In contrast this model classifies buildings (or ERA) by ES, HS and WS and their changes during renovations. During a PREN only HS and WS can be altered. Changes of ES are only possible during TREN. Changes are determined by the building type and the actual ES of the building. The changes of HS and WS are described by substitution matrices (see Fig. 1). Substitution of WS depends on the newly installed HS. All these fractions depend on BT. If renovation is skipped after time RP, replacement of HS and WS still occurs but is restricted to efficiency improvements and does not allow for alteration of the energy carrier.

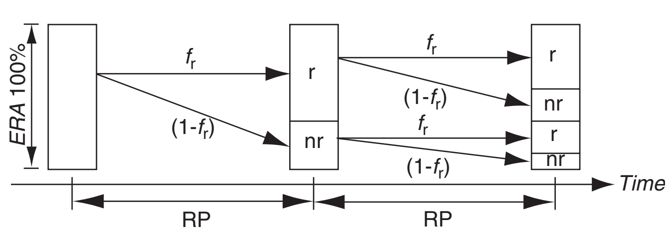

Fig. 3. Sequence of renovation: after each renovation period (RP) a certain fraction f_r of energy reference area (ERA) undergoes renovation (r) or retains its state (nr) until the next renovation time is reached.

3.2. New construction submodel

New ERA is constructed if the demand (DERA) exceeds the actual stock. The demand is calculated separately for each building type as

$$\mathrm{DERA(BT)} = \left(\sum \mathrm{P} \times \mathrm{OR}\right) \times f_{\mathrm{B}}(\mathrm{BT}) \times \mathrm{ERAF(BT)}, \quad (1)$$

where P is the population divided into segments by age, sex and nationality (Swiss/foreigner), OR is the segment-specific relative occupation ratio for all building types, $f_{\mathrm{B}}(\mathrm{BT})$ is the BT-specific demand fraction and ERAF(BT) is the mean ERA per flat of type BT.

In Eq. (1) the sum over $(\mathrm{P} \times \mathrm{OR})$ runs over all population segments yielding the total number of flats. Note that OR includes the demand for secondary living space (recreation, etc.) as well as a small fraction of presently uninhabited flats.

If DERA falls below the actual total ERA, the retrofit gain (see above) is reduced. If this does not compensate the decrease in demand, part of ERA becomes empty. Then demolition may cause total ERA to decrease.

Again, the procedure follows the model by Wüest & Partner (1994). In addition, input parameters are used to assign energy standards, heating and hot water systems according to the probabilities given in Fig. 1.

3.3. Energy consumption and CO_2 emissions

The energy demand for heating (EDH) and hot water generation (EDW) is expressed as

$$\mathrm{EDH(BT, ES, HS)} = \mathrm{ERA(BT, ES, HS)} \times \frac{\mathrm{HDA(BT, ES)}}{\mathrm{EEH(HS)}}, \quad (2)$$

$$\mathrm{EDW(BT, WS)} = \mathrm{P} \times n(\mathrm{BT}) \times \mathrm{HWD} \times \frac{\mathrm{SED}}{\mathrm{EEW(WS)}}, \quad (3)$$

where BT is the building type, ES is energy standard, HS, WS is type of heating and hot water system, respectively, HDA is heat demand per area, EEH, EEW is energy efficiency of heating and hot water system, respectively, P is total population, $n(\mathrm{BT})$ is the fraction of P living in a building of type BT, HWD is the hot water demand per capita, SED is the specific energy demand (given in energy demand per volume).

Finally, the CO_2 emissions are obtained from energy consumption with the help of emission factors of the respective energy carriers.

4. Data

In this section, we summarize the origin of the data for the input parameters. We indicate where data are based on our own assumptions.

4.1. Initial building stock

The building stocks for 1990 and 2000 were obtained by evaluating the Swiss Census 1990 and 2000 (BFS, 1990, 2000). The older data set is used to validate the simulation procedure (see Section 5), the younger serves as the initial state for the scenario calculations. The building stock is given as energy reference area (ERA) categorized by construction year, building type (BT), type and time of last renovation, energy standard, heating and hot water system. We distinguish between three BT: single family house (SFH, one to two flats), small multiple dwelling (SMD, three to six flats) and large multiple dwelling (LMD, more than six flats). Buildings not exclusively used for living (e.g. including office space) are characterized according to the total size of the building. The heating and hot water systems are divided into seven categories: oil, gas, electricity, wood, district heating, heat pump and solar. Initially, all buildings are assumed to have 'reference energy standard'. Note that ERA is not identical with the living area obtained from the census but 20% larger (Preisig and Pfäffli, 2004).

In the census data the time of renovation is only given if the renovation took place during the last 30 years, but even then the type of renovation is not known. Therefore, time and type of renovation of the initial building stock were assigned by applying the renovation rules described above to each building from its construction year to the time when the simulation begins (1990 or 2000).

4.2. ERA demand

The population segments are taken from the scenario 'Trend' of the Swiss Federal Statistical Office (BFS, 2004c) extending to the year 2040. The scenario is extrapolated to 2050 using to the trend given in (BFS, 2002). The total population increases until 2030 and decreases thereafter (Table 3). The segment specific occupation ratio (OR) was extracted from the same census data of 1990 and 2000 (BFS, 1990, 2000). The observed slight increase of OR results mainly from the growing numbers of single households, of older people and of secondary homes. The relative growth rates of OR are assumed to be cut in half each decade until 2050. The relative demands (f_B) as well as ERA per flat (ERAF) were also extracted from the 1990 and 2000 census. The data are given in Table 3.

A constant renovation period (RP) of 25 years is assumed. This value is also used by Wüest & Partner (1994), Christen and Meyer-Meierling (1999) and Schwaiger (2002).

If not mentioned otherwise, the fraction of realized renovations (f_r) is 0.7 as Wüest & Partner (1994) propose. This means that in the long run 70% of the residential buildings are periodically renovated. The demolition factors, also taken from Wüest & Partner (1994, Fig. 4.6, p. 21), are 0.6% and 3% 50 years after construction and PREN, respectively, increase to 6% and 34% 75 years after construction and PREN, respectively, and reach 100% 119 years after construction and 92 years after PREN. The BT-dependent retrofit gain was calculated from the 1990 and 2000 data to be 79% for SFH, 49% for SMD and 58% for LMD. Besides upgrading unused space, the numbers also include changes of use, e.g. when industrial space is transformed to flats. Since most new buildings already use the maximum space allowed by law, the retrofit gain is assumed to decrease linearly with time to reach zero in 2030.

Table 3
Input parameters and results for the reference scenario from 1990 to 2050

			1990	2000	2010	2020	2030	2040	2050
Population (P)		(million)	6.75	7.20	7.48	7.54	7.55	7.43	7.29
Relative demand according to BT (f_B)	SFH	(%)	32.4	32.9	33.4	33.9	34.4	34.9	35.4
	SMD	(%)	20.4	19.8	19.7	19.5	19.4	19.2	19.1
	LMD	(%)	47.2	47.3	46.9	46.6	46.2	45.9	45.5
ERA per flat (ERAF)	SFH	(m^2)	145	153	160	165	168	170	172
	SMD	(m^2)	101	106	110	113	115	116	117
	LMD	(m^2)	90	92	94	96	98	99	100
Total demand of flats		(million)	3.13	3.58	3.90	4.08	4.13	4.05	3.97
Total demand of ERA (DERA)		(million m^2)	344	411	465	501	518	515	511
Hot water demand per capita		(m^3/(cap yr))	18.3	18.5	18.7	18.9	19.1	19.3	19.5
Specific energy demand for hot water generation		(MJ/m^3)	146	146	146	146	146	146	146
Final energy consumption for heating		(PJ/yr)	200	205	199	189	178	168	159
Final energy consumption for hot water		(PJ/yr)	24	26	27	28	28	28	27
Final energy consumption total		**(PJ/yr)**	**224**	**231**	**226**	**217**	**206**	**196**	**186**
CO_2 emissions		**(Mt CO_2/yr)**	**12.3**	**12.5**	**12.2**	**11.6**	**11.0**	**10.5**	**10.0**

4.3. Energy demand and emissions

The installation of heating systems in buildings constructed between 1990 and 2000 were extracted from the Swiss Census 2000 (see Fig. 1a for SFH). The assumed trend for the period 2000 to 2030 is similar as in Prognos (1996) and Aebischer et al. (2002). It implies increasing shares of heat pumps and gas supplied hot water systems (HS) at the expense of oil and electricity. For SMD and LMD the quota for gas becomes even more important.

The substitution matrices for HS were obtained from the census data in two steps: a first estimation was obtained by comparing the Swiss Census 1990 and 2000 data. This procedure does not properly account for substitutions of heating systems of the same type. Then the substitution matrices were adjusted (fitted) until the model (started with the initial data for 1990 and run till 2000) would reproduce the actual distribution of heating systems in 2000 for buildings constructed before 1990. The resulting substitution matrix for SFH is shown in Fig. 1b. Similar results are obtained for SMD and LMD. Analogously, the fraction of new hot water systems for new and refurbished buildings of type SFH, SMD and LMD, respectively, were calculated. The resulting ERA for the year 2050 is shown in Fig. 4.

The specific heat demand (HDA), shown for new SFH in Fig. 2, follows the data by Prognos (1996) and Aebischer et al. (2002) until 1990, decreases faster after 1990, reaches the SIA standard (SIA, 2001) for new buildings in 2013 and the current MINERGIE standard by 2050. Based on Aebischer et al. (2002) it is assumed that during a PREN and a TREN, HDA is reduced at most by 8% and 15%, respectively, depending on the year of construction and building type. Not every refurbishment leads to a reduction in heat demand; often buildings are only repainted or kitchen or bath are renewed. This explains the rather small HDA reduction achieved by renovations.

Data for the energy efficiency of heating and hot water systems are taken from Aebischer et al. (2002) as well as for

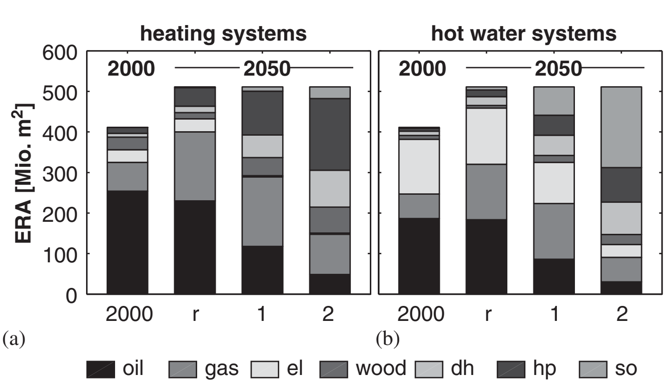

Fig. 4. Total energy reference area (ERA) of Swiss residential sector subdivided (a) by heating system and (b) by hot water system. Data are shown for the initial building stock in 2000 (left bar) and for the final building stock in 2050 for the reference case (r) and for the forced actions scenarios 1 and 2. The heating and hot water systems are oil, gas, electricity (el), wood, district heating (dh), heat pump (hp), solar (so).

Table 4
CO_2 emission factors for different energy sources in Switzerland according to the Swiss Greenhouse Gas Inventory (SAEFL, 2005)

Energy source	Emission factors (ton CO_2/TJ)
Oil	73.7
Gas	55.0
Electricity	0
District heating	12.8
Wood	0
Solar	0

The current district heating energy is made up by 25% of fossil energy. In Switzerland electricity is produced by hydroelectric and nuclear power and therefore virtually free of CO_2 emissions. The emission factors are assumed to be constant over time implicating a future contribution of fossil energy to district heating of 25%.

the per capita hot water demand and its specific energy demand (Table 3) and the fraction of people living in different building types. The data are extrapolated from 2030 to 2050. The emission factors of the Swiss GHG inventory (SAEFL, 2005) for CO_2 are given in Table 4. They are kept constant for the simulation period. Finally, for district heating the present relative partition among the different energy resources is used (Swiss energy statistics (BFE, 2005)).

5. Accuracy and limitations

In this section, we address the accuracy and the limitations of the simulation procedure. The accuracy of the projections presented in this work depends on both, the uncertainties in the input scenarios and the accurateness of the updating procedure. The later is mainly determined by the parameters ‘renovation period’ and ‘fraction of realized renovations’.

One has to keep in mind that not every parameter has the same influence on the overall uncertainty of energy demand and emissions. Information on the existing building stock at the beginning of the simulation period and the assumptions made regarding frequency and nature of the renovations have the largest impact on the long-term behaviour of the model. Unfortunately, the temporal resolution of the data from the census regarding the initial building stock is coarse (intervals of 5 years for newer buildings, up to 15 years and more for old ones). This has to be kept in mind when looking at the simulation runs shown below where for computational reasons a time resolution of one year has been adopted.

To check the reliability of the updating procedure we run simulations from 1990 to 2005, starting with the building stock obtained from the 1990 census, and compare the results for the year 2000 with the building stock obtained from the Census 2000 data. As it turns out, the development of ERA for new and old buildings can be reproduced fairly well. In Fig. 5 we compare the modelled final energy consumption and CO_2 emissions with the real data from the energy statistics. The simulation shows a small

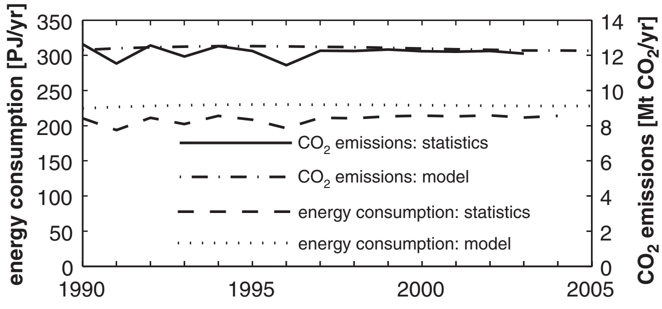

Fig. 5. Final energy consumption and CO_2 emissions from 1990 until 2005. Results from model simulations starting in 1990 are compared with data from the Swiss energy statistics (BFE, 2005) by assuming that 65% of the electricity is used for home appliances and lighting (Jochem and Jakob, 2004) and has to be subtracted from the residential final energy consumption. Furthermore, data from the Swiss GHG inventory (SAEFL, 2005) are used. Both datasets have been corrected according to the annual heating degree days.

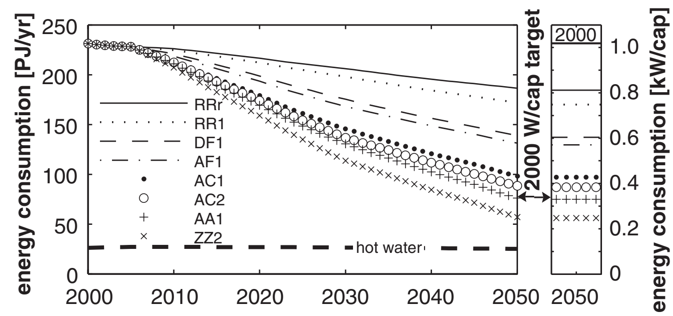

Fig. 6. Total final energy consumption for heating and hot water generation in the Swiss residential sector from 2000 to 2050 (left) and per capita energy consumption in 2050 compared to 2000 (right). Results for different scenarios are shown and the required target is displayed. See Table 2 for definitions of scenarios.

overestimation in the energy consumption. This may be ascribed to the secondary homes and flats which in the simulation are assumed to be fully heated year-round. Since the Census 2000 data indicate that in secondary homes the relative fraction of electricity and wood is significantly larger than in primary homes, the CO_2 emissions are expected to be less sensitive to the presumed effect from the secondary homes,[8] hence, the better agreement found for CO_2 emissions in Fig. 5. In any case, one has to keep in mind that the focus of the simulations presented below is primarily on relative changes in energy and emission targets and not on absolute values.

6. Results and discussion

In this section, the potential is analyzed to reduce the energy demand and CO_2 emissions of the residential sector to levels which are compatible with the goal of the 2000 W/capita and the 2 °C climate target. The appropriate pathways are discussed in terms of the scenarios introduced in Section 2 and summarized in Table 2.

6.1. *The 2000 Watt Society in 2050*

Fig. 6 shows the final energy consumption of the residential sector modelled for the period 2000 to 2050 for different scenarios. The corresponding per capita values for the years 2000 and 2050, respectively, are given in the small frame on the right side of the graph. The target value for the 2000 Watt Society is 80 PJ/yr, far below the value 190 PJ/yr reached by the reference scenario (RRr) in 2050. The same applies to the RR1 scenario which differs from the reference case by the transition to less carbon intensive energy systems. Since the latter scenario is also more energy efficient, the energy demand is slightly smaller than for the RRr scenario.[9]

With a target corresponding approximately to the MINERGIE standard for new and renovated buildings (scenario DF1), an energy reduction of 40% is possible. By comparing the DF1 and AF1 scenario, which only differ in the energy standard (ES) of new buildings (standard A instead of D), we conclude that the contribution of new buildings to the reduction is small compared to the role of refurbished buildings. Adequate measures during renovation are more important as demonstrated by comparing the AF1 and AC1 scenario. The latter causes the per capita energy consumption to drop by 55% until 2050. Yet, all these scenarios clearly remain above the 2000 W/capita target. This goal is only reached by the AA1, but only slightly missed by the AC2 scenario. In the former, new and refurbished buildings need to have an energy standard corresponding to MINERGIE-P, while the latter emphasizes energy systems with greater efficiency.

For the sake of completeness, in Fig. 6 the ZZ2 scenario is included in which all new and refurbished buildings are realized according to zero energy standards. The scenario demonstrates the lower bound of the energy consumption as well as the transition speed of the system. Ultimately, the energy demand of this scenario drops to the level determined by the hot water consumption. Note that the efficiency of hot water generation does not vary much. Obviously, the relative share of the energy demand for hot water generation increases when the target for space heating is lowered.

In Fig. 7a the contributions of the different energy resources to the final energy demand are shown for the different scenarios in 2050.

6.2. *The 2 °C target*

Fig. 8 shows the calculated CO_2 emissions and their reductions relative to the 1990 emissions obtained for similar scenarios as in Fig. 6. Remember that the 2 °C target requires an emission reduction to 20% of its 1990 value, i.e. to about 2.5 Mt CO_2/yr. It can only be reached

[8] Note that electricity in Switzerland is free of CO_2 emissions, see Table 4.

[9] The larger energy efficiency is mainly due to the preferential use of heat pumps.

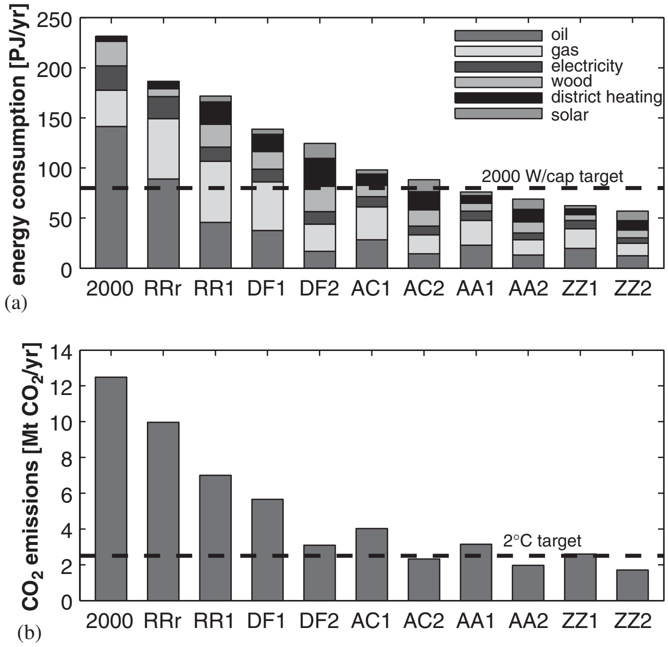

Fig. 7. Final energy consumption by energy source (a) and associated CO_2 emissions (b) for heating and hot water generation in the Swiss residential sector by 2050 for different scenarios. The energy consumption and emissions for the year 2000 are shown on the left. Results for 2050 for different scenarios are shown (see Figs. 6 and 8) and the required targets are displayed.

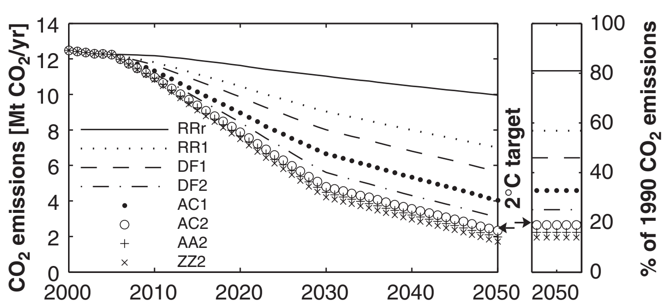

Fig. 8. CO_2 emissions due to heating and hot water generation in the Swiss residential sector from 2000 to 2050 (left) and the percentage reduction by 2050 compared to 1990 emissions (right). Results for different scenarios are shown and the required target is displayed. See Table 2 for definitions of scenarios.

by the AC2 scenario. Scenario AC1 which differs from AC2 by a more moderate move toward renewable energies (forced action 1 instead of 2, see Fig. 1) demonstrates the strong impact of renewable energy carriers. This can also be seen from Fig. 7b showing the CO_2 emissions in 2050 for the scenarios. Note that the reference case RRr leads to an emission reduction of 20% only. More substantial reductions (up to 40%) would be achieved with the RR1 scenario which differs from the reference case by an enhanced shift to renewable energies and more efficient energy systems. The reduction of the DF1 scenario amounts to 50%, while the DF2 scenario comes close to the 2 °C target.

How reliable are these numbers? As it turns out, the parameter 'fraction of realized renovations' (f_r) (see Fig. 3) taken from Wüest & Partner (1994) as 0.7 has a modest influence on the model results. By using 0.65 and 0.75, respectively, the predicted final energy consumption in 2050 varies by ±0.6% for the reference case (RRr) and by ±3% for the AC2 scenario. For the CO_2 emissions the variation would be ±0.7% and ±10% for RRr and AC2, respectively. As expected, CO_2 emissions are more sensitive to enhanced refurbishment according to forced energy standards.

6.3. Economical aspects

Compared to the reference energy standard (Fig. 2, R = E), improvements cause additional costs. These costs are better known for new buildings. For instance, based on experiences made in Switzerland and Germany, standard A buildings (20% of R) were realized with 10–20% higher costs (Spescha, 2002). Yet, as shown above the refurbishment of existing buildings has a larger influence on the energy needs, at least during the next 50 years. As demonstrated for several buildings in Switzerland, the C standard can technically be achieved by refurbishments without many problems. Yet the additional costs strongly depend on the year of construction and the architecture. Recently, available data on additional costs for energy saving investments for refurbishment of residential buildings (Jakob et al., 2002; Jakob, 2006) would allow to estimate additional costs for scenarios discussed above but go beyond the scope of this paper. However, one conclusion is obvious: the longer the time period available for the transition, the smaller the costs, because the energy-relevant changes can be combined with renovations which become necessary for other reasons. Furthermore, a larger fraction of new buildings is constructed during a long transition period. Or expressed differently: the sooner a more severe energy policy is adopted for the building sector, the smaller will be the total costs to meet the future challenges of sustainable development.

To conclude this section it should be noted that we have only discussed the possibilities and limits of transformation from the point of view of the demand side. An additional investigation would have to look at the production side that is at the consequences for the energy providers. Particularly, such an analysis would have to look at the technical feasibility and costs caused by a different demand structure (more renewable energies, more electricity for heat pumps, less fossil energies, etc.).

7. Conclusions

Ambitious efforts are necessary to reach the 2000 W/capita and 2 °C targets until 2050. We have shown that the central element of a successful strategy is to reduce the specific heat demand of existing buildings during renovation and to substitute the heating and hot water systems by less carbon intensive ones. Both targets could be (nearly) reached with the AC2 scenario (Table 2), which implies that the standard of heat demand after renovation of existing buildings amounts to only 60% of the specific heat demand of new buildings constructed at that time according to the reference case. Simultaneously, the heating and hot water systems would have to be substituted according to the forced action scenario 2 (Fig. 1f). For new buildings, the requirements are even stronger, although new buildings play only a minor role in the total energy demand.

Two important questions remain open: The first refers to the additional cost of a 'strong' scenario like AC2. The second question addresses the necessary dynamics of the energy supply system, especially for those scenarios which aim at the 2 °C target, since they require the availability of renewable energy resources. If such energies could even be made available more quickly than assumed for the 'forced action 2' scenarios, the 2 °C target could also be reached with less ambitious energy standards for renovated and new buildings, yet the 2000 W/capita target would then be missed. In fact, Fig. 7 suggests that there is more (technical and economical) flexibility to reach the 2 °C than the 2000 W/capita target. Since an energy cap as such cannot be a direct goal of sustainable development, one could be tempted to dismiss the 2000 W/capita target all together. However, as the recent price increases on the oil market demonstrate, beside climate policy there may be other reasons (such as resource limitations and political instabilities) to reduce our dependence on energy. In any case, the building sector plays a key role in the global and national energy policy.

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