让我们共同打造气候中和的未来
Building a climate-neutral future together

Sino-Swiss Cooperation on Zero Emissions Building

Technical Report

The Swiss decarbonization roadmap for 2050 and related policies for the building sector

ENGLISH VERSION

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Building a climate-neutral future together

This report has been produced within the framework Sino-Swiss Zero Emissions Building Project; an international collaboration funded by the Swiss Agency for Development and Cooperation in partnership with the Chinese Ministry of Housing and Urban-Rural Development.

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The Sino-Swiss Zero Emissions Building Project is an international collaboration funded by the Swiss Agency for Development Cooperation in partnership with the Chinese Ministry of Housing and Urban-Rural Development. The project aims to reduce greenhouse gas emissions and enable carbon neural development of the building sector in China by sharing Swiss know-how on sustainable and zero emission building.

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Image: ZEB China Demonstration project. Training building, Long Shan Shu Yuan Middle School, Shoaxing, Zheijiang Province. Courtesy of Shaoxing Future Community Development and Construction Co.

1. Swiss national roadmap to decarbonize the building sector by 2050

Energy Strategy 2050 for Switzerland

Following the reactor melt down in Fukushima in 2011, the Swiss Federal Council and Parliament decided to phase out Switzerland' s use of nuclear energy. This decision, as well as other far-reaching changes in the international energy environment, require a restructuring of the Swiss energy system.

The milestones of the process towards the Energy Strategy 2050 were:

- March 2011: As a result of the Fukushima disaster, the Federal Council instructs the Federal Department of the Environment, Transport, Energy and Communications (DETEC) to review the existing energy strategy 2007 and update the existing Energy Perspectives 2035.
- 2012: Adoption of a first package of measures for the Energy Strategy 2050 which aims to increase energy efficiency and promote renewable energies
- 2013: Adoption of the action plan "Coordinated Energy Research Switzerland", a first round of adjustments to Energy Act is decided and proposals for further revision of the energy act are circulated
- 2014-2016: Technical work and parliamentary process for integral revision of the Energy Act
- 2017: Acceptance of revised Energy Act through a public vote
- 2018-2022: Updating of the outdated Energy Perspectives 2035
- 2022: Publication of the Documentation on Energy Perspectives 2050+ , analysing different scenarios for an energy system that is compatible with the long-term climate goal of net-zero greenhouse gas emissions by 2050 and, at the same time, ensures a secure energy supply

The core elements of the Energy Strategy 2050 are as follows:

- Phasing out nuclear energy
- Action plan "Coordinated Energy Research Switzerland" - Swiss Competence Centers for Energy Research
- Innovation promotion:
  - Promotion of pilot, demonstration, and lighthouse projects by the Swiss Federal Office for Energy (SFOE).
  - Support for market introduction of innovative technologies through the action program SwissEnergy
  - Competitive tendering for energy efficient use of electricity.
- Parliamentary initiative 12.400
  - Increase of grid surcharge for promotion of renewable energies to 1.5 Rp./kWh
  - Partial to full reimbursement of grid surcharge for electricity-intensive companies
  - Regulation of self-consumption of Photovoltaic on-site electricity production, providing the right to use on-site produced electricity for self-consumption without attracting grid charges.
- New energy law:
  - Measures to increase energy efficiency
    - Buildings
    - Mobility
    - Industry
    - Appliances
  - Measures to expand renewable energy:
    - Subsidy scheme for promotion of PV systems and replacement of fossil heating system
    - Improvement of legal framework, e.g. providing leaner and faster approval processes
  - Nuclear phase-out:
    - No renewal of general licenses
    - Gradual phase-out of existing nuclear power plants with safety as sole criterion for the shut down-date
  - Measures to adapt the electricity grids to cater for more renewable power production.

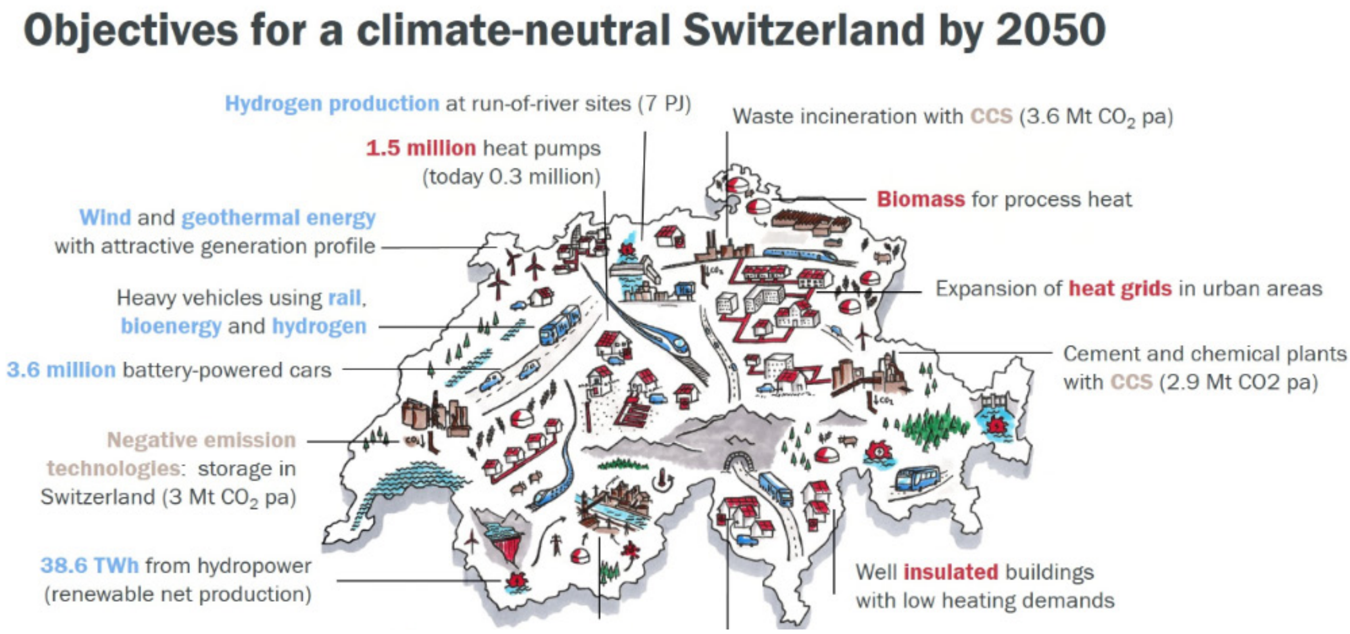


Image. Dina Tschumi. Prognos AG.

Image. Energieperspektiven 2050+ (2022). BAFU.

Long-term scenario "Energy Perspectives 2050+"

Background

The Energy Perspectives represent a central quantitative basis for the energy policy in Switzerland since the 1970ies. They have been completely updated in 2007 and adapted and expanded in 2012 for the Swiss Energy Strategy 2050 [5]. In 2020 the most current Energy Perspectives 2050+ (EP2050+) were published, using the latest framework data and technology developments.

The Energy Perspectives 2050+ analyze with different scenarios ("ZERO") how to develop an energy system that is on one hand compatible with net-zero greenhouse gas emissions by 2050 and on the other hand, ensure a secure energy supply. The scenarios are not prophecies, but they show consistent possibilities of how the energy system – i.e. energy demand and supply – could develop under plausible conditions that are assumed to be probable today.

The net-zero scenarios differ in their combination of technologies and the speed of the renewable energy transition in the electricity sector.

However, the variants of the net-zero scenarios do not fundamentally differ in the assumptions applied for the technology types and efficiency measures. The Energy Perspectives 2050+ focus on the scenario "ZERO Basis" as the key variant [6]. While the EP2050+ cover all sectors relevant for the energy domain, our report focuses on the building sector containing buildings of private households as well as the service sector.

We look at the main drivers reducing energy consumption and greenhouse gas emissions in buildings according to the EP2050+ including space heating/cooling, warm water heating as well as installations such as ventilation systems, lighting or air conditioning. Moreover, as in the EP2050+ itself, we mainly focus on the "ZERO Basis" [7] scenario for summarizing the main results of the Energy Perspectives 2050+ for the building sector.

[5] The three main pillars of the Swiss Energy Strategy 2050 consist of a nuclear phase-out (following the Fukushima reactor accident in 2011), the expansion of renewable energies and the increase of energy efficiency.

[6] Differences of other net-zero scenarios in comparison to ZERO Basis:

- Scenario ZERO A: more electrification, well thermal networks
- Scenario ZERO B: less electrification and more relevant role of gas (biogas and electricity-based methane
- Scenario ZERO C: less electrification, higher importance of thermal networks, rest with electricity-based fuels

[7] The ZERO Basis variant scenario develops today' s foreseeable trends in technological development further into the future. It assumes a high and as early as possible increase in energy efficiency and a significant electrification. Heat grids are gaining importance in urban areas. Synthetic fuels and hydrogen play a subordinate role. Carbon capture and storage is used in waste incineration plants and cement production to reduce fossil CO2 emissions. Remaining GHG emissions are offset by sinks or by negative emission technologies, which remove CO2 from the atmosphere and storing it, thereby generating on-balance negative CO2 emissions. This includes technical removal methods such as the capture and storage of CO2 from the atmosphere or biomass CCS, but also natural removal methods such as the afforestation of forests.

Relevance of the building sector in Switzerland

Buildings are highly relevant in terms of energy demand and greenhouse gas emissions:

- Final energy consumption: In 2020, approximately 45% of the final energy consumption in Switzerland took place in the building sector (including space heating, warm water, lighting, building services, ventilation etc.). Only considering space heating – the largest energy consumer in buildings – the final energy demand amounts to 30%.
- Greenhouse gas emissions: In terms of greenhouse gas emissions the building sector accounts for 1/3 of energy related emissions respectively for 1/4 of the total emissions in Switzerland.

Background about electricity in Switzerland

Electricity in Switzerland is mainly generated by hydropower and nuclear power, and with small proportions also with renewable (e.g. PV, wind) and fossil energy sources. Today' s electricity mixture is therefore considered nearly free from greenhouse gas emissions. According to the energy strategy 2050 of Switzerland electricity from nuclear power plants will fully be replaced by renewable energies, particularly PV

Thus, also the future electricity mix will be nearly free from fossil energy sources. Nevertheless, it is still crucial to reduce electricity demand as much as possible through efficiency measures, in order to succeed in the transformation from fossil fuels to electrification of the energy system.

Main drivers of reducing greenhouse gas emissions in the building sector

According to the energy perspectives 2050+ the following three main measures will lead to a reduction of greenhouse gas emissions up to net zero by 2050 in the building sector:

- Increase of energy efficiency (electrical appliances, installations and building envelope)
- Strong electrification of the heating system with decentralized electric heat pumps
- Expansion of thermal networks

While the first measure contributes to a reduction of energy consumption, the other two measures include the use of renewable energy sources leading to the decarbonization of the HVAC system.

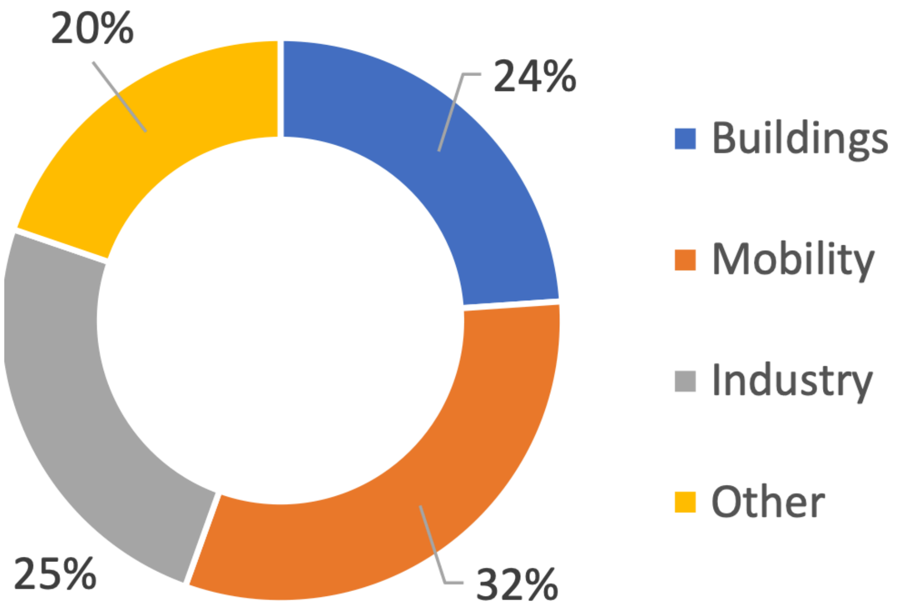


Figure 1. Breakdown of CO2 emissions in Switzerland. Source: BAFU 2022

Energy efficiency: Reduction of energy consumption

Space heating accounts for approximately 30% of the final energy consumption of Switzerland and for about 70% of the energy consumption in buil¬dings. In future, the space heating consum¬ption will be reduced due to different measures consis¬ting of energy-saving renovations of existing buil¬dings, replacement of old buildings to new ones, construction of new buildings with high energy effi¬ciency and last but not least more efficient heat¬ing systems. The development of efficiency of building envelopes is thus mainly determined by:

- rates of energy-saving renovations of existing buildings
- quality of energy-saving renovations of existing buildings
- standards of new buildings

Today, the renovation rates range from 0.8-1% per year. The EP2050+ assume that they will in-crease in future, reaching a peak of about 1.3% in 2040 and steadily decreasing again to below 1%. Limiting factors for a sharp scaling up of renova¬tion rates are the amount of investment required, the natural investment cycles (avoidance of strand¬ed investments) and the limited availability of skilled work force. On the other side, technolo¬gical and economic progress is expected for the building and insulation materials leading to a higher renovation quality.

Therefore, the thermal conductivity of the used building components is reduced by time (U-values = Heat transfer coefficient) and thus, the energy consumption of renovated buildings decreases (Figure 2a). For example, thermal insulation materials with current U-values of 0.35-0.4 W/m2K are expected to be improved in future to about 0.1-0.05 W/m2K. Window glazing (today’ s U-values mostly around 1 W/m2K) will more and more reach U-values of 0.5 W/m2K thanks to triple glazing with coated glasses and inert gas filling. The energy standards applied in the EP2050+ for renovated and new buildings are derived from the MuKEn 2014. For new buildings the standards are based on the norm SIA 380/1. According to the MuKEn 2014 the limit for the heating requirement of renovations is about 50% higher than the requirements for new buildings. Figure 2b shows the expected development of specific heating requirement after full renovation and of newly constructed residential buildings. For the average specific space heat consumption of building stock of service sector buildings a similar dynamic is expected, but at a lower consumption level if compared to residential buildings.

Moreover, in Switzerland space-heating demand will be reduced due to fewer heating degree days caused by climate change. In hot climate regions such as China but also in Switzerland, this will result in increasing cooling demand.

Overall, the energy consumption for space heating in buildings will decrease over time (in total and per capita). Besides space heating, buildings contain other energy consumers:

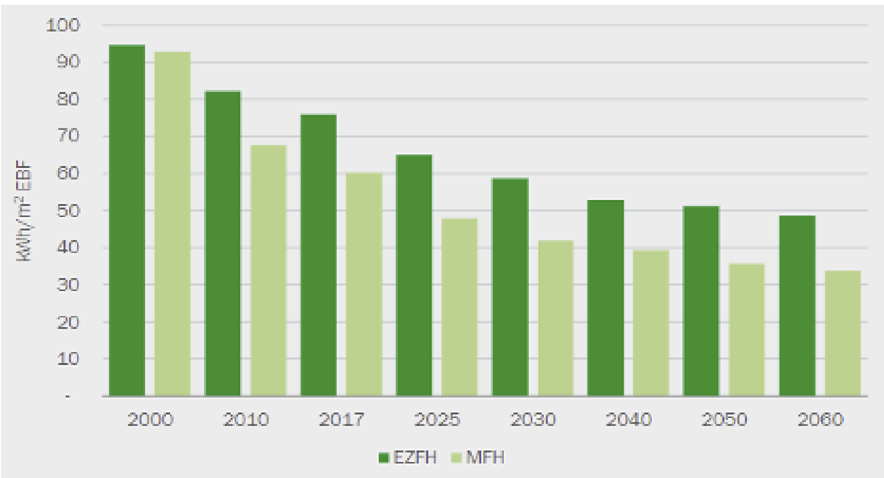


Figure 2a. Evolution of specific heating demand of residential buildings (Scenario ZERO Basis) – full renovation; Values are in kWh per square meter of energy reference area (EBF). © Prognos AG, TEP Energy GmbH,

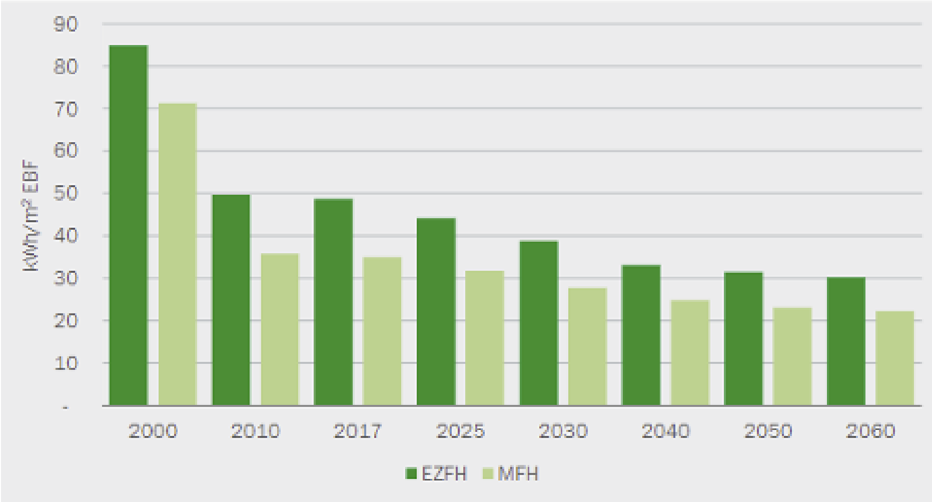


Figure 2b. Figure 2b: Evolution of specific heating demand of residential buildings (Scenario ZERO Basis) – new constructions; Values are in kWh per square meter of energy reference area (EBF) © Prognos AG, TEP Energy GmbH, INFRAS AG. Source: BFE | energy perspectives 2050+:

- Warm water: Energy for the heating of water is expected to decrease by about 10% until 2050. In most buildings warm water will be provided over the central heating system becoming more efficient with the increased use of heat pumps. Furthermore, water saving installations will more often be applied.
- Lighting: Energy for lighting is expected to decreasby 70% until 2050 thanks to increased efficiency and installation of LED.
- Air conditioning, ventilation and building services: While ventilation and building services get more efficient, the demand for cooling in summer will increase. The number of ventilation systems will increase which will be compensated by technical development and increased share of heat recovery. Overall, this leads to a small reduction of energy consumption until 2050.

Decarbonization of the heating system: Heat pumps and thermal networks

Besides the efficiency of a building envelope, the decarbonization of the heating system is a key area for transforming the building sector towards net zero greenhouse gas emissions. According to the EP2050+ the most relevant technologies comprise of heat pumps as well as thermal networks.

The heating structure of the building stock arises from installed heating systems in new buildings and from heating replacements in existing buildings. In 2017 about 80% and 10% of the in-stalled heating systems in new residential buildings were heat pumps and thermal networks, respectively. According to the scenario ZERO Basis gas and oil heating systems are no longer in-stalled in new residential buildings after 2025. In future, newly installed heating systems will al-most only consist of heat pumps (about 70%) and thermal networks (about 30%) (Figure 3).

Also for the heating replacements in existing residential buildings heat pumps and thermal networks will become the most important technologies. Moreover, a small proportion of solar heat will be used as complementary measure to other heating systems and especially for the heating of warm water. While oil heating systems will not be replaced by oil anymore from 2025-2030 on, one to one replacements of gas heating systems will gradually decrease, reaching below 5% after 2040. In the remaining gas heating systems biogas will be used. As the building sector requires relatively low temperatures compared to the industry sector, wood will mainly be applied to produce process heat in industry. For some buildings that cannot be connected to thermal networks (e.g. due to insulation restrictions) heating with wood will also be used in the long-term.

With an annual rate of about 1.3% of the existing floor area the share of new residential buildings is low in relation to the total stock . In combination with the assumed lifetime of 25 years for gas and oil heating systems the heating structure for the building stock is only changing slowly (Figure 4a). The combination of efficiency measures (reduction of heat energy consumption) and decarbonization of the heating system leads to the greenhouse gas emission reduction pathway to nearly zero by 2050 in residential buildings (Figure 4b).

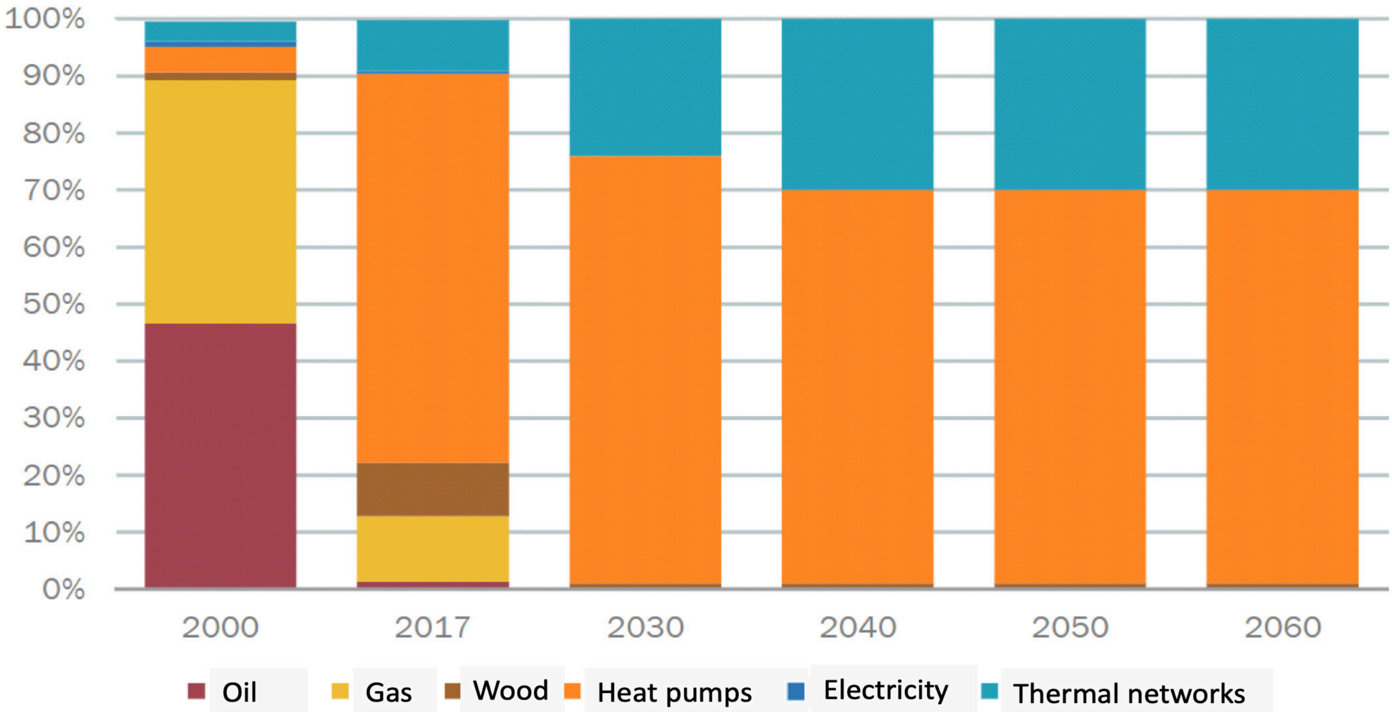


Figure 3. Share of heating systems in newly built Multiple Family Homes (Scenario ZERO Basis) © Prognos AG, TEP Energy GmbH, INFRAS AG. Source: BFE | energy perspectives 2050+:

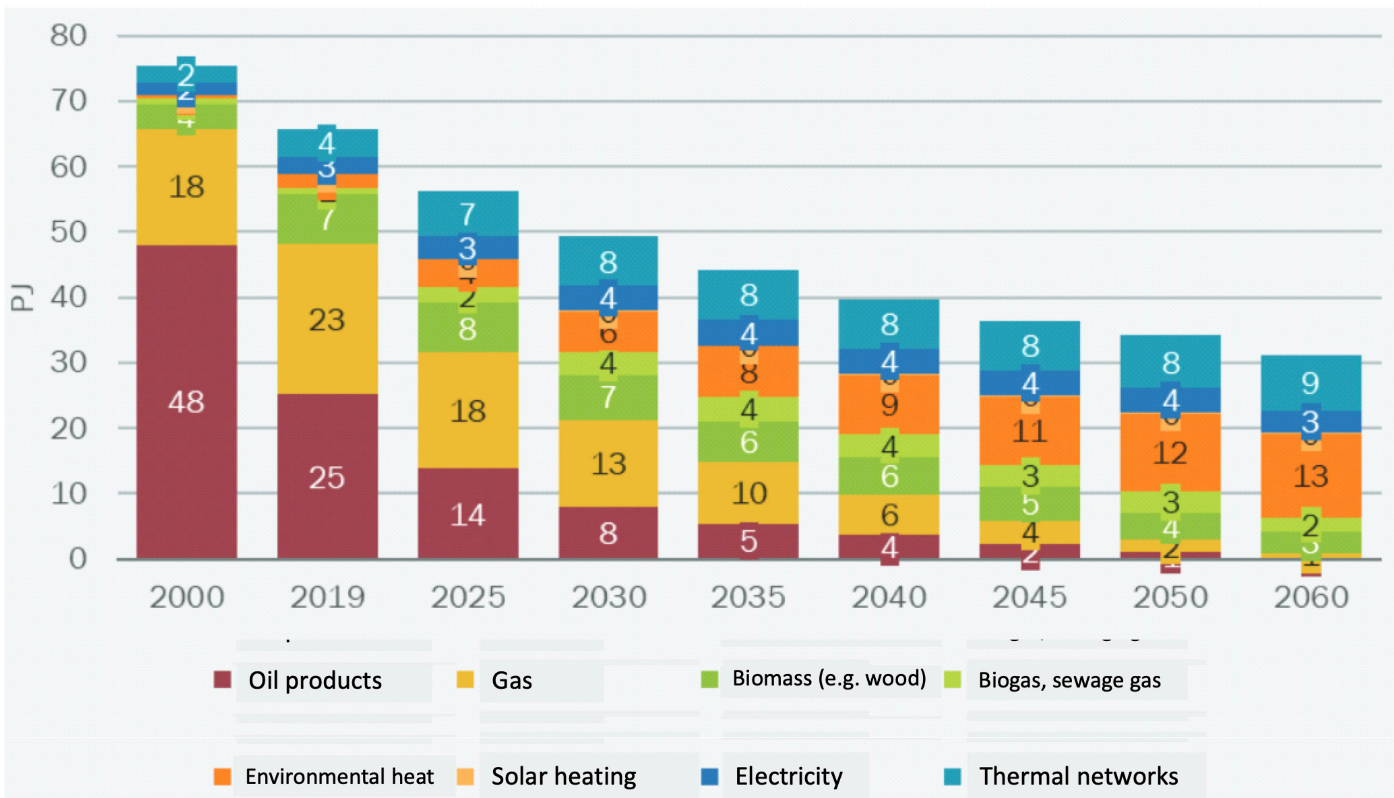


Figure 4a. Development of space heating consumption by energy source in service buildings (Scenario ZERO Basis); Environmental heat and Electricity are used in heat pumps © Prognos AG, TEP Energy GmbH, INFRAS AG. Source: BFE | energy perspectives 2050+:

Specific information and comparison with service buildings

The trends described for residential buildings apply for service buildings as well. These trends basically contain:

- Decarbonization of heating system: analogous to residential buildings the key technologies used for the heating of service buildings will be heat pumps and thermal networks. However, for service buildings thermal networks, wood biomass and gas/biogas heating systems are of relatively higher importance than for residential buildings (Figure 4a).
- Improved building efficiency: like in residential buildings, the renovation of service buildings will lead to a lower heating demand. However, the renovation rates and replacements of service buildings are expected to continue to be higher than in residential buildings. Moreover, the widespread use of ventilation systems increases the energy efficiency of heating. Both factors are leading to a stronger reduction of heat energy demand. According to the EP2050+ the specific heat demand in service buildings will be halved by 2050 (Figure 5).

Decentralized electric heat pumps

Already from 2025 on decentralized heat pumps (air/water, brine/water, and groundwater) will become the most important heating system to produce space heat in buildings. The number of installed heat pumps will increase by a factor of five from today to 2050.

Furthermore, the heat efficiency of heat pumps will increase by time due to higher source temperatures (e.g. regeneration of geothermal probes), lower supply temperatures needed in new and renovated buildings as well as improved power system efficiency of the heat pump itself. Depending on the energy source used, the heat efficiency of heat pumps is expected to increase from about 2.8 – 4 (in 2020) to 3.5 – 6 (in 2050).

Thermal networks for heating and cooling at district level

Thermal networks that use renewable energy sources and provide heating (and cooling) to buildings are also a key technology for a comprehensive greenhouse gas reduction in the building sector. Especially in dense settlement areas they will play a significant role, as buildings there can often only

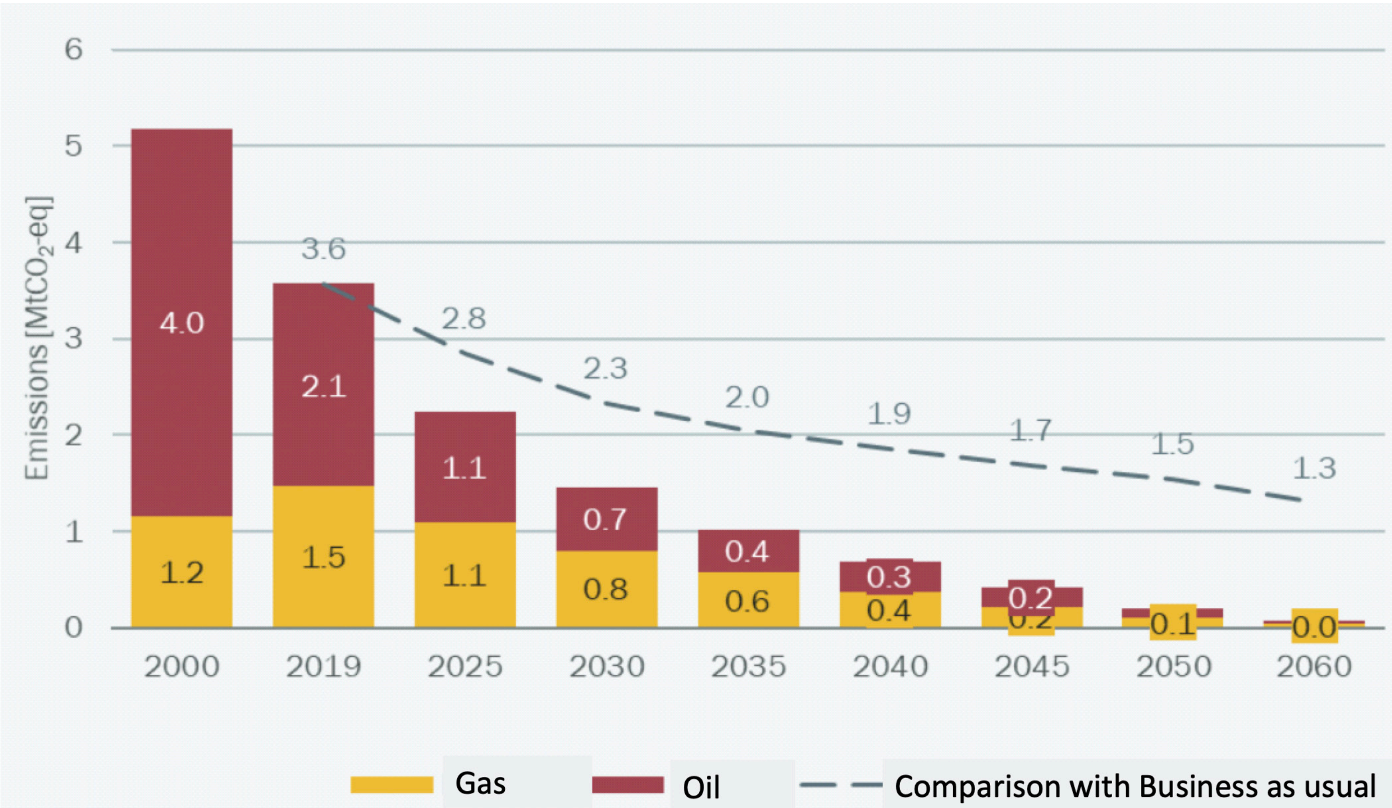


Figure 4b. Development of GHG emissions by energy source in service buildings (Scenario ZERO Basis) © Prognos AG, TEP Energy GmbH, INFRAS AG. Source: BFE | energy perspectives 2050+:

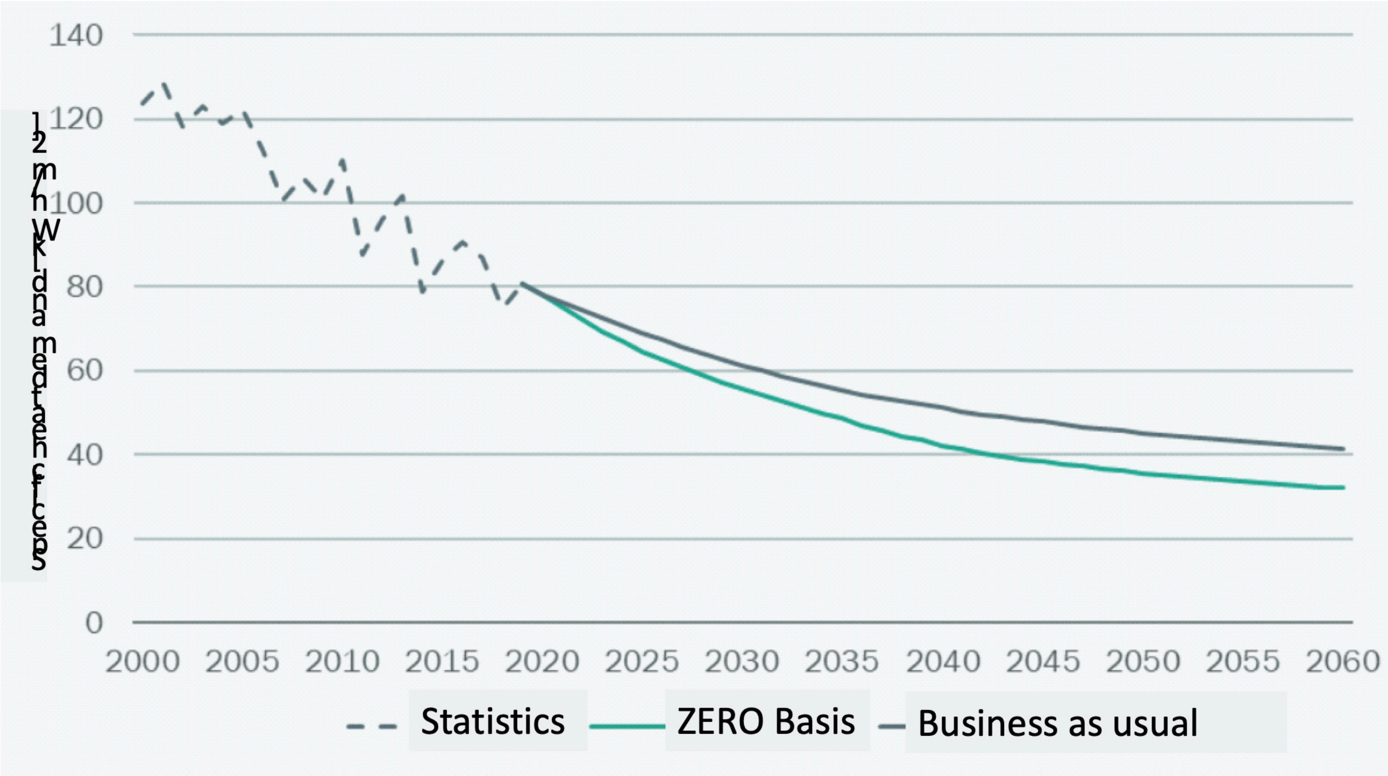


Figure 5. Evolution of specific heating demand of service buildings; values are in kWh per square meter of energy reference area © Prognos AG, TEP Energy GmbH, INFRAS AG. Source: BFE | energy perspectives 2050+:

be supplied with renewable energies by means of thermal networks. Thermal networks are particularly important for larger apartment houses (covering about 30% of the heating systems in 2050 compared to 10% in single family houses) as well as service buildings. According to the EP2050+ the demand for district heating systems in residential and service buildings will double from 2019 to 2050.

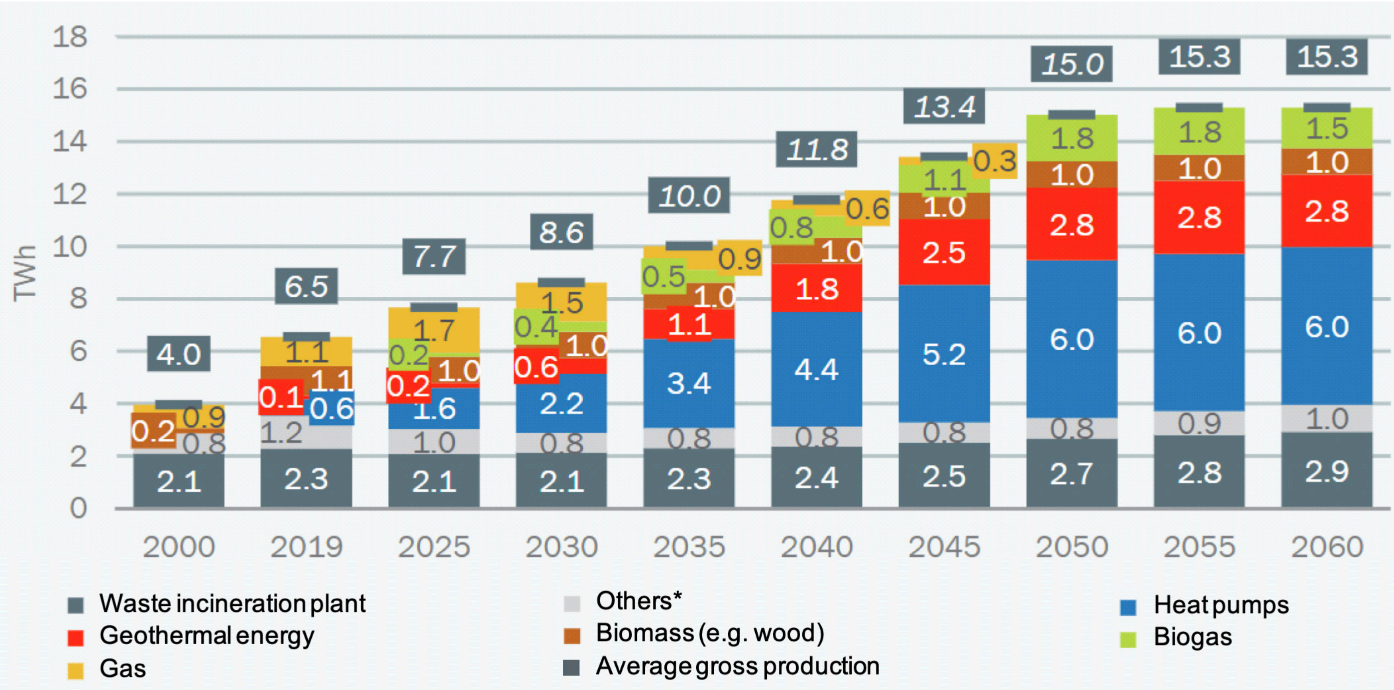
The energy sources used in thermal networks today mainly consist of heat from waste in-cineration plants, industrial waste heat, wood and gas. In future, large heat pumps (mainly use of groundwater, lakes and rivers), but also geothermal energy and biogas will gain of importance for the generation of district heating (Figure 6).

Conclusion from the EP2050+

According to the EP2050+ it is possible to reach nearly net zero greenhouse gas emissions by 2050 in the building sector. All the necessary technologies are already available today. The biggest challenge lies with scaling up the NET. Scaling up of the markets and research will lead to technical progress and innovation.

Residual emissions come from few remaining gas heating systems. The EP2050+ apply robust technologies – i.e. mainly heat pumps and heat grids – that exist already and will be further improved and become more efficient. Electric heat pumps become the most relevant system for the generation of space heat in buildings, while district heating systems are an important supplement, particularly in densely built-up areas and for larger buildings. Electricity-based energy sources (e.g. power-to-gas) are not applied in the building sector.

Moreover, efficiency measures in buildings play a crucial role. These consist of increased energy efficiency for electrical devices, equipment and building envelope. Overall, the energy consumption and space heating in buildings will decrease over time (in total and per capita). Electricity consumption will stay constant in total respectively slightly decrease per capita (more electricity is needed for the heat pumps, however, this is nearly compensated with the increased efficiency of the heating systems and the building envelope).



*others = nuclear energy, waste heat, other renewable energies

Figure 6: Thermal networks: Development of energy sources used in thermal networks (Scenario ZERO Basis) © Prognos AG, TEP Energy GmbH, INFRAS AG. Source: BFE | energy perspectives 2050+:

The principal trends of used technologies and efficiency increase also applies for service buildings. In contrast to residential buildings, service buildings will use more thermal networks and biomass and the efficiency of their building envelopes are expected to increase faster.

Building related key features of the Swiss CO2 act 2021

In 2020 the Swiss Parliament agreed on a revised Federal Act on the Reduction of Greenhouse Gas Emissions (hereafter CO2 act) which would have strengthened the Swiss climate policy and brought the policy instruments in line with the international commitments of the Paris Agreement. However, the act was put under a public referendum and was rejected by the Swiss electorate in the public vote on 13 June 2021. As the planned elements in the proposed act still can be of interest for the Chinese counterparts, a summary is given below. The focus is on the building sector related instruments.

Instrument	Description	Relevance for sector
Mandatory CO_2 limits for buildings (new)	New buildings may no longer emit CO_2 from fossil fuels, which is already standard today. Existing buildings are allowed to continue to emit CO_2 unless the heating system is replaced. In this case an upper limit of 20 kg of CO_2 emissions per square meter of living space per year has to be respected from. The value is reduced by five kg of CO_2 in five-year steps.	The instrument includes a mandatory upper limit for CO_2-emissions of existing buildings which becomes effective, whenever the heating system is replaced. In well insulated buildings or buildings with renewable based heating systems, the upper limit is anyhow respected. In all other cases, efficiency measures or conversion to a renewable based heating system or connection to a district heating system is required. If measures such as the installation of a heat pump are required for compliance, the owners can apply for financial support from the climate fund.
National CO_2 tax (continued and strengthened)	Since 2008, the federal government levies a CO_2 tax on fossil fuels such as heating oil, natural gas and coal in form of an incentive tax. Those who cause an above-average amount of CO_2 pay more, others less. With the revised law the Federal Counsel would have been authorized to raise the levy to a maximum of 210 CHF per tonne of CO_2 (approx. 0.5 CHF per litre of heating oil, approx. 0.042 CHF per kWh of natural gas). However, an increase from today's tax level of 120 CHF per tonne only is made if CO_2 emissions do not decrease sufficiently. Two thirds of the money is being distributed back to the population and the economy. The rest flows into the climate fund for financing climate mitigation actions.	The levy makes it financially worthwhile for building owners and tenants to use less heating oil or to heat with a heat pump, wood or solar energy. Households that do not heat with oil or natural gas pay no CO_2 tax at all.
Climate fund (new, encompassing also various existing instruments)	The proposed climate fund promotes climate-friendly investments such as financing of district heating networks or charging stations for electric cars or the procurement of electric buses. In the case of buildings, the fund was to support building refurbishment for lowering energy consumption and installation of CO_2-free heating systems.	The Climate Fund ensured the continuation of the tried and tested federal and cantonal buildings programme and the existing technology fund. The Swiss buildings programme is today a major driver in the market for building refurbishment and renewable energy based retrofit of heating systems. The subsidy granted is typically between 20 to 50% of the total investment cost. (www.dasgebaeudeprogramm.ch).
Compensation obligation of fuel importers **(continued and strengthened)**	Importers of petrol and diesel must offset part of the CO_2 emissions of the imported fuels with climate mitigation measures. From 2025, at least 20 percent of CO_2 emissions must be offset by projects in Switzerland. The rule set for the offset projects is similar to the rules for projects under the Clean Development Mechanism (CDM) under the Montreal Protocol. The revised law sets an upper limit for the surcharge to consumers which would have been raised from 0.05 CHF per liter of petrol or diesel today to a maximum of 0.12 CHF per liter.	In the building sector, existing offset projects and programmes under the compensation obligation provide finance for e.g. replacement of existing fossil fuel based heating system with renewable based ones, the setup or extension of district heating systems, end user efficiency measures such as efficient water taps, or intelligent controllers for heating systems. The subsidy granted is typically between 20 to 60% of the total investment cost.

Table 1. Instruments of Swiss CO2 act related to the building sector (Status 2021)

2. The Swiss legal, economic, educational and information instruments for the implementation of the energy strategy in the building sector

National level

Legal

The national level is of lesser importance regarding legal requirements for energy in buildings. In Switzerland, this is mainly the responsibility of the Cantonal (State) level.

Instrument	Regulator	Summary
Constitution	n.a.	Art 89 BV, Abs. 4 delegates regulation for energy consumption of buildings to the Cantons
Minimum Energy Performance Standards and energy labels for electrical devices and technical installations in buildings[10]	SFOE	MEPS and energy labels for a wide range of applications (e.g. lights, household appliances, electronic equipment, electrical machines) MEPS for water heaters, hot water storage appliances, ventilation systems
Compensation obligation for importers of fossil transport fuels[11]	SFOE	A certain share if the emissions from burning imported fossil transport fuels has to be compensated through projects implemented in Switzerland. This also includes building efficiency measures and heating system retrofit.

Table 2. Legal instruments at national level

Economic

In Switzerland, the national level is important when it comes to financing of energy and climate related activities for buildings. The reason being that levies and taxes on energy are regulated at the national level. There are Cantons which collect additional taxes on electricity (e.g. Basel-Stadt). One share of the funds is redistributed to the households and industries, the other share is used for investment support to renewable heating systems and efficiency measures in buildings.

Education and information

The development of the entire energy sector is proceeding rapidly and there is also a great need for building renovation. These challenges require a sufficient number of competent specialists who are actively involved in this dynamic field. High quality and easily accessible primary and continued vocational training are therefore of paramount importance for reaching a zero-emission building stock. The national program SwissEnergy integrates, coordinates and partly funds the sector-wide activities. Experience has shown, that for achieving a relevant impact the activities need to be well coordinated and integrated with activities of other relevant stakeholders in the sector like trade and professional associations, lobbying groups or training institutions. Only a multi-stakeholder approach can ensure that the know-how reaches down to the level of construction and renovation of buildings and efforts of the different levels are in line and form synergies.

As energy use in buildings highly depends on the individual behaviour of the building users and investment decisions are ultimately made by the building owners, information and awareness raising for the public and specifically for the building owners has a high relevance. In Switzerland these activities are also supported by the program “SwissEnergy”.

Instrument	Implementer	Summary
CO_2 levy[12]	FOEN	CO_2-intensitiy related levy on fossil heating fuels. At date, the levy is at 120 CHF per Tonne of CO_2eq.
Building subsidy program[13]	FOEN / Cantons	Subsidies for efficiency improvement and renewable heating systems. In 2020, the equivalent amount of 40 CHF per capita was paid out. The funding is through the CO_2 tax and the Cantons.
Compensation projects[14]	FOEN	Performance based funding system for project reducing GHG emissions in Switzerland. There is a wide range of applicable project types. The methodology used is closely related to approach for Clean Development Mechanism (CDM) projects, with adaptation and simplification for the Swiss compensation market.
Grid surcharge for the promotion of electricity from renewable energies[15]	SFOE / Pronovo	A levy of 0.023 CHF / kWh is applied on electricity. The funds are used for promoting renewable electricity generation.
One-off investment grant for Photovoltaic systems[16]	SFOE / Pronovo	For PV systems on buildings a one-off payment is granted, covering up to 30% of total investment cost. Funding source is the national grid surcharge (see above).
Program ProKilowatt[17]	SFOE / ProKilowatt	For uneconomical electricity saving projects or programs, a grant is given which covers up to 30% of total investment cost. Every year there are three to four competitive auctioning rounds where projects /programs can apply. Selection of projects / programs is based on the requested funding level in CHF per kWh of savings. Funding source is the national grid surcharge (see above).

Table 3. Economic instruments at national level

Instrument	Implementer	Summary
National information website on primary and continued vocational training in the building sector[18]	SwissEnergy, SFOE	Provides links to training opportunities for building specialists and professionals.
Program "Education campaign for buildings"[19]	SwissEnergy, SFOE	In order to successfully implement the energy and climate strategy in the building sector, more competent specialists are needed. With the education campaign, the industry wants to ensure that sufficient qualified specialists will be available in the future. In a broad stakeholder dialogue together with the industry and educational institutions a roadmap and specific measures to be implemented was developed.
Program "Renewable Heating"[20]	SwissEnergy, SFOE	Platform for information on heating retrofit. As part of the program a free of cost on-site consultancy is provided to building owners. The consultancy provides a broad overview on available technology options and costs as well as an optimized integral approach for building retrofit, based on the object specific situation.
School teaching aids [21]	SwissEnergy, SFOE	Provision of school level teaching aids and information on energy and climate as a teaching topic.
National energy newspaper, fact sheets and success stories on energy use in buildings[22]	SwissEnergy, SFOE	The program Swiss Energy provides a wide range of information material for building owners and tenants. This also includes a printed newspaper with information and success stories which twice a year is sent to all building owners in Switzerland.
Coordination of building labels on energy and environmental (Zero emission buildings)[23]	SwissEnergy, SFOE	Institutions for green building labels receive funding through SwissEnergy. The Swiss Federal office of Energy is coordinating the different labels available at the national scale. The label family includes differentiated labels with focus on energy and climate, indoor quality and integral sustainability.

Table 4. Educational and information instruments at national level (non-exhaustive)

Cantonal level

Legal

In Switzerland, regulation and enforcement of building construction lies mainly with the Cantons.

Economic

In co-ordination and co-financing with the national government, all twenty-six Cantons in Switzerland implement tax discounts for investments in energy performance of buildings as well as subsidy schemes for energy efficient and low carbon emission buildings. The subsidy mainly addresses retrofit of existing buildings, as new buildings are adequately covered through the technical regulation and the available labels which provide market incentives.

The financial support provides strong incentives to building owners to go beyond the legally required and market standard ambition level for making their building energy efficient and low emission. The level of subsidy provided is typically in the order of 20 – 50% of the total investment cost, depending on the Canton and the specific measure.

Education and information

The Cantons play an important role in informing building owners and the public on energy issues in buildings. This is primarily through targeted energy consultancy, information along the building approval process, after work information events and specific training courses on technical issues and correct implementation of standards.

Instrument	Regulator	Summary
Technical regulation on energy use and CO_2-emissions of buildings	Building departments of the cantonal administration	Each Canton is responsible for issuing its technical regulation on energy and emissions. A wide reaching but not full harmonization is achieved through the "Sample regulations of the Cantons on energy in buildings" (MuKEn[43]) which are issued by the assembly of the energy directors of the Cantons (EnDK[44]).
Accreditation of private building control staff	Cantons	Some cantons make use of accredited private sector staff for design and construction compliance checks. The persons must be accredited by the cantonal building authority.

Table 5. Legal instruments at cantonal level

Instrument	Implementer	Summary
Building subsidy program[47]	Cantons / FOEN	Subsidies for efficiency improvement and renewable heating systems. In 2020, the equivalent amount of 40 CHF per capita was paid out. The Cantons are responsible for administering the subsidies. The funding is through the national CO_2 tax and the Cantons. Each Canton puts an individual focus for the supported measures depending on their local priorities. Some Cantons provide additional funding for measures which are not supported at the national level.
Tax discounts on investments for energy performance of buildings	Cantons / National Tax Authority	In most Cantons, investments related to decarbonization and energy efficiency of buildings benefit from a tax discount. The tax rules allow to deduct the investment amount from the income on annual basis. Recently, efforts have started to revise the tax rules, so that it will be possible to spread deduction of the investments from a specific year to multiple tax periods. This will ensure that also large investments (higher than the total annual income of the investor) still receive the full incentive.

Table 6. Economic instruments at cantonal level

Instrument	Implementer	Summary
Vocational training schools	Various	Vocational training schools are operated by the Cantons to provide primary and continued vocational training in various fields related to buildings and renewable energies.
Public energy consultancy	Cantons	Each Canton has an energy office or energy agency which provides basic information and low level and industry independent consultancy for building owners.
Large range of different information and awareness event	Various	The Cantons run different formats for providing energy and sustainability related information to building owners and building sector specialists.

Table 7. Educational and information instruments at cantonal level (non-exhaustive)

3. The Swiss key stakeholders for the implementation of the energy strategy in the building sector

National level

Stakeholders at the national level include Government Authorities as well as private organizations. The key stakeholders and their respective role are summarized in table 8.

There is close interaction between the national, cantonal (State), municipal level as well as with the private sector stakeholders.

Stakeholder	Role
Swiss Federal Office for Energy[49] SFOE	• Energy related acts and ordinances • National support program Energie Schweiz (Energy Switzerland) • Statistical data and reporting on energy use and production • Public information related to e.g. energy in buildings • Coordination of building related national research programs • Coordination of international activities, e.g. with International Energy Agency IEA • Long-term energy scenarios (e.g. EP2050+) • Studies on specific energy related topics • Coordination of building labels • Coordination of subsidy programs for buildings (in co-operation with FOEN).
Federal Office for Environment[50] FOEN	• Climate related acts and ordinances • Statistical data and reporting on greenhouse gas emissions • Studies on specific climate related topics • Emission related energy taxes
Association "Energiestadt"[51] (Energy Cities)	• Competence center for local energy and climate policy in Switzerland, bringing together Swiss municipalities, from large cities to small mountain villages for information sharing and collective action through continuous commitment. • Continuous development and administration of the Label "Energy City" [52] • Information, practical guidelines and support to activities at city and municipal level
Coordination office "2000-Watt-Society"[53]	• Methodological work on methodologies and tools for long-term sustainability • continuous development and administration of the Label "2000-Watt-District" • Program Smart Cities • Program "Sustainable Energy Regions"
Association MINERGIE[54]	• Development and certification of the Label family MINERGIE • The different ambition levels of the MINERGIE label cover operational energy and embodied emissions of buildings as well as comfort and indoor climate aspects for near-zero and zero emission buildings.
Sustainable Construction Network Switzerland[55] (NNBS)	• Development and certification of the Label SNBS (Standard Sustainable Building Switzerland) • The SNBS label integrates not only energy and climate related criteria, but covers sustainability in an integrative form and provides guidance for near-zero and zero emission buildings

Table 8. Key stakeholders at national level

Cantonal level

As mentioned above, in Switzerland the cantonal level (could be compared to State level in China) is of high importance for the building sector as the regulatory power for energy use in buildings is with the 26 Cantons. Each of the cantons operates it' s own Energy Office (Energiefachstelle). Table 9 lists the most relevant stakeholders at the cantonal level.

Municipal / local level

In Switzerland the importance of the municipal level depends on the Canton. In some Cantons the authority for building approvals and compliance checking is delegated to the municipal level, in others it is with cantonal authorities. The municipal and local level is important because there is continuous (not only building related) interaction between the Municipality and/or local stakeholders such as the Utilities and the building owners. The geographical proximity provides a good entry point for information and target oriented interaction with building owners.

Stakeholder	Role
Energy Office[63]	• Technical design of regulation on energy use and production in buildings • Enforcement of the technical regulation on energy use and production in buildings at the cantonal level (building approval) • Monitoring and evaluation of enforcement quality • Tools and forms for building design and approval • Coordination of building approval processes at cantonal or municipal level • Energy related consultancy and information for building sector professionals and the public • Education and training of building sector professionals
Energy Agencies	• Some Cantons operate separate energy agencies which deal with information, consultancy and education. The regulatory tasks remain with the Energy Office while the day to day routine work is sourced out to the Energy Agency.
Building Owners Associations[64] HEV	• Energy related information to private sector building owners • Advocacy and political lobbying for interests of building owners • Legal and administrative support for building operation and building transactions • Lists of local and regional building professionals and service providers

Table 9. Key stakeholders at cantonal level

Stakeholder	Role
building authority of the municipality	• Enforcement of the technical regulation on energy use and production in buildings (if delegate to the municipal level), building approval and compliance checking • Information and consultancy to building owners. Very often, the technical know-how and staff capacity at the municipal level is however restricted and the municipal authority acts merely as an intermediary for linking to the right addresses.
Utilities (Electricity, Gas)	• Customer support and information • Technical Consultancy on heating systems and building efficiency measures • Some Utilities operate municipal level subsidy schemes for energy efficiency and GHG mitigation
Heating System Suppliers	• Typically, they are the first contact and information point for building owners for replacement of heating system. Therefore, it is of highest importance that they are trained and motivated to promote sustainable technologies and not just the well-known "fossile" technologies.

Table 10. Key stakeholders at municipal level

Professional Associations

In the Swiss building sector, a number of professional associations are active. Associations are highly relevant in providing the market with the required number of qualified professionals which can drive the building sector towards zero emissions. Associations do not only provide basic technical information and practical guidelines; they also offer basic and advanced education courses in their specific fields of profession.

So they are key stakeholders for the transition process for reaching the net-zero emission target.

However, they also must represent the interest of their members. These are often not in favour of a rapid transition as this puts their traditional field of know-how and commerce at risk (e.g. oil-based heating systems). Therefore, the opposition of associations to policy processes can also form a substantial barrier for needed transformation of the sector.

Stakeholder	Role
Swiss society of Engineers and Architects[67] SIA	• Switzerland's leading professional association for construction, technology and environment specialists. With over 16'000 members from the fields of engineering and architecture, the SIA is a professional and interdisciplinary network whose central aim is to promote sustainable and high-quality design of the built environment in Switzerland • Develop, update and publish standards, regulations, guidelines, recommendations and documentation, which is of vital importance for the Swiss construction industry • Typically, the technical regulation by the cantonal and national Authorities makes reference to SIA standards
Building Envelope Switzerland [68](Gebäudehülle Schweiz)	• Basic and advanced training courses in all aspects of the building envelope professions • Develop innovative, forward-looking solutions and products in cooperation with product manufacturers, specialists in the building envelope, science, research, technology as well as architecture and planning
Building Services Association[69] (Suissetec)	• High-quality services for manufacturers/suppliers, planners and installers in the heating, ventilation, sanitary, water, gas and plumbing sectors • Education, networking, political lobbying
Swiss Association for Refrigeration [70] SVK	• Trade association for commercial refrigeration, industrial refrigeration, air conditioning and heat pumps • Provide information and training aids • Basic and advanced education • Guidelines and policy development for the cooling sector in cooperation with FOEN
Schweizerischer Verein von Wärme- und Klima-Ingenieuren[71] SWKI	• Network of building technology professionals • Education, training, guidelines
Swiss Real Estate Association[72] SVIT	• Education, networking, political commitment, know-how and innovative services for the real estate industry

Table 11. Shortlist of professional associations

4. The role of Research Institutes and data for drafting concepts for regulations of the next generation

As per Art. 89 Abs. 4 of the Swiss Constitution, the development of technical regulations in the building sector is within the responsibility of the 26 Cantons (i.e. State level). As an overarching framework, the model regulations of the Cantons on energy use in buildings (MuKEn) define "building blocks" for the regulations at the cantonal level in form of mandatory and voluntary modules. The MuKEn are periodically (each 4-5 years) updated (see also ZEB China 2022 for more details) and coordinated with activities and GHG emission targets at the national level.

Any revision of the MuKEn integrates latest research findings, field data, technical and economic progress since last revision, and political priorities. The availability of representative and up to date data is of utmost importance for updating the regulations. While research can inter alia provide technical sound and economically optimal solution as well as behavioural economic theory models, the design of the legislation also must be effective "on the ground". This includes effective enforcement system, financial support schemes and much more. The basis of effective policy design is evidence-based decisions. This requires specific and up to date data. Some of the main sources of data for building sector policy design in Switzerland include:

- Periodic field monitoring of performance of buildings (sample based, e.g. to identify performance gaps between design performance and field performance)
- Sample based evaluation of effectiveness of construction permit processes (e.g. quality of private controls of energy related building permit applications)
- Cost data gathered from subsidy programs (e.g. for monitoring cost of technologies)
- Surveys and interviews with building owners (e.g. on barriers for implementation of measures)
- Information gathered from energy consulting activities for building owners (e.g. on decision processes and information sources of building owners).
- Comparison and analysis of international experience and practices (e.g. technical concepts for building codes).

In Switzerland different institutions and networks are active in research for the building sector. In the following a non-exhaustive list is provided:

Image: Freepik

Institution / Network	focus of activities related to buildings
National Research Program Buildings and Cities[79]	• Sustainability strategies for sites and districts, Optimised interaction of production of energy, storage, distribution and consumption • Buildings and sites as energy service providers long-term reduction of the energy consumption of old buildings • BIM in life cycle assessment • Embodied energy, minimisation of material flows, use of energy, material and building data at planning and operation stages • Cooling in view of the future climate • Building automation, monitoring and system optimisation • Heating systems with low CO_2 emissions and low electricity consumption in the winter. • Research on Consumers, market, policy • Feedback systems • Incentive systems for sufficiency • Acceptance of building automation solutions: influence of privacy and security, flexibility of use, user interfaces.
Swiss Federal Laboratories for Materials Science and Technology (EMPA)[80]	• Sustainable built Environment (Materials & Processes, Structures & Systems, Integration & Demonstration, Circular Economy, Data Science) • Energy (Energy Supply, Conversion and Storage, Energy Demand, System Integration) • Resources and Pollutants (raw materials availability and criticality, resilient supply chains, reduction of greenhouse gas emissions, circular economy and recycling of building materials)
Swiss Competence Centers for Energy Research (SCCERs)[81]	• Future Energy-Efficient Buildings & Districts (SCCER FEEB&D) • Heat & Electricity Storage (SCCER HaE) • Competence Centre for Research in Energy, Society, and Transition (SCCER CREST)
Federal Institutes of Technology (ETH) Zurich and Lausanne, Universities of Applied Sciences[82] (HSLU, ZHAW, FHNW, OST, BFH)	• Wide range of activities
Private sector Consultants	• Regulatory design, socio-economic research, behavioural economics, subsidy programs, policy evaluation, etc.

Table 12. Building related research institutions and networks (non-exhaustive)

5. Next generation of technical regulation for buildings

Introduction

Energy demand and carbon emission from buildings can be drastically reduced by applying today' s best practice and emerging technologies [Ürge-Vorsatz et al., 2012]. However, many of these opportunities are not realized, although being already cost-effective, due to specific market and behavioural failures. Literature has long recognized that implementing policies—individually tailored in form, magnitude and timed to address these failures — can help to close this so-called "energy efficiency gap" [Schwarz et al., 2020; Mowery et al., 2010]. Most effectively the variety of instruments (e.g. control and regulatory mechanisms, economic and market-based instruments, fiscal instruments and incentives, and support, information and voluntary action) work in synergy in a so-called policy mix [Kern et al., 2017; Rogge, K. S., Reichardt, K., 2016].

In addition, policies from outside the energy domain often have a significant impact on the building stock transformation [Ivalin et al., 2021]. Nevertheless, Technical Energy Regulations (TERs) - control and regulatory mechanisms that traditionally set minimum requirements for energy use and generation in buildings - are seen as one of the most cost-effective policies for closing the energy efficiency gap [Lucon et al., 2014], and are thus an essential part of such a policy mix.

In the following, we first outline the state-of-the-art of TERs based on an international review and derive policy design principles for next-generation TERs. Second, we outline the challenges and propose three TERs ideas. The last section provides a brief outlook for embedding TERs in a comprehensive regulatory framework.

International Overview

Historically, TERs have proven effective and efficient for advancing building decarbonization. However, researchers increasingly recognize the limitations of prevalent TER designs and have thus begun to discuss the development and implementation of TERs that overcome these limitations. Schwarz et al. (2020) provide a detailed overview of the state-of-the-art, leverage points, and innovative approaches in TERs, and derive policy design principles from five European case studies (i.e., Denmark, France, England, Switzerland, Sweden).

The following five challenges of current TER design or leverage points have been outlined in literature: (i) further increase in energy efficiency, (ii) consider "embodied energy", (iii) increase the share of renewable energies, (iv) close the "performance gap", and (v) accelerate the renovation rate. Besides considering embodied energy, all of the outlined leverage points above have been considered in status quo TERs of the selected five European countries albeit to various decrees. The table below presents an overview on the state-of-the-art of the TERs in each of the five identified countries, and sketches the status of the five most important leverage-points.

Below we outline the status quo and innovative examples addressing these leverage points.

i) All countries shifted towards performance metrics for the entire building' s energy use to further increase energy efficiency but retained prescriptive requirements for envelope efficiency or individual building technologies. As an innovative example, Denmark increased energy efficiency by introducing voluntary low-energy classes and announcing far in advance when they would become mandatory, thus providing long-term targets for the construction industry.

ii) Despite the increasing importance of embodied impacts, historical and current TERs, however, concentrate on energy use during the operational phase, and do not set requirements for embodied energy. However, France will begin to reduce embodied energy by taking a lifecycle perspective for performance metrics and adopting requirements for the construction phase in the next update of its thermal regulations for building.

iii) In contrast to the historic TER setting, the current status quo increasingly regulates renewable energy in buildings, through more stringent performance-based renewable requirements and specific prescriptive regulations or bans of certain technologies. England, in addition, introduced carbon emissions as the key performance metric in its building regulation. Switzerland in contrast adopted two prescriptive requirements that aim to increase renewable energy in buildings. First, they stipulate that new buildings must produce a certain amount of electricity on-site. Second, they require the 1.1 million Swiss buildings that have an oil or gas boiler to install a heating system based on at least 10% renewable energy in case of a boiler replacement or achieve an at least equivalent amount of energy efficiency gains.

iv) the performance gap - the difference between calculated and measured energy use - is only addressed in most current TERs, through compliance checks of planning and construction. In contrast to the status quo, the Swedish building regulation aims to close the performance gap by checking compliance based on measured building performance.

v) To address a notoriously low retrofitting rate most analyzed countries distinguish between regulations for new buildings and retrofits and for example allow the latter to comply with purely prescriptive requirements only. France is trying to accelerate the building stock transformation through retrofit obligations addressing the most energy-demanding buildings.

The MuKEn:2014 takes a key role in Switzerland's transition towards a carbon-free building sector. It is a state-of-the-art regulation and beyond that takes a pioneering role through mandatory on-site electricity generation and renewables for heating. However, the successor of the MuKEn:2014 could learn from innovative approaches of TERs of other frontrunner countries. In the following, we transfer the insights we gained from analysing international and innovative TER to Switzerland.

i) To increase energy efficiency, the next TER could reduce the number of individual regulations and instead focus on two central performance metrics, namely the total energy demand and the primary energy demand including on-site electricity production.

ii) To consider embodied energy, taking a lifecycle perspective and, first, include additional energy and carbon sources in the performance metric or, second, add a new performance metric for embodied energy only would be potential ways forward.

iii) To increase the share of renewables, a MuKEn:20XX could, first, accelerate the phase-out of oil and gas boilers in buildings and, second, extend the system boundaries of energy regulations from buildings to neighbourhoods. A CO2 emission performance met-

		Denmark	France	England	Switzer-land	Sweden
Energy Efficiency	Performance	Yes	Yes	Yes	Yes	Yes
	Prescriptive	Yes	Yes	Yes	Yes	Yes
	Capacity	-	-	-	Yes	Yes
Embodied Energy & Carbon	Performance	-	Yes (pilot)	-	-	-
Renewable Energy	Performance	Yes	Yes	Yes	Yes	-
	Prescriptive (direct)	Yes	Yes	-	Yes	-
	Prescriptive (indirect)	Yes	-	Yes	-	-
	Prescriptive (ban)	Yes	-	-	Yes	-
Performance Gap	Compliance Check	Yes	Yes	Yes	Yes	Yes
Accelerate Retrofit	Requirements when retrofitting	Yes	Yes	Yes	Yes	Yes
	Requirements to retrofit	-	Yes	-	-	-

Performance requirements define a metric on a systemic (i.e. building) level (e.g. kWh/m^2 or CO_2/m^2), prescriptive requirements in contrast define specific metrics for individual building parts (e.g. U-Value in kW/m^{2}K) or renewable heating systems for heating re-placements, capacity requirements define maximal allowed peak values (e.g. W/m^2 for heating demand).

Table 13. Overview of key leverage points for building decarbonization and related BEC design options. Source: Innovative designs of building energy codes for building decarbonization and their implementation challenges; M. Schwarz et al. / Journal of Cleaner Production 248 (2020);

ric would be another potential way to increase the share of renewables in the building sector.

iv) To close the performance gap, the next TER in Switzerland could, first, adjust the current compliance check or, second, switch to a compliance check based on measured data.

v) To accelerate retrofits, Switzerland could follow the French example and include requirements that enforce the retrofitting of low energy-efficiency buildings.

By synthesizing the implementation challenges for the innovative examples across our five case studies, we derive six policy design principles for TERs. These are generally applicable and ensure TERs function effectively – thus often separating the successful TER implementations from the failures. We recommend that policymakers apply these principles when implementing innovative TER designs to ensure broad acceptance across all actors in the construction sector – particularly important in view of TERs mandatory nature. Table 14 provides an overview of our six TER design principles and outlines examples illustrating how to follow them.

Challenges of new TER

According to the international comparison, MuKEN:2014 is a state-of-the-art TER. However, impact analysis confirms that even if the MuKEn:2014 is fully implemented all over Switzerland, the Swiss CO2 target of net-zero will still fall short by approximately 30% [DOI: 10.13140/RG.2.2.12307.22568].

Through techno-economic optimization, retrofit solutions for the Swiss building stock could be identified which achieve specific CO2 emissions below 10 kgCO2/m2 - typically at CO2 avoidance costs of 200-400 CHF/tCO2 compared to cost-optimal solutions. The technically and economically optimized solutions are characterized by three measures at the building level:

i) partially improve the building envelope in terms of energy efficiency,

ii) replace oil and gas heating systems as far as possible with renewable heating systems and

iii) use photovoltaics and, where appropriate, install battery storage systems.

Analyzing the Pareto fronts in more detail, the ideal

TER design principle	TER design examples
Keep additional burdens for building owners light	• Include technical feasibility and cost-effectiveness tests • Combine TERs with additional policies such as zero-interest financing to lighten the burden of upfront investment
Create long-term regulatory certainty	• Align TERs with national energy and climate targets • Pre-announce upcoming TERs • Integrate continuous improvement processes
Beware technology-specific requirements	• Ensure that multiple technology options are available
Anticipate the impact of new regulations on smaller actors	• Support small firms by reducing unnecessary soft costs • Help small authorities by removing the burden of capacity-intensive compliance control
Promote knowledge of innovative design	• Pre-announce upcoming TERs • Conduct test programs • Build upon voluntary labels • Learn from frontrunner legislation
Integrate TERs in the local context	• Leverage the existing infrastructure • Consider the level and pace of ongoing grid decarbonisation • Leverage domestic resources • Consider the quality of the domestic construction industry • Check political feasibility

Table 14. Overview of BEC design principles and design examples. Innovative designs of building energy codes for building decarbonization and their implementation challenges; M. Schwarz et al. / Journal of Cleaner Production 248 (2020);

retrofit measures and system selection are trade-offs along the multicriteria optimization. A retrofit option and a heating system are selected and, if applicable, a solar system is defined. Since a heating system is already installed in the building, the optimisation process can either keep the existing system (oil or gas-fired boilers, biomass, electric or district heating) or select a new and more efficient system (air source heat pump, ground source heat pump, biomass, cogeneration heat and power system or gas boiler). Figures 7 and 8 show the optimal combination of building envelope and systems for all single and multiple family dwellings archetypes. The size of the individual markers represents the relevant building floor area in m2. The graphic shows that roof renovations are the most frequently performed upgrade in single-family houses since this usually represents the most cost-effective action. The most promising heating systems are wood pellet systems or air source heat pumps. In certain cases, the optimisation shows that electric heating systems may be retained after renovation, though this occurs in less than 5% of all optimised solutions for single family houses.

Generally speaking, to reach the target of <10 kgCO2/m2 both a partial retrofit of the building envelope and a change of the heating system are recommended. Replacing fossil-fuelled heating systems is mandatory for nearly all buildings to reach the net-zero goal.

Further results indicate that a district solution with thermal networks in cities would be appropriate for 50-80% of more densely populated neighbourhoods. The investment costs of such district solutions are between 20 and 25% lower than stand-alone building solutions [Murray, P. et al, 2020].

By scaling the technically and economically optimal solutions to the entire building stock, CO2 emissions could be reduced by up to 80%. The remaining 20% CO2 direct emission of the Swiss building stock must be solved at the regional or national level. Transforming the energy supply infrastructure (electricity and gas) into a carbon-free system is a prerequisite for achieving the net-zero target. The above analysis shows that achieving the net-zero target for the Swiss building stock is technically and economically feasible.

Next generation of TER

To provide the best possible regulatory environment for encouraging stakeholders to develop the building stock in the intended direction, the following TER ideas have been developed to discuss the next generation of TER. New TERs should be built on performance criteria, which directly address targets, e.g. CO2 emissions. Prescriptive regulations which describe constructions, e.g. wall insulation and hope of CO2 reductions, are neither effective nor straightforward in their application. Because of this, we propose three performance criteria: Capac-

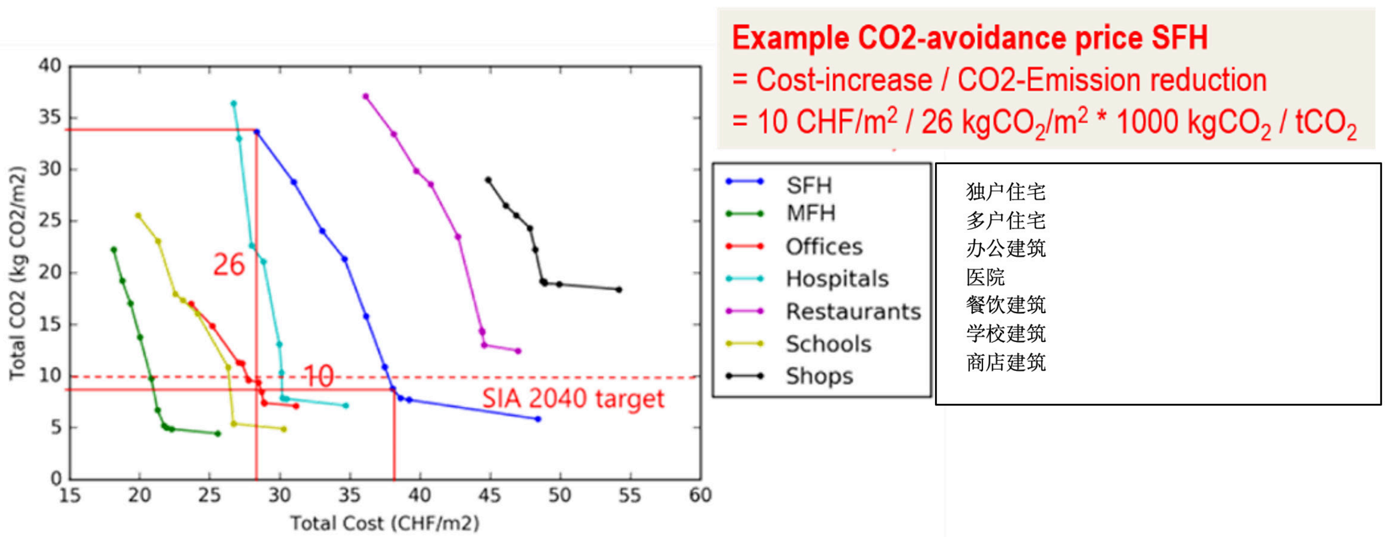


Figure 7. Figure 7: Average Pareto front for single family, multi-family and non-residential buildings, representing the Swiss building stock. The life-cycle emissions represent annualized CO2 emissions over the lifetime of the components used and their operation. Optimal transformation strategies for buildings, neighbourhoods and districts to reach CO2 emission reduction targets,
Energy and Buildings, Portia Murray et al., Volume 207, 2020;

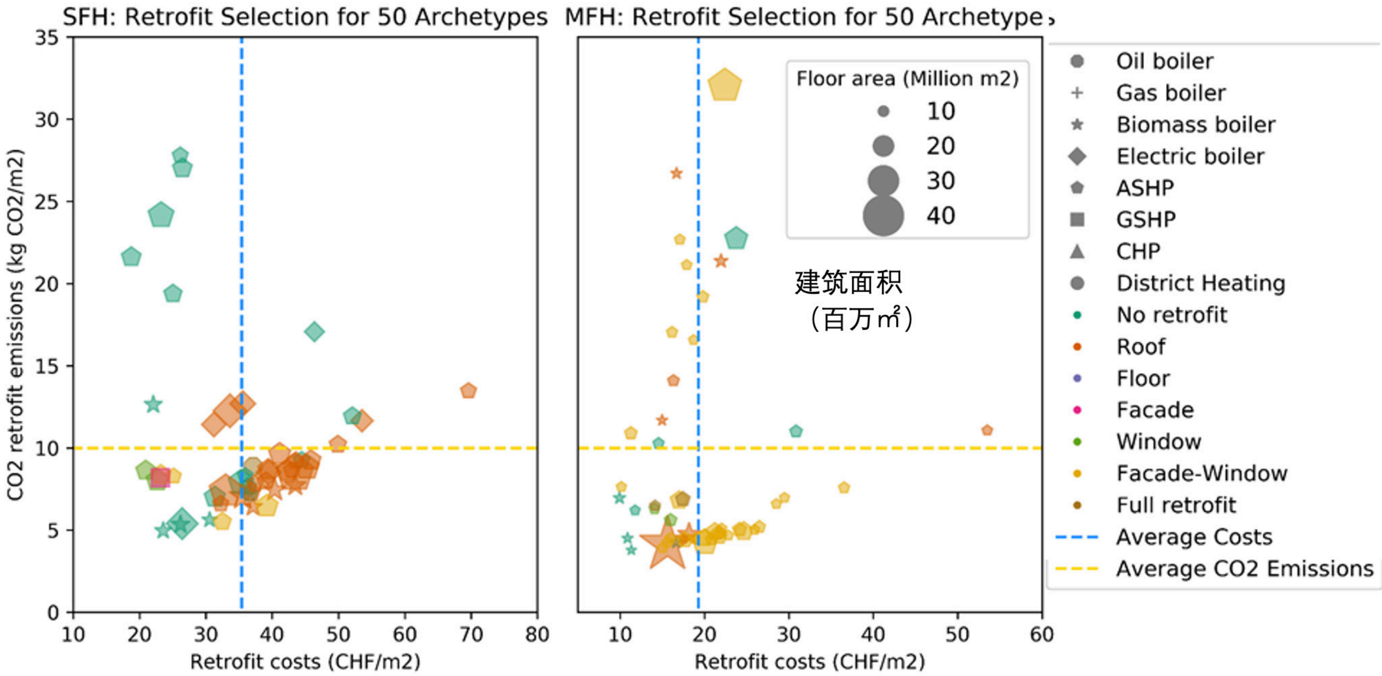


Figure 8: Comparison of deterministic Pareto front with multiple stochastic Pareto fronts resulting from the Robustness analysis. Optimal transformation strategies for buildings, neighbourhoods and districts to reach CO2 emission reduction targets, Energy and Buildings, Portia Murray et al., Volume 207, 2020

ity limits, share of renewable energy and embodied CO2 emissions.

Regulation of Capacity Limits

The «Capacity Limit» TER targets the design and construction phase of a building. The evaluation of the building energy calculations showed that the maximum system capacity could represent the energy efficiency of a building in a marginally worse way than the advanced calculation of the annual energy demand. However, with a TER "Capacity Limit", the certification can be simplified and the impact extended:

i) Simplification: The calculation of the system capacity is based exclusively on the chosen construction and the selection of materials and equipment. Operational assumptions such as solar gains, internal loads, occupancy, etc. can be neglected.

Implementing such a TER can be performed similarly to the predecessor by verifying compliance with limit values during the planning phase. Or easier during the construction phase by inspecting the capacity data of the installed systems.

ii) Extension: The switch to renewable energy sources (see also below) is a major challenge for the electricity, gas and heat infrastructures. Their magnitude and their corresponding supply capacity are limited by the installed networks. By limiting the capacity of a building, the TER influences infrastructure requirements directly by regulating the necessary network and reserve capacities and incentivising storage capacities at the building level.

Regulation of the Renewable Share

The «Energy Mix» TER targets the operation phase of a building. Energy consumption and greenhouse gas emissions are significantly impacted during building usage. The proposed TER limits the amount of caused CO2 emissions by the supplied energy. The building owner or tenant can comply with the CO2 limits by reducing his consumption, choosing low- or zero-CO2 energy products and/or increasing its on-site renewable energy production. (e.g. photovoltaics, biomass boilers, etc.). The enforcement of such a TER could be performed by Smart Meters and Digital Data Platforms.

Regulations of the Embodied Emissions

The «Embodied Emissions» TER targets the design phases and upstream material production of the building industry. An increasing proportion of the environmental impact in Switzerland's building stock no longer comes from the use phase, but from

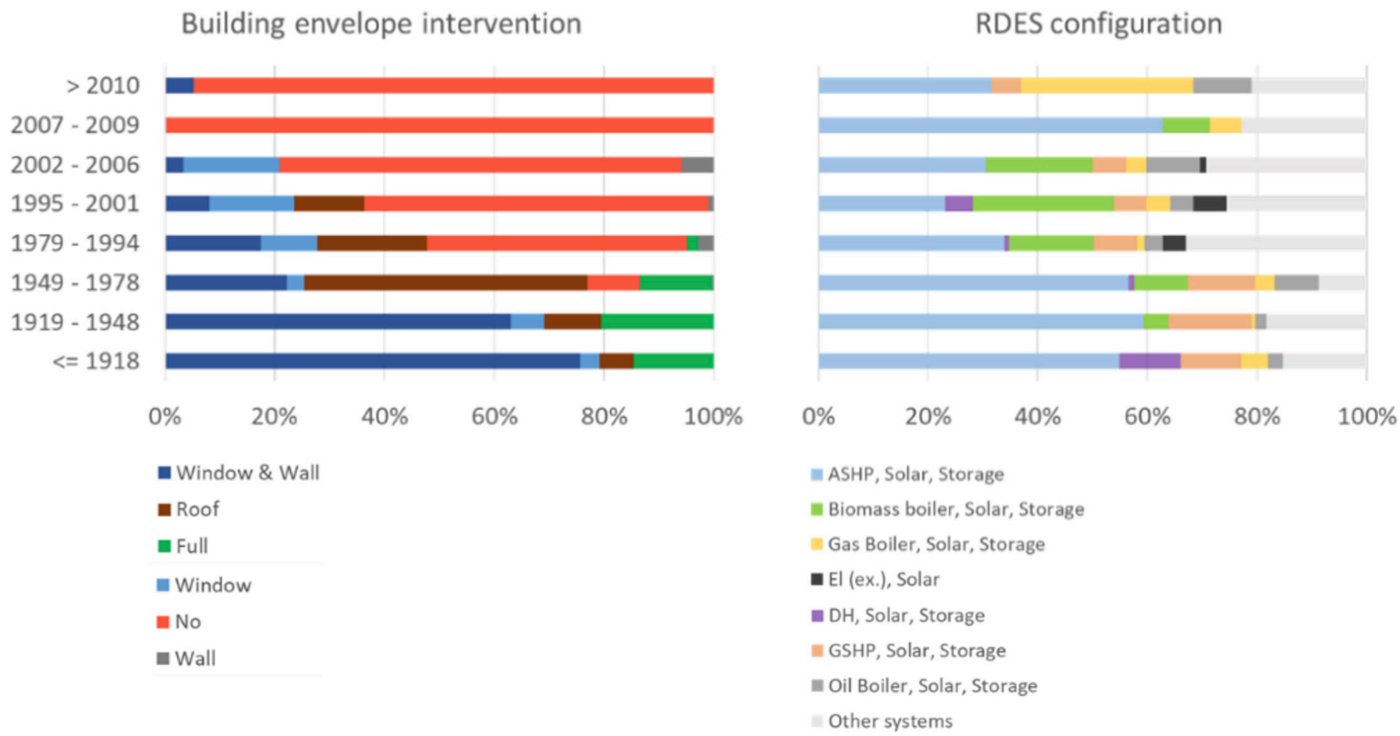


Figure 9. Typical solutions under 10 kg CO2, eq/ m2 annually, ranked in by building age (Photovoltaics are the most popular choice in the solar system category.© Source: Optimal transformation strategies for buildings, neighbourhoods and districts to reach CO2 emission reduction targets, Energy and Buildings, Portia Murray et al., Volume 207, 2020

the "ecological rucksack" that building materials bring with them, i.e., from the emissions that occur during the production phase (embodied emissions). Approximately half of those emissions will come from new buildings while the other half originates from retrofitting the existing building stock, while the impact from demolition and decommissioning only accounts for a minor share . Therefore it is critical to investigate and implement the solutions aimed at reducing such embodied impacts. Circular economy provides a framework of how to reduce environmental impacts arising throughout the life cycle of materials through various circular strategies (e.g. rethink, reduce, refurbish, recycle) [Potting, J. et al., 2017]. Implementing such circular strategies in the building industry comes with a set of specific challenges due to the unique layout of the construction sector.

i) The current material flows in the construction sector are highly imbalanced as the input flows are much higher than potential secondary resources coming out of the system.

ii) Long and very diverse lifetimes in the building sector make business models dealing with secondary resources from buildings complex.

iii) The broad diversity and increasing complexity of materials require different circular strategies depending on the various materials used.

iv) Construction projects are highly customized and the multitude of stakeholders involved complicates standard solutions.

v) Besides some promising pilots, a large knowledge gap about which materials are in the building stock, and when will they come out where, and in which quality, exists. In sum, these aspects also affect how future TER could address incorporating embodied emissions in their regulations. Labels, material passports, building material databases and pilot projects for individual materials as well as for entire buildings are promising signs of the industry moving into this direction. However, given the large uncertainty about which circular strategies will be most effective, current regulations largely concentrate on prescriptive requirements regarding the deconstruction phase and waste disposal.

The new TERs also allow the technical and economic potentials of larger-scale solutions to be exploited. The suggested performance-based measures for buildings, namely "Capacity Limiting" and "Energy Mix", can also be applied analogously at the neighbourhood and district scale. Spatial planning, including energy planning, could create supplementary incentives to emphasise larger-scale solutions.

A further consideration for an effective TER could be binding reduction paths for limits or target values. The legislature thereby commits itself over the long-term and constrains its negotiating scope while enabling building owners to prepare themselves for the upcoming limits and allowing them to choose the optimal time to conduct renovation work. At the same time, the building industry gains security for its product and service development since these would comply with future regulations, thereby encouraging innovation.

Outlook on future TER

The proposed TERs affect the entire life cycle (construction, operation and decommissioning) of a building. By subdividing the complex CO2 regulation problem of buildings into interrelated but consistent measures, a regulation framework can be built which consist of transparent and comprehensible parts that can be easily and effectively enforced. Moreover, each TER, which covers a particular part of the framework, will target the relevant decision-makers, e.g. TER ‚capacity limit ‘ influence the work of architects, TER ‚renewable share ‘ influences the behaviour of the owner and TER ‚embodied emissions ‘ can be reduced by the building material industry. Such tailored TERs, coordinated by the framework, could achieve the greatest impact of reducing CO2 emissions.

The presented work focuses on technical energy regulations, which have increased energy efficiency in the past and will effectively decrease CO2 emissions in the future. However, we acknowledge that such control and regulatory instruments work best if embedded and coordinated in a more comprehensive policy mix [Rogge, K. S., & Reichardt, K., 2016; Kern et al. 2017], as no single TER can address all the market and behavioural failures [Lee, W. L., Yik, F. W. H., 2004]. The coordination with other policy instruments, either economic and market-based (e.g. subsidies) or fiscal (i.e. taxes) instruments, or support, information and voluntary action, although not the focus of this work, will be essential to achieve the most significant possible impact. Furthermore, determining income and policy cost effects of the various mixes of regulatory instruments should also be examined and, if necessary, coordinated. This will establish holistic conditions for achieving the national objectives, like the net-zero goals of Switzerland.

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