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sweet swiss energy research for the energy transition

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Summary

This report defines the four identified pathways scenarios of the SWEET-SURE project as well as five scenarios representing disruptive events. The development of these scenarios are based on a interdisciplinary and inclusive approach including the project’s research partners and the SURE stakeholder forum. The scenarios are described in detail and corresponding information to quantify the scenarios using energy models is provided. Beyond this, model connections of the comprehensive analytical framework of SURE are sketched, highlighting the major parameters and variables exchanged between the SURE models for the national analysis. As such, this report represents a fundamental document for the application of the analytical framework and the collaboration among the modelling teams in SWEET-SURE.

Zusammenfassung

In diesem Bericht werden die vier im Rahmen des SWEET-SURE-Projekts identifizierten Pfadszenarien sowie fünf Szenarien für Störereignisse beschrieben. Die Entwicklung dieser Szenarien basiert auf einem interdisziplinären und integrativen Ansatz, an dem die Forschungspartner des Projekts und das SURE-Stakeholder-Forum beteiligt waren. Die Szenarien werden detailliert beschrieben und es werden entsprechende Informationen zur Quantifizierung der Szenarien mit Hilfe von Energiemodellen bereitgestellt. Darüber hinaus werden die Modellverbindungen des umfassenden analytischen Rahmens von SURE skizziert, wobei die wichtigsten Parameter und Variablen hervorgehoben werden, die zwischen den SURE-Modellen für die nationale Analyse ausgetauscht werden. Damit stellt dieser Bericht ein grundlegendes Dokument für die Anwendung des analytischen Rahmens und die Zusammenarbeit zwischen den Modellierungsteams in SWEET-SURE dar.

Résumé

Ce rapport définit les quatre scénarios de trajectoire identifiés dans le cadre du projet SWEET-SURE ainsi que cinq scénarios représentant des événements perturbateurs. Le développement de ces scénarios est basé sur une approche interdisciplinaire et inclusive incluant les partenaires de recherche du projet et le forum des parties prenantes de SURE. Les scénarios sont décrits en détail et les informations correspondantes pour quantifier les scénarios à l'aide de modèles énergétiques sont fournies. En outre, les connexions des modèles du cadre analytique global de SURE sont esquissées, mettant en évidence les principaux paramètres et variables échangés entre les modèles SURE pour l'analyse nationale. En tant que tel, ce rapport représente un document fondamental pour l'application du cadre analytique et la collaboration entre les équipes de modélisation dans SWEET-SURE.

Riassunto

Questo rapporto definisce i quattro scenari di percorso identificati del progetto SWEET-SURE e cinque scenari che rappresentano eventi dirompenti. Lo sviluppo di questi scenari si basa su un approccio interdisciplinare e inclusivo che include i partner di ricerca del progetto e il forum degli stakeholder di SURE. Gli scenari sono descritti in dettaglio e vengono fornite le informazioni corrispondenti per quantificare gli scenari utilizzando i modelli energetici. Inoltre, vengono delineate le connessioni tra i modelli del quadro analitico completo di SURE, evidenziando i principali parametri e le variabili scambiate tra i modelli SURE per l'analisi nazionale. Questo rapporto rappresenta quindi un documento fondamentale per l'applicazione del quadro analitico e la collaborazione tra i team di modellazione in SWEET-SURE.

1 Introduction

In view of a system transformation to a much higher share of renewable energy, SURE addresses the need for an integrated assessment of sustainability and resilience, analysing the multiple dimensions of environment, use of natural resources, public health, economics, security of supply, and social well-being. Therefore, a novel analytical framework is being applied that involves several energy models and other quantitative tools. To apply the analytical framework in a coordinated way, deliverable D2.1 provides the main specifications for the analysis. This deliverable includes narratives of long-term pathways for the transformation of the Swiss energy system as well as of the sudden disruptive events used to assess the sustainability, robustness and resilience of the energy transition to a carbon-free economy by 2050. These consistent and coherent storylines are used as a skeleton for a structured implementation in subsequent quantitative analyses in SURE. No preference or likelihood of the narratives is assigned. Instead, they are built upon the status-quo of knowledge and modelling expertise in scenario generation in energy systems analysis.

The narratives for pathways and disruptive events have been conducted in close coordination with the members of the SURE Stakeholder Forum and the SURE partners of the whole consortium. Prior to the definition of the narratives, a comprehensive review of pathways to achieve the net-zero transition has been performed, and in particular, those proposed in the new Energy Perspectives study EP2050+ [1], the Swiss Competence Centre for Energy Research Joint Activity Scenarios and Modelling [2], and the Competence Center for Research in Energy, Society, and Transition [3], as well as relevant risk analyses studies from the Federal Office for Civil Protection (FOCP) [4]. The objective of the literature review was to understand how narratives defined in these studies describe the evolution of society, policy and technology and to gain knowledge on the main risks and disruptive events foreseen by experts who participated in the relevant studies from the Federal Office for Civil Protection.

The SURE pathways deviate from the traditional practice of defining storylines for the pathway based on the simple introduction of variations in technology development and its rate of deployment. This is because the Swiss energy transition is at crossroads of geopolitics-technology-society developments calling for a better and more holistic understanding of the trade-offs and synergies between these three dimensions. Hence, the SURE pathways cover this three-dimensional space with different socio-economic challenges for climate change mitigation. A strong focus has been put on supporting policy and decision-making to succeed in a sustainable and resilient transformation of the Swiss energy system and economy. Since future developments in the energy and transport systems cannot be exactly foreseen, four different storylines have been developed for the long-term evolution of the Swiss energy system, to which four different disruptive events and shock scenarios are applied to assess their performance across a number of sustainability and resilience indicators.

It should be noted that pathways are not predictions of what is likely to happen or what will happen. Rather, taken collectively, they are used to explore the range of possible outcomes over the next 30 years. Although they do not provide a comprehensive description of future uncertainty, they intend to encompass a significant range of possible outcomes for the energy system in 2050. Thus, the SURE pathways can be used to shape a sustainable strategy that is resilient to that uncertainty. It should be noted that the pathways are based on existing and developing technologies and do not consider the possibility of entirely new or unknown technologies emerging. The definition of the pathways does not impose preferences or likelihoods.

The current deliverable defines the first set of pathways and disruptive events for SURE, as a refinement of these storylines is foreseen after the third year of the project to incorporate not only more recent developments and insights in the Swiss and global energy markets and climate goals, but also new insights gained from the quantitative analysis within SURE. Besides, based on the collaboration of the SWEET SURE project with other SWEET Consortia established in the SWEET CROSS and SWEET Co-evolution projects, insights and findings from these studies will be included in the next round of the definition of the narratives.

2 Definitions of *pathways* and *shocks*

2.1 What is a *Pathway*?

In the context of SURE, a pathway is the temporal evolution of the energy system towards a future state. Its concept ranges from sets of narratives of potential futures to solution-oriented decision-making processes to achieve desirable energy and climate goals (Figure 1). A pathway focuses on the techno-economic and socio-economic trajectories and involves various dynamics, goals, and actors across different scales.

In SURE, a pathway is defined across technical, environmental, economic, societal and resilience dimensions, and results from the output from the SURE modelling framework. The latter could include investments in energy supply and end-use technologies & infrastructure, energy flows between technologies and sectors, energy prices by sector and fuel, GHG emissions per sector, use or fuel, trade quantities, expenditures and revenues, economic output per sector, employment by sector, regulations and laws, social norms and consumer behaviour, security of supply and reliability, etc.

The definition of pathways in SURE is motivated primarily by three questions:

1. What are the near-term and long-term future choices that define the pathway, including, for example, energy efficiency and climate mitigation goals or achievements, technology mixes and use, policies and regulations?

2. What are the key decision-making outcomes from each pathway, including economic costs and implications for a sustainable and resilient energy transition

3. What actions today could influence the availability and use of future options?

One can differentiate between two types of pathway which characterise the future evolution of the energy system from different perspectives, especially when it comes to the achievement of future objectives: namely, explorative or normative pathway scenarios.

Explorative or descriptive pathways portray what could happen in the external environment of the energy system. An example is the continuation of the current trends in energy consumption and use and the current policies for the future. The latter is commonly used when one defines the so-called “Baseline” or “Reference” scenarios.

Normative, or decision support pathways, show what should happen in the future to achieve certain strategic targets. An example of a normative pathway is the achievement of net-zero GHG emissions in 2050. Such a normative scenario would identify the configuration of the energy system that meets this target. Another example of a normative scenario is the imposition of certain renewable or energy efficiency targets, where one is interested in the resulting energy system configurations

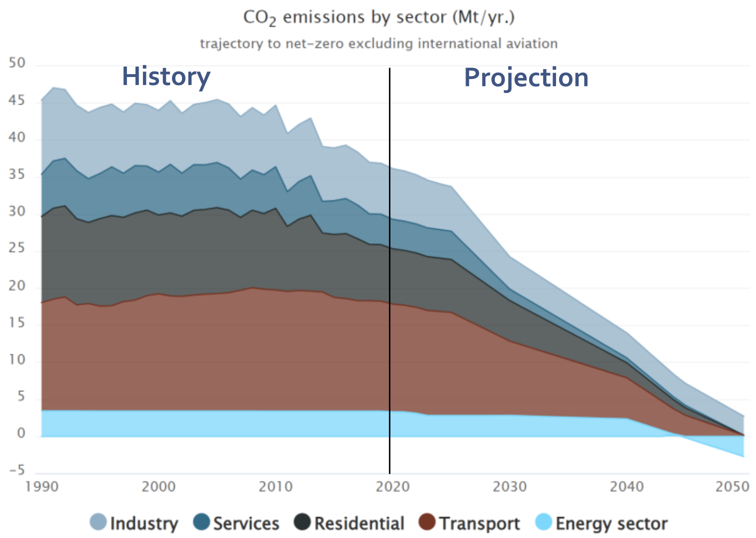

Figure 1: An example of a pathway to net-zero CO_2 emissions in Switzerland [2]

2.2 What is a *shock*?

While pathways are the primary tool for examining the impacts of decision and policy actions on the future configuration of the energy system, extremes such as weather events, societal and political swings and financial shocks can also affect the future. While these extremes are hardly predictable, particularly in a long-term perspective, we should be aware that such events might happen and should not be neglected in decision-making.

In the SURE terminology, a *shock* is an extreme event that occurs suddenly at a future point in time of a pathway. Similar to a pathway, the shock concept is based on a narrative and has multiple dimensions: environmental, societal, political, financial and technical. A shock narrative defines the shock not only towards the dimensions but also towards attributes such as time (when it occurs), location (where it occurs), duration (how long it lasts), and intensity (how strong the shock is).

A shock in SURE can be transient or disruptive. A transient shock might be considered out of the ordinary in the “statistically low probability of occurrence” sense [5]. These events might be anticipated but not necessarily planned for. A disruptive shock might be considered out of the ordinary in the “beyond common perceptions of a probable future” sense. While the drivers of a disruptive shock might be currently anticipated, the speed and scale at which these drivers accelerate the transformation of the energy system might not be.

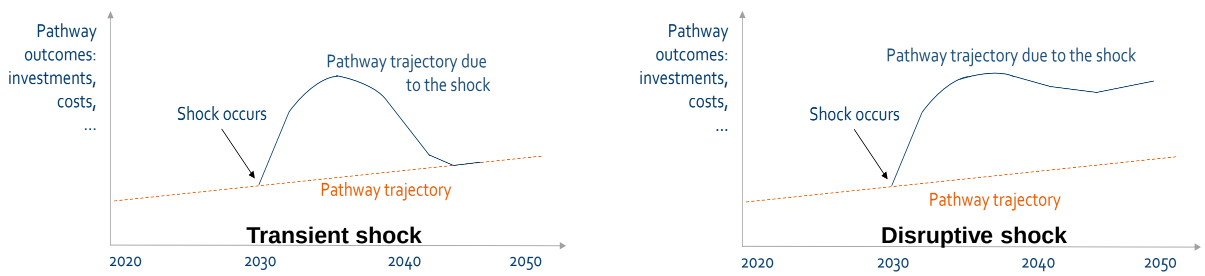

Figure 2: Comparison between a *transient shock* and a *disruptive* shock.

A transient shock usually does not alter the end of a pathway. In contrast, a disruptive shock alters the end and can lead to a new pathway (Figure 2). However, the effects of a transient shock maybe long-lived as well, even if its drivers are not in place anymore. In this regard, a transient shock can also be disruptive. Thus, within SURE, we abstain from pre-defining if a shock will be transient or disruptive. Instead, we let the SURE analysis determine its impacts based on the modelling results.

3 Definition of SURE long-term pathway scenarios

In energy modelling, scenario-building exercises consider factors such as technology development, energy markets, policies and geopolitical considerations, climate mitigation, societal attitudes and others in their scenario assumptions. The intension of the SURE pathway scenarios is to provide a framework for thinking about the future configuration of the Swiss energy system rather than a definitive view of how the future will look. Each scenario models a different set of responses to the above factors. By comparing them, an assessment of the drivers of the various outcomes, opportunities and pitfalls can be made. The SURE consortium does not have a single view of how the Swiss energy system might evolve, so none of these scenarios should be considered as a forecast.

3.1 Brief literature review on pathway scenarios development

Below is a summary of long-term pathway scenarios from IPCC, the European Commission, and the Swiss studies that served as the basis for developing the SURE long-term pathway scenarios. It should be noted that the section is not a catalogue of all scenario studies that were performed at Swiss, European or global levels but focuses on the most widely used scenarios that serve as the basis in the literature to derive several additional scenarios. Therefore, we briefly describe scenarios from official sources or large research projects focused on scenario development. We exclude ad-hoc scenarios developed in the context of scientific and non-scientific publications.

Pathway scenarios for global perspectives

IPCC built the earliest scenario-building exercises for reaching climate targets in 1990. The fifth assessment report of IPCC (AR5) was the first one relying on external scenarios developed by the research community. These were the Representative Concentration Pathways (RCP) that split the narrative of the scenario into four key dimensions: socio-economic, radiative forcing level, climate model and emissions. This partitioning allows parallel scenarios for each dimension rather than using a single storyline involving all dimensions [6]. Hence, most of the literature builds around the RCP concept, often integrating it with additional dimensions to expand the socio-economical and environmental coverage of the defined scenarios. However, climate lays at the core of these analyses and serves as a starting point for scenario development. The RCP scenarios considered mainly the GHG emissions, the short-lived emissions and the level of land use. Several national climate scenarios are derived from the RCP framework worldwide, e.g., the Swiss CH2018 scenarios [7].

In the sixth assessment report of IPCC (AR6), the concept of RCP has been expanded. The Shared Socioeconomic Pathways (SSPs) were introduced, in which socioeconomic aspects and climate mitigation assumptions (based on RCPs) are decoupled and used as orthogonal dimensions in a Scenario Matrix Architecture ([8], [9]). The SSP scenario assumptions include three main attributes: climate policy goals, policy regime goals and the implementation limits and obstacles related to the definition of these policies. The framework of SSPs contains five main scenarios from which different reference (baseline) scenarios can be developed. The SSP 1 scenario focus on sustainability, SSP 2 is a middle-of-the-road scenario, SSP3 assumes regional rivalries, SPP 4 places emphasis on inequalities, and the SSP 5 scenario is based on the continuation of fossil-fuel development. All scenarios consist of a narrative, quantified population, GDP and urbanisation trajectories, and qualitative assumptions on the energy and land use sectors. These elements serve as the starting point for the further quantitative elaboration of the SSPs, including using three of the four RCPs forcing targets that were applicable (6.0, 4.5, and 2.6 W/m2).

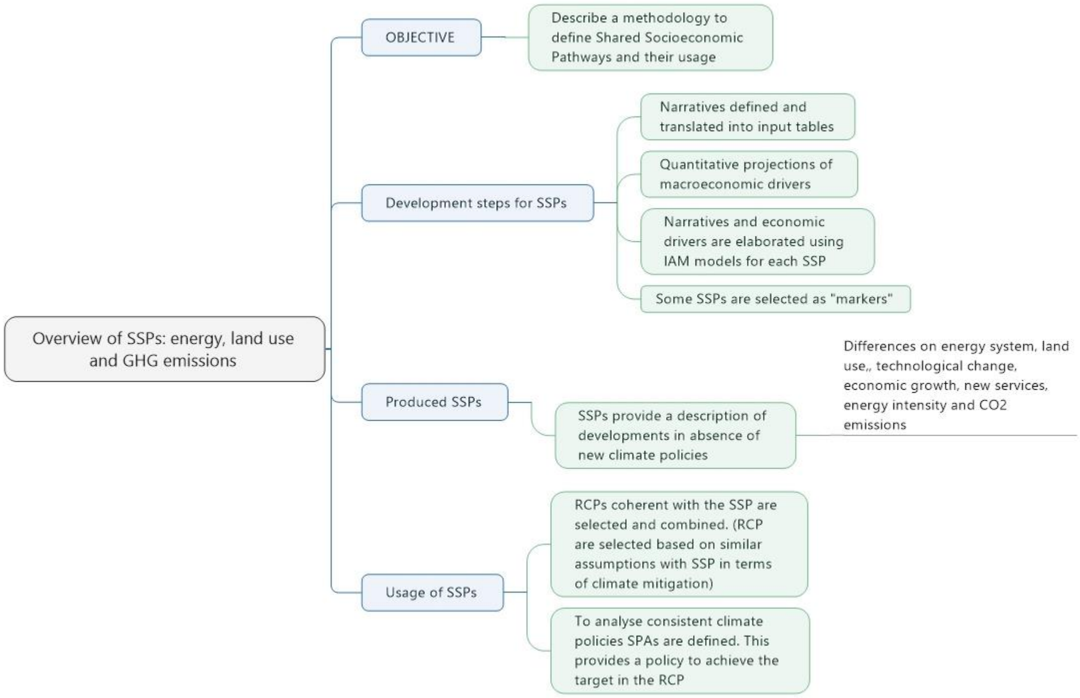

Figure 3: Representation of the SSP scenarios (source: from [10])

Another major global scenario study is the International Energy Agency "World Energy Outlook" series. This flagship publication of the IEA has appeared every year since 1998. It provides critical insights into global energy supply and demand in different scenarios and their implications for energy security, climate targets and economic development. The recent World Energy Outlook 2022 [11] includes three scenarios, one normative and two explorative. The Stated Policies Scenario (STEPS) is based on a detailed sector-by-sector review of the policies and measures in place or under development. It reflects an exploration of the current policy landscape. The Announced Pledges Scenario (APS), which was first introduced in the 2021 edition of the World Energy Outlook, explores the developments in the energy system by assuming that governments will meet, in full and on time, all the climate-related commitments that they have announced such as longer-term net-zero emissions targets and pledges in NDCs. Finally, the Net Zero Emissions by 2050 (NZE) Scenario is a normative scenario that works backwards from a defined outcome: stabilising global average temperatures at 1.5°C above pre-industrial levels.

The World Energy Council (WEC), an UN-accredited energy body with more than 3000 members in 90 countries, has published since 2013 three explorative pathways. The difference between the IPCC and IEA scenarios is that the definition of the WEC scenarios is based on participatory processes with strong involvement of stakeholders from the extensive WEC members network [12]. The three WEC scenarios have musical names to facilitate their communication. These names are also used as a trademark of the WEC study: the Modern Jazz scenario that assumes a market-led, digitally disrupted world with fast-paced and uneven economic growth describing an entrepreneurial future that presents new system integration, cyber security, and data privacy challenges. Unfinished Symphony describes a strong, policy-led world, with long-term planning and united global action to affordable decarbonisation, which is driven by bottom-up commitments to address climate change at the sub-national level and expansion of the focus from climate change mitigation to a broader, socially inclusive and economically affordable sustainable development agenda. And the Hard Rock scenario assumes a fragmented world with inward-looking policies, lower economic growth and less global cooperation driven by the rise of populist leaders, implying that this scenario evolves into a story of regionally firmer security foundations rather than total fragmentation.

European decarbonisation pathways scenarios

The European Commission Directorate-General for Energy (DG ENER) conducts several quantitative impact assessments of policy packages in the form of scenario-based analyses. In Energy Roadmap 2050 [13], apart from the baseline scenario (Scenario 1), also scenarios focusing on energy savings (Scenario 2) and technological developments such as a diversified supply portfolio (Scenario 3), high renewable shares (Scenario 4), delayed CCS deployment (Scenario 5) and low public acceptance for nuclear power (Scenario 6) are defined. In the "Clean Energy for all Europeans" study, the scenarios were normative and structured around GHG emissions targets to achieve a 40% reduction in 2030 and 80-85% in 2050 compared to 1990, energy efficiency targets from 27 to 33% in 2030 (compared to a baseline trajectory) or 30% renewable targets in 2030 [14]. In the study "A Clean Planet for All", which aimed at climate neutrality in the EU by 2050, the assessed scenarios focused not only on technology development and targets as in the previous studies, e.g., the scenarios looking at achieving decarbonisation by switching to electricity (ELC scenario), hydrogen (H2 scenario) and e-fuels (P2X scenario), stronger deployment of negative emissions technologies (1.5TECH scenario) or stronger efficiency measures (EE scenario) but they are also considered scenarios related to the transition to a more circular economy (CIRC scenario) and more sustainable lifestyle changes (1.5LIFE scenario). The study also included a scenario with a cost-efficient combination of the above options (COMBO scenario). Finally, in the assessment of the "Fit-for-55" package [15], the assessed scenarios had a strong policy focus as they aimed at achieving a 50-55% GHG emissions reductions in 2030 from 1990 with regulatory-based measures for increasing energy efficiency and renewables (REG scenario), with an expansion of carbon pricing and ETS to buildings and transport sectors (CPRICE scenario), and a combination of regulatory and carbon pricing measures (MIX scenario). The study also assessed a variant of MIX that for the first time included intensified fuel mandates for aviation and maritime sectors (ALLBNK scenario).

Besides the European Commission, the openENTRANCE project started in 2019 (with a completion date of April 2023) developed and assessed low-carbon transition pathways in Europe. The project defined four scenario narratives across the dimensions of "smart society", "policy exertion", and "technological novelty" [10]. The Gradual Development storyline assumes an equal part of societal, industry, and policy action to achieve energy transition, but it is the least ambitious narrative compared to the others. The narrative assumes a rather strong electrification, continuous policy push necessary to keep sight of short-, medium- and long-term goals and moderate market pull, demand side participation and carbon pricing, and necessary human inertia mitigation policies. The Techno-Friendly narrative is characterised by economies of scale of mainly supply-side novel technologies, a top-down technological revolution driven by market pull and ambitious carbon pricing, while society is open to large-scale infrastructure projects and it is more techno-friendly in general. The Directed Transition envisions a strong continuous incentive-based policy push to support certain technology options both in the supply and demand sides (e.g., ICT, floating offshore wind, H2-based energy and transport services, CCS in niches), ambitious carbon pricing, while societal efforts and citizen-led initiatives are minimal. Finally, the Societal Commitment assumes a smart life style, circular economy, advanced digitalisation, and avoidance of externalities in the energy and transport sector triggered by strong market-pull initiatives, ambitious carbon pricing, and bottom-up revolution of prudent and cooperative individuals, communities and decision/policy makers.

Swiss scenarios

The Swiss Federal Office of Energy has commissioned the development of "Energy Perspectives" since the oil crisis in 1973. The "Energy Perspectives 2050" [16] provided the basis for the revision of the Swiss energy policy after the reactor accident in Fukushima by examining three main scenarios: the WWB scenario is a fossil central baseline scenario with a nuclear exit after 50 years of nuclear power plants lifetime, the POM scenario included policies and measures for a stronger expansion of solar and wind energy and gas turbines combined cycles for replacing the nuclear power plants, while the NEP scenario aimed at 1 – 1.5 t CO_2 per capita by 2050 (a target compatible with the first NDC submission of Switzerland) by additionally focusing on stronger efficiency measures. The recently published “Energy Perspectives 2050+” [1] comprised four successful net-zero GHG emissions by 2050 scenarios and a reference scenario. The reference scenario (WWB) is an instrument-based scenario that includes the policies and measures that were decided in the Swiss energy strategy of 2018 [17], aiming at assessing the energy demand and supply configuration and the resulting GHG emissions from the implementation of the Swiss energy strategy. The ZERO-Basis scenario is a normative scenario aiming at net-zero GHG emissions by 2050. It focuses on technical instruments to achieve energy efficiency and renewable energy targets aiming to provide insights on the measures and technology mixes needed for achieving climate and energy targets and their cost and energy security implications. The ZERO-Basis scenario also has three variants: the ZERO-A variant that focuses on stronger electrification, especially in the heating sectors, the ZERO-B variant that continues the reliance on gas, including synthetic gas, and the ZERO-C that places more emphasis on district heating and PtL options.

In the Swiss Competence Centre for Energy Research Joint Activity Scenarios and Modelling (SCCER JASM), three core scenarios and four variants of them were defined for exploring the Swiss energy transition [2]. The BAU scenario implements the policies in place until December 2019. The EPOL scenario fully implements the Swiss Energy Strategy 2018, including renewable and efficiency targets. The CLI normative scenario imposes the net-zero CO_2 emissions from fuel combustion and industrial processes target by 2050 and many of the measures described in the 2021 revision of the CO_2 Act [18]. The variants of CLI were defined across the dimensions of international cooperation and energy markets, technological progress, resource availability and social acceptance. The ANTI variant of CLI assumes low international cooperation in mitigating climate change that results in limited technological progress in clean technologies and weaker integration of Switzerland into the global energy markets, as well as it triggers increased social resistance to the implementation of large-scale and low-carbon projects that limits the exploitation of the sustainable available renewable potentials. The SECUR scenario prioritises energy security and reliability of the energy system by minimising import dependency, promoting domestic grid reinforcements and assuming a society keener on using domestic renewable resources to reduce the carbon intensity of the Swiss economy and willing to accept and pay for it. The MARKETS variant of CLI assumes higher global cooperation and integration of Swiss and international energy markets with increased availability of imported biofuels, e-fuels, hydrogen and electricity to achieve decarbonisation through affordable domestically produced or imported energy. Finally, the INNOV variant builds upon the higher integration of Swiss and international energy markets, and it additionally assumes a global coordinated effort to reduce global climate change that increases R&D expenditures to low-carbon technologies, together with circular economy policies and schemes that in Switzerland and the World, as well as higher contributions from the society and higher social acceptance in adopting new and clean technologies.

<u>Lessons learned from existing storyline descriptions</u>

The storyline development in literature relies on two main methodological approaches [10]:

- Identification of the dimension of analyses determining the number of individual storylines
- Selection of key drivers and features of the individual storylines highlighting the uniqueness of each one.

In terms of dimensions considered in the storyline development, the following approaches are used [10]:

- Single-dimensional storylines: This approach develops a storyline mainly across a single dimension. It usually emphasises different key uncertainties in the future, while the number of uncertainties is not restricted. Examples of single-dimensional storylines are those focusing on different technical pathways (e.g., achieving decarbonisation via electrification, e-fuels, or energy efficiency measures and combinations of them) or those performing Monte Carlo analyses across different uncorrelated random variables, the IEA WEO scenarios and the

EP2050+ scenarios. The disadvantage of this approach is that the storylines are not substantiated enough, or the uncertainties are large and arbitrarily selected.

- Multi-dimensional storylines: These storylines usually span across two or three dimensions emphasising possible future worlds. Each dimension is characterised by two extremes, i.e., a “positive” and “negative” development. This means that the storylines are defined via a quadrant (2-D storylines) or cube (3-D storylines) etc. Examples of multi-dimensional storylines are the IPCC SSP scenarios (2-D) and the SCCER JASM scenarios (3-D). The advantage of this approach is that it captures the uncertainty surrounding the increasingly complex energy systems. This approach also facilitates to incorporate non techno-economic characteristics of future developments, such as attributable to social aspects of the energy transition. Consequently, trans- and interdisciplinary storylines can be featured by this approach for which combined expertise from several scientific disciplines (including engineering, economics, environmental sciences and social scienes and humanities) is needed. The disadvantage is that the storylines become complex, with many elements in their definition that can confuse the users of the scenario results.

The selection of the drivers and features of the storylines is based on two main questions that compose the reasoning of a particular setting of assumptions in a narrative aiming to enable research questions in the context of the long-term transition analyses [10]:

- *Why* a certain development is expected to happen (drivers of the storyline)
- *What* happens (features of the storyline)

3.2 A multi-dimensional storyline framework in SURE and its design requirements

In SURE, storylines of the long-term pathways and shock scenarios are based on multiple dimensions that expose key uncertainties and disruptions as coordinates. In such as multidimensional framework, the further from the centre of the coordinate system, the higher the exposure to a particular uncertainty/disruption is. In this regard, the SURE storylines describe a multi-disrupted future energy system being fundamentally different from the existing one.

Besides the multi-dimensionality, there are three more design requirements in SURE for the narratives of the long-term pathway and the disruptive events scenarios. The first requirement is that the narratives need to have enough distance in the coordinate system to have substantial differences in the sustainability and resilience indicators derived from them and used in the Multi-Criteria Decision Analysis. The second requirement is that the narratives are defined across a handful set of dimensions that balance between insights gained from the SURE analysis based on these narratives and complexity in the definition of the storylines.

The third design requirement of the SURE narratives is that they should also reflect the ongoing global climate debate. While Switzerland has committed to net-zero GHG by 2050, the target is to be achieved with the use of Internationally Transferred Mitigation Options (ITMOs), the availability of which largely depends on the climate change mitigation ambition in other world regions.

3.3 Controllable and uncontrollable uncertainties in the energy transition

A future description of the Swiss energy system is confronted with many controllable and uncontrollable uncertainties. Controllable uncertainties are the ones lying inside a particular future energy world from the different actors of the energy system. These uncertainties reflect steering options, strategies, policies and regulations. On the other hand, there are also uncertainties outside the Swiss energy system. These are uncontrollable uncertainties, and from today’s point of view, there are too many. Examples of uncontrollable uncertainties are the geopolitical and economic development, the novelty and availability of technologies or the society’s attitude and lifestyles.

In the first stakeholder workshop of SURE in April 2022, the project's stakeholders and partners were asked to identify the most important uncertainties surrounding the future evolution of the Swiss energy system. The results from this poll are presented in Figure 4 and are dominated by uncontrollable uncertainties. Many of them stem from the international context and the strong dependence of the Swiss energy system on global markets. For instance, geopolitics, the development of low-carbon or negative emissions technologies, economic growth and the establishment of new global markets for carbon and hydrogen are among the key ones that are heavily influenced by global trends. On the other hand, uncertainties such as consumer behaviour and demographic growth are uncontrollable uncertainties lying inside Switzerland. The controllable uncertainties in Figure 4 are the electrification of the demand, and the availability and exploitation of domestic renewable resources, which can be tackled with relevant regulatory and policy measures.

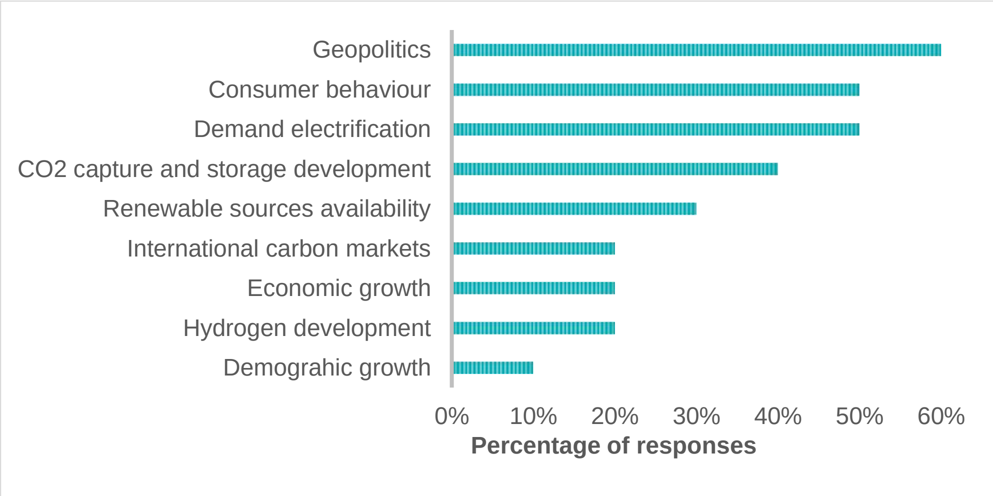

Figure 4: Main uncertainties identified by the SURE stakeholder forum based on the stakeholder workshop in April 2022 in Zürich

3.4 Clustering uncertainties into dimensions for storylines

Following up on the discussion in the first stakeholder workshop of SURE in April 2022 on pathways and shocks, the driving forces of the identified uncertainties were clustered into three main dimensions.

- **Geopolitical and international markets**: Geopolitical development, the global economy's performance and worldwide trade of energy commodities have been strongly interlinked. A positive development in this dimension is global economic prosperity, together with harmonic international relationships that foster coordinated actions to clean and affordable energy and promotes the establishment of new energy and emissions markets such as those for hydrogen and CO_2. However, the other extreme is uneven economic growth with geopolitical tensions and conflicts that lead to isolated regions and claims to power for exploiting resource-rich territories.

- **Availability of novel technologies**: Technological progress has always been an uncertainty. The new developments boosted by digitalisation, such as smart-homes, peer-to-peer trading and prosumers, and exploitation of leading-edge information and communication technology, combined with emerging technologies like hydrogen, carbon capture and storage, and electromobility support the pathway transition towards a low-carbon energy system. Still, a technological breakthrough cannot be prescribed, and the possible bandwidth of known technological eventualities should be foreseen.

- **Society's attitude and politics:** So far, there has been a significant gap between the purpose and intention of sustainable lifestyles and reality. Despite the good availability of low-carbon technologies, products and services, society is still reluctant to adopt them due to large inertia. In this regard, the role of the younger generation becomes increasingly important in achieving an economically efficient energy transition or resulting in high societal costs and conflicts. Besides, politicians and politics are under pressure to deliver framework conditions to adapt much faster to the energy transition towards a low-carbon economy. The two extremes in this dimension involve a smarter society with awareness of energy and environmental concerns and committed to a circular economy and a society with high inertia and many information asymmetries that trigger technological scepticism of emerging technologies and persistence in a perceived "comfort zone".

3.5 Research and policy questions addressed in the SURE pathways

The objective of the SURE pathways is to contribute to understanding the drivers, uncertainties, strategies and consequences of the energy transition by exploring policy and research questions such as:

1. Where can the current lifestyles and foreseen technological developments lead us towards the energy transition? What drivers and strategies will be key to reducing emissions under modest technological development in the next decades and a loose social commitment?

2. What technological innovations could have a major impact on an effective Swiss transition? What policy incentives and regulatory framework will steer their successful deployment and adoption?

3. To what extent the energy transition can rely on the societal commitment and stronger cooperation between Switzerland and the European and global energy markets?

4. How far can we rely on market forces, new business models, and social innovations? What are the main risks if we mainly depend on market decisions governing energy transition?

5. Which other options exist in energy transition if neither technological nor societal innovations are visible and what to do in the more challenging situation of little cooperation with the international markets in the case that energy policy-making is fragmented and collusive?

3.6 Detailed description of the SURE long-term pathway scenarios

In the SURE project, four storylines describe possible developments of a low-carbon energy system. Since there are many uncertainties surrounding the long-term configuration of energy supply and demand, we do not state preferences and likelihood for these storylines. Instead, we are indifferent and expect several narratives to happen likewise. Even though there are different key drivers in each storyline, they all share some common features:

- While the characterisation of a storyline emphasises a particular set of drivers, this does not mean that these drivers are not also important for other storylines to a certain extent. However, they are most pronounced in the storyline explicitly discussed.

- To reach ambitious climate change mitigation goals, high shares of renewables and demand-side participation from individuals, firms and communities are a kind of prerequisites that are present in all storylines aiming at decarbonisation trajectories compatible with limiting global warming to below 2^{o}C or 1.5^{o}C by the end of the century compared to pre-industrial levels.

Bringing together the major insights in the previous sections of this document, the three-dimensional topology shown in Figure 5 emerges as a meaningful approach to set stories around key drivers and uncertainties in the energy transition.

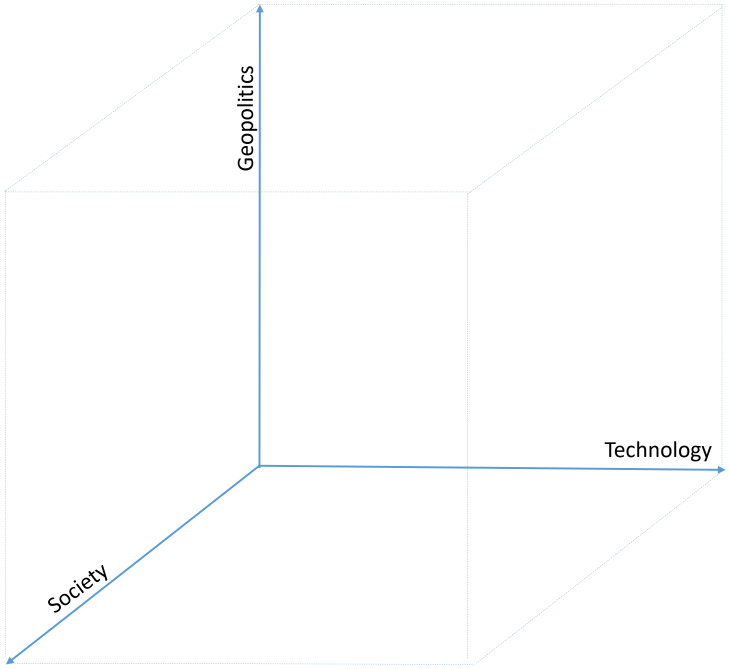

Figure 5: The 3D framework of pathway definition in SURE

The dimensions in Figure 5 are conceptually shaped by considering the positive quadrant aspects on:

- Society: represents a world in which effective policy measures successfully steer the energy transition to decarbonisation, which is also supported by sustainable behaviours and lifestyles of individuals, companies and communities.
- Technology: it represents a state of the world where key technologies for decarbonisation, such as hydrogen, CCS and negative emissions technologies, are enjoying rapid learning rates and are brought early into commerciality.
- Geopolitics: in the positive development of this dimension, there is strong international cooperation in promoting integrated energy and carbon trading markets to achieve an affordable, secure and environmentally sustainable transition.

Based on these definitions, the combination of dimensions results in four storylines. When defining the storylines, we avoid overemphasising one dimension at the expense of others, and we follow a more holistic approach by including elements of all dimensions in them. This also reflects to some extend interlinkages between the dimensions. Figure 6 lists the major cornerstones of the four SURE storylines on a general level. The names these long-term scenario are illustrative and inspired by the way people would move on these transition pathways.

Figure 6: Main elements of the four overarching SURE Pathway Scenarios (SPS)

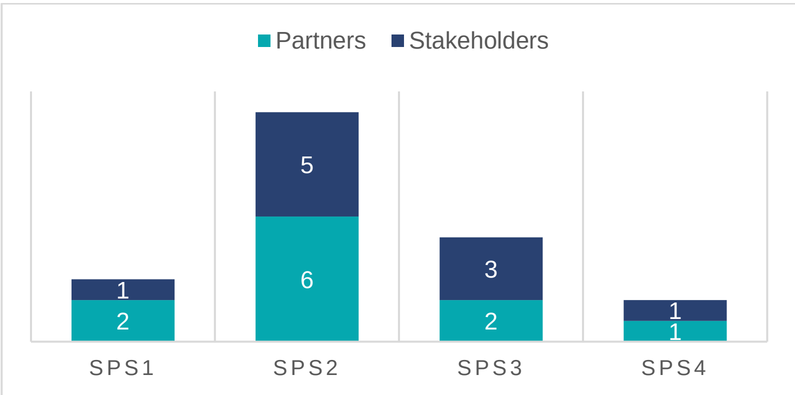

Figure 7: Number of partners and stakeholders contributing to the development of each storyline

A more detailed description of the SURE storylines for the long-term pathways is given in the following. The storylines were co-developed with the stakeholder forum of SURE and the SURE partners (for detailed information on the stakeholder workshop related to scenario develpment, see the SURE annual report 2022[1]). Figure 7 shows the responses received from the first stakeholder workshop on defining the long-term pathways in co-designing the storylines. Each participant was asked to select one of the four storylines and elaborate on its main features related to:

- The integration of Switzerland in energy trade in the EU and globally
- The development of gas, electricity, CO_2 transport and heating networks in Switzerland
- The prospects of hydrogen and Power-to-X in Switzerland and abroad
- The adoption and development rate of clean technologies in Switzerland and abroad
- Lifestyles and circular economy practices in Switzerland

[1] https://www.aramis.admin.ch/Dokument.aspx?DocumentID=69652

As shown in Figure 7, most of the responses received were for SPS2 and SPS3 storylines that reflect situations similar to the one experienced in the current (2022) energy crisis. This outcome indicates the influence of today's geopolitical and energy landscape on the views of the participants. It also highlights the challenge in participatory processes to bring stakeholders away from near-term insights, views and visions when co-designing long-term energy pathways narratives. Nevertheless, the discussions provided enough insights for developing the storylines of the four SURE long-term pathway scenarios.

3.6.1 SPS1: Team Sprint

In this storyline, the world gradually shifts to implement green economy strategies. Most governments reach a consensus on driving environmental sustainability and resilience through related policies and practices. The market mechanism emissions trading is introduced globally as one of the instruments to reduce carbon emissions and increase the penetration of renewable energies. Governments come together to support standards and protocols to improve energy efficiency and adopt circular economy practices. Society has become aware of the challenge of climate change mitigation and demands more effective action from local and national governments. Bottom-up (societally-led) and top-down (government-led) approaches come together to make society embrace cleaner and smarter lifestyles and shifts in energy consumer behaviours. Energy efficiency increases in industrial, agricultural and individual households sectors, while energy demand is reduced due to changes in social norms and collective behaviour towards "energy-sufficient" lifestyles. In the household sector, neighbourhoods are transformed to be more attractive in terms of energy efficiency and self-sufficiency.

At the same time, governments look closely at the energy security issue and reliability of energy service provision, especially when the energy systems are based on high shares of weather-dependent renewable energy. Besides reinforcing domestic energy infrastructures, regionally integrated energy markets are also gradually developed based on coordinated actions to ensure good availability of traded zero-carbon energy commodities such as hydrogen, e-fuels, biofuels and electricity.

While in the early part of the scenario period, the energy sector is regulated in more detail through taxes, feed-in tariffs, subsidies and state-funded building renovation programmes to encourage affordable and clean energy solutions, governments also introduce new financial incentives in the long term. Energy producers leverage these incentives to ease the financial burden of transforming their business and profit from clean liquids, synthetic fuels and other renewables. Clean technologies adoption and deployment increase, including hydrogen and PtX pathways, when solar PV and wind energy widely penetrate the energy mix.

In this narrative, the reduction in energy demand and the adoption of circular economy concepts reduce GHG emissions. Due to global cooperation and effort in mitigating climate change, Internationally Transferred Mitigation Options (ITMOs) are available at competitive prices. Territorial accounting systems are in force but sometimes give the wrong incentives risking too many exports of CO_2 emissions from rich countries. To support the latter, also CO_2 grids are developed connecting the European countries.

Nevertheless, with clearer carbon policies worldwide, fossil fuel producers leverage existing assets and exploit grants and new mechanisms to pivot their business towards clean energy, more sustainable industrial feedstock and new energy-related services. Under the combined effect of policies and technologies, demand for fossil fuels globally peaks around 2030, with coal peaking in the mid-2020s and oil and gas fifteen and twenty years later.

This storyline's dominant drivers for action are: societal values, strong global governance, integrated planning and business models.

3.6.2 SPS2: Mountain Hike

In this narrative the world gravitates toward a multi-polar order, and the international governance systems are weakened. The economy becomes more volatile, and international trade agreements are not fully implemented due to rising nationalistic policies that make export-oriented growth less important as an economic growth strategy. This leads to stagnating global GDP growth that affects open economies like Switzerland.

There is sometimes bilateral cooperation and an increase in regional coordination. Still, nations are generally more concerned with local than global issues, as bilateral trust-based agreements are more difficult in a multi-polar order. Switzerland trades energy commodities with a closed and reliable team of countries, and more introverted solutions are developed. While the integration of Switzerland with the European countries remains quite harmonised, there is a ”disintegration” outside the EU. This minimum collaboration is necessary as the European countries depend on each other, but there are no strong market exchanges.

Most countries use whatever capabilities they have to achieve local energy security. The shift in energy policy priority from environmental sustainability to energy security triggers trade conflicts that hinge on import tariffs. Import duties increase the import prices of energy producers.

Due to the weakened international organisations, resource access and conflict resolution have become more complicated worldwide. There is a tendency to reduce the energy import dependency to the minimum possible, if not zero, from regions with geopolitical instability. As a result, the trade volumes of energy commodities and fuels are reduced.

Many countries look to their own sources of strength and develop energy resources (not necessarily renewable) that are abundant in their territory to hedge against import risks. Switzerland also relies upon its energy sources, including non-clean energy ones, a potential prolongation of the lifetime of existing nuclear power plants and introduction of thermal plants for flexibility and reserve provision, and investments in “winter power” renewable options due to fear of scarcity. However, the country attempts to exhaust its domestic renewable potential, setting it as a high priority via policies that drive investments but potentially overlooking other damages that could be caused to the environment.

The resource scarcity challenges make regions accelerate new models of a circular economy. Technological innovation continues to happen, as it is driven by policies that accelerate domestic renewable deployment, and leap-frogging to offset low adaptation rates to limited resources also occurs. In addition, efficiency gains from more intelligent homes and other buildings advance to reduce consumption and increase energy security. Still, technological innovation is happening at a relatively slow rate due to limited technology transfer between regions, and it is regionally clustered.

The focus on energy security and affordability does not necessarily limit the adoption of clean technologies. For instance, domestic green hydrogen and synfuels gain momentum to offset the limited imported quantities of energy molecules, even if they are expensive options compared to gas imports. However, green hydrogen and PtX penetration are challenged by conflicts in territories rich in solar and wind resources.

Society adopts personal lifestyles that could lead to more energy security. In this regard, individuals, groups, firms, and communities adopt behaviours promoting energy efficiency and savings to reduce consumption and imports. As energy efficiency becomes a national goal, building renovation and equipment replacement is increased. Citizens are willing to pay for secure and reliable energy services, but fears of disruption in energy service provisions make them hesitant to adopt clean and green solutions quickly. For instance, modal shifts and equipment changes occur in the context of necessary renewals at the end of often an “extended” lifetime due to financial constraints and lack of trust in not proven alternatives. In this regard, citizens are independent of the national targets and energy use follows the same typical patterns with small annual increases.

Domestic CO_2 emissions mitigation is not a high strategic priority in this narrative for many regions, including Switzerland. There is a trade-off between energy security and sustainability, which might make ambitious emissions reduction goals more difficult, but not impossible, as this depends on “a coalition of the willing”. In this context, emissions credit systems remain relevant, while CO_2 transport networks are not widely developed, mainly for high-output industries.

The low economic growth imposes financial constraints on developing and maintaining energy infrastructures. The infrastructure deployment depends on the energy resources used. As imports are reduced, electricity and heating grids gain importance over gas grids and expand further. There is a need for high development of all energy networks to use all available domestic energy.

However, the financial constraints in infrastructure expansion result in electricity grid congestion. Besides the temporary planned load curtailments throughout the year, there are also risks of unplanned electricity and heating supply disruptions due to extreme weather events as the electricity and heat supply becomes more weather dependent. In this context, demand-side management becomes important and more flexibility from consumers is required. Households also demand “own” electricity production and storage solutions. To increase energy security, as regional conflicts and limited trade impede cross-border infrastructure, expansion of energy storage (electricity, heat and gas) occurs at large scales together with a focus on baseload units (e.g., hydro and geothermal).

3.6.3 SPS3: Single Trail Run

The decarbonisation agenda is stalled as fragmented worldwide policies have the character of “quick fixes” and face limited availability of investment for energy transformation. Ambitious national emissions reduction targets are often characterised as “too expensive” by leaders in several countries. While the goals of a sustainable and resilient energy system transformation are not abandoned, governments establish policies that balance security, social welfare and environmental concerns based on the local context without much consideration of regional or global impacts. These policies emphasise local economies, which help meet national needs while developing local markets.

With growing fragmentation, there is also a growth of inequality both among and within countries. Economic growth is high in industrialised and middle-income countries, while low-income counties lag. The global economy is volatile and regional constraints also contribute to the constrictions of finance, leading nations to turn to local energy supply solutions. Local business models emerge in which companies engage with local communities, developing local knowledge, adapting global best practices to local contexts and developing new technologies for local needs.

The fragmentation of political and economic systems weakens trade relationships. Energy security concerns emerge, and national governments choose the lowest cost and most attractive resources. They are increasingly investing in regional resource development and utilising selective bilateral trade relationships with a few strategic partners to ensure access to energy resources.

Although environmental concerns remain on national agendas in many regions, weak economic performance and low international cooperation challenges global issues such as climate change mitigation. Environmental sensitivity develops at local scales, and the global climate change mitigation challenge slides down in the list of priorities for national governments. Still, the climate change mitigation goal is not abandoned, but the globally connected energy sector diversifies. There are investments in both carbon-intensive fuels and low-carbon energy resources. At the same time, environmental policies focus on local issues around the middle- and high- income areas. As signals to investors related to decarbonisation are not clear in all regions, there is moderate progress in clean technologies on average. However, technology development is high in high-tech economies and sectors.

Communities seek to build a more sustainable and resilient future locally. Consumers rely on best-fit solutions for energy supply and demand that maximise local benefits. They increasingly want products and energy services customised for local contexts, and they have a high willingness to pay energy producers with high local content. Individuals revert to their own identities and cultures, and individualistic lifestyles emerge. Uneven efforts for energy efficiency and equipment replacement between different consumers characterise these lifestyles.

The development of local energy networks is supported by decentralised energy supply, accelerated building renovations, a wide spread of e-mobility and smart mobility and the development of local heating networks supplied by heat pumps. Digitalisation changes societal practices and contributes to energy savings, e.g., online shopping and home office enjoy wide social acceptance. Governments further support local energy self-sufficiency and place regulations for net-zero emissions buildings.

3.6.4 SPS4: Walk & Talk

In the fourth narrative, the currently observed trends in energy supply and use consumption continue. Technology performance improvements continue to occur at decelerated rates compared to the past. The energy and climate policies in the Swiss legislative acts continued at different intensities during the post-2030 period. They contributed to a modest energy system transformation compared to the rest of the three storylines. The same holds for the bilateral and international agreements between Switzerland, neighbouring countries, the EU and other regions.

In this narrative, access to the European electricity and gas markets weakens over time from today's levels, following similar trends with the current development of the corresponding bilateral agreements and negotiations. Electrification continues in the heat demands for buildings following the historical rates of renovation and equipment replacement. In mobility, the momentum of electric vehicle sales is maintained in the future following the technology improvements. However, the penetration of electricity in heating and mobility demands decelerates after the decommissioning of the last nuclear reactor in Switzerland. Local heat networks based on hydrogen and heat pumps emerge to serve more areas and reduce upfront costs for the residential sector to replace the heating equipment.

Efficiency continues to increase in this narrative, supported by the continuation of the relevant policies and measures. However, as lifestyles do not significantly change from today, the use of more efficient equipment and appliances is associated with rebound effects in energy consumption in some sectors, which partially offset the gains.

Large consumers increase their focus on gas fuel; overall, the gas network is extended from its current capacities. Towards the end of the projection period, hydrogen grids also emerge, mainly around industrial clusters and centres of aviation and cargo road traffic. These sectors are pushed for emissions reductions from the ETS and environmental policies in place. In this regard, power-to-liquids for aviation become an option in this storyline.

The Road we Stand continues the emissions reduction trends observed in the past but does not intensify the climate policy. Environmental awareness exists in society, and laws about net-zero new buildings are passed and supported, together with a modest increase in the CO_2 levy. As Switzerland continues to couple its emissions trading system with the European one and continues reducing emissions from the ETS sectors at the same linear reduction factors of today, domestic CO_2 mitigation emerges but at a limited scale as CO_2 networks do not develop at wide ranges.

In the electricity supply, the phase-out of the existing nuclear capacities is completed as planned with 60 years lifetime for the reactors. Non-hydro renewables partially cover the emerging electricity supply gap. Still, wind and alpine solar PV do not take off as climate policy signals are not strong enough to improve their competitiveness compared to alternative options.

The fourth SURE narrative serves as a benchmark of the other three, as it explores the future energy system configuration given the current framework of policy, technology and energy behaviour development. It should be noted that the macroeconomic outlook used in the SPS4 builds on recent demographic and economic projections for Switzerland and provides the basic framework upon which the other three narratives build.

3.7 The SURE modelling framework used to assess the narratives

The SURE modelling framework consists of a large set of different mathematical models which are orchestrated to provide a comprehensive view of the transformation of the Swiss economy and energy system towards net GHG emissions in 2050. GEM-E3 is a general equilibrium model suitable for assessing the development of the structure of the Swiss economy in the different long-term pathways and shock scenarios of SURE. The Swiss TIMES Energy systems Model (STEM) is a full energy systems model suitable for identifying future energy system pathways based on macro-economic, technology and policy developments. EXPANSE is also an energy systems model suitable for scaling down national-derived energy configurations to cantonal and municipality energy and infrastructure mixes. The Building Stock Model (BSM) is a sectoral model covering the energy service demand and supply of space heating, and other energy uses in the building sector. Finally, SURE-GRID is a detailed electricity network model assessing the impacts of the energy configuration mixes on the electricity infrastructure.

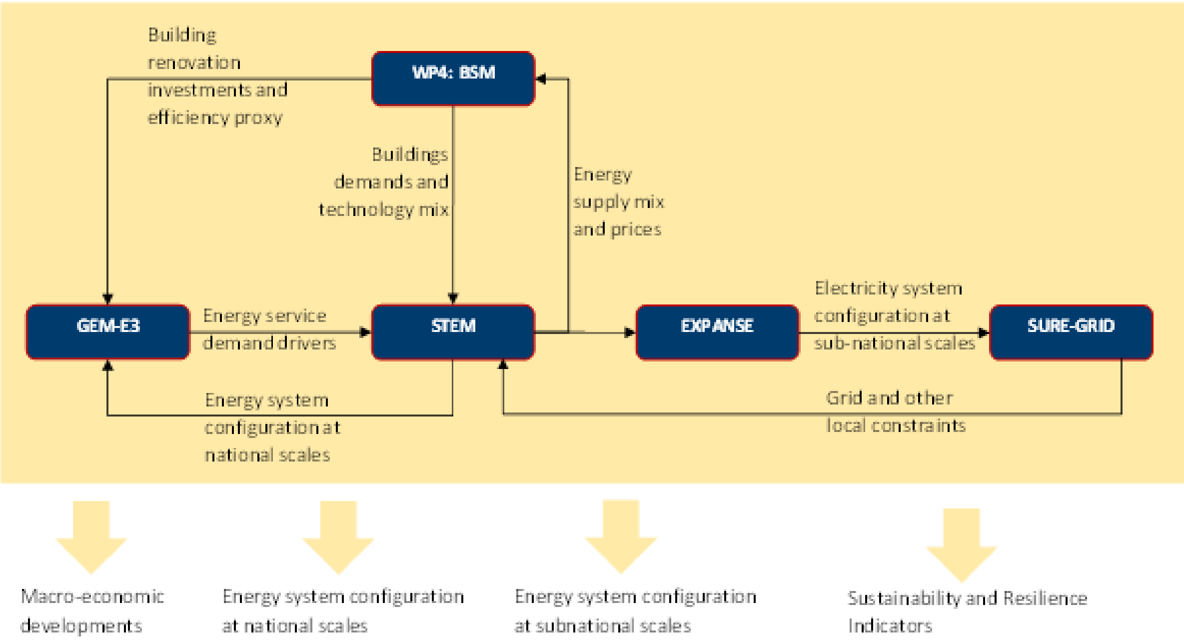

Figure 8: Major energy model interactions in SURE to inform the Swiss national analysis

When quantifying a storyline, the modelling framework of SURE is involved. The application of the models follows a specific sequence of interactions which is shown in Figure 8:

a. First, GEM-E3 and STEM perform iterations to converge in the developments of the national energy and economic systems. Once this is achieved, the buildings energy service demands refinement is performed via STEM and BSM exchanges.

b. The re-calculation of the developments in the energy supply and use in buildings would induce further changes in the supply sector of STEM and consequently to the households incomes. These changes are to be accounted for in the economic developments. In this regard, the second round of iterations between GEM-E3 and STEM starts to re-align the macroeconomic impacts from the energy system configuration. It is expected that the second round of GEM-E and STEM exchanges to have fewer iterations than the first one.

c. Once the national developments in the energy and economic systems have been identified, the configuration of the national energy system is scaled to the sub-national level with the help of the EXPANSE model. The latter provides its input to the required spatial resolution to SURE-

GRID for the detailed assessment of the response of the electricity transmission grid to the electricity supply and use calculated by the energy system models.

d. SURE-GRID feedbacks any electricity grid constraint violations back to STEM for adjusting the electricity supply and use dispatch. As no major changes in investments in energy supply and demand technologies are expected to occur from the re-dispatching that STEM performs, there is no need to further iterate with GEM-E3 or BSM models. However, in the case of re-dispatching, STEM provides its output to EXPANSE for alignment of the national and sub-national energy supply and demand mixes. As the re-dispatching of electricity supply and use respects the grid requirements, there is no need to re-iterate EXPANSE and SURE-GRID.

The following comprehensive Input-Output matrix sheds light on the major parameters and variables exchanged between the models.

Table 1: Major parameters and variables exchanged between the SURE models for the national analysis

Parameter / variable category	GEM-E3	STEM	BSM	EXPANSE	SURE-GRID
"Reference" economic outlook	Input				
Population	Input				
International fuel prices	Input	Input		Input (electricity)	
Mobility demand		Input		Input	
Heating and cooling degree days		Input	Input	Input	
GDP development	Output				
Sectoral economic developments	Output	Input	Input		
Households income	Output		Input		
Energy Reference Area		Input	Output (buildings)		
Sectoral energy service demands		Input	Output (buildings)	Input	
Energy investments at a national scale	Input	Output	Output (buildings)	Output (electricity)	
Energy mixes at a national scale	Input	Output	Output (buildings)	Output (electricity)	
Energy investment at subnational scales				Output (electricity)	Input (electricity)
Energy mixes at subnational scales				Output (electricity)	
Energy prices (domestic)	Input	Output	Input	Output (electricity)	

The overview of the main parameters and variables exchanged between the models shows that the complete SURE modelling framework does not require many exogenous variables. The most important ones are assumptions on demographic development, heating and cooling degree days, international fuel prices and import availability, and mobility demands which are not fully covered by the scope of the models in SURE. Macroeconomic developments and energy service demands (except mobility) are entirely generated within the framework.

3.8 Key assumptions of the four SURE narratives

This section summarises the main assumptions of the narratives. The SURE modelling framework includes energy systems models, sectoral models and macro-economic general equilibrium models that all interact with each other, and the input from one model is used by another. In this regard, the SURE framework does not need many exogenous assumptions to quantify the storyline. For example, energy service demands for buildings are endogenously generated from the interaction of the general equilibrium model and the buildings sectoral model. However, a reference macro-economic and demographic projection is needed as a starting point for the SURE framework, summarised in Table 2.

Table 2: Main macro-economic assumptions used for deriving the reference outlook of GEM-E3

	2020	2030	2040	2050
Population (million)	8.7	9.4	10.0	10.4
Number of households (million)	3.9	4.2	4.5	4.8
Working population (full-time equivalent)	4.3	4.4	4.6	4.7
Reference GDP (billion CHF_{2017})	695.6	846.4	981.6	1125.1
NACE C10-C12 Food & tobacco (% in GVA)	1.8	1.5	1.4	1.4
NACE C13-C15 Textiles (% in GVA)	0.2	0.1	0.1	0.1
NACE C17-C18 Paper and Pulp (% GVA)	0.3	0.3	0.2	0.2
NACE C20-C21 Chemicals and Pharmaceuticals (%GVA)	7.3	10.1	12.8	15.9
NACE C23 Minerals (% GVA)	0.4	0.3	0.3	0.3
NACE C24 Metals (% GVA)	0.3	0.2	0.2	0.2
NACE C25-C26 Metal products (% GVA)	5.0	5.5	5.6	5.3
NACE C28 Machinery (% GVA)	1.9	2.2	2.2	2.1
NACE B, C16, C22, C27, C29, C31-C33 Other manufacturing (%GVA)	3.1	3.3	3.2	2.9
NACE E Water supply etc. (% GVA)	0.3	0.3	0.3	0.3
NACE F Construction (% GVA)	5.5	6.0	6.5	6.9
NACE G Wholesale and retail Trade (% GVA)	15.1	18.8	21.8	23.8
NACE H,J Transport and Information/Communication (% GVA)	8.4	9.3	10.0	10.3
NACE I Accommodation and food services (% GVA)	1.6	1.5	1.4	1.4
NACE K Financial and Insurance activities (% GVA)	9.3	11.5	14.6	18.4
NACE O Public administration and defence, social security (% GVA)	10.4	11.1	11.7	12.0
NACE P Education	0.6	0.6	0.6	0.6
NACE Q Human health and social work activities (% GVA)	8.0	9.7	11.4	12.7
NACE L,M,M,R-U Other services (% GVA)	20.0	21.0	22.1	22.9
NACE A Agriculture (% GVA)	0.6	0.5	0.5	0.5

Source: SWEET CROSS data platform [19] *and EP2050+* [20]

In quantifying the different SURE long-term pathways, the macroeconomic and demographic developments shown in Table 2 are the starting point from which GEM-E3 calculates the narrative-specific economic development. Therefore, for the SPS1 – SPS3 narratives, no specific GDP trajectory is given exogenously. In addition, population development is assumed to be the same across all four SURE long-term pathways.

In contrast, the development of the heating and cooling degree days is assumed to vary across the storylines. These are derived from the Swiss climate scenarios CH2018 [7]. We focus on the RCP4.5 and RCP2.6 climate scenarios, mapped to the SURE storylines, as shown in Table 3. Because SPS1 – SPS3 all arrive at net-zero GHG emissions, the assumption is that the rest of the world undertakes a similar effort that results in a global average temperature increase by the end of the century to a maximum of 1.5^{o}C from the pre-industrial levels. On the other hand, the SPS4 storyline follows a trajectory incompatible with the net-zero emissions target. The assumption in SPS4 is that the rest of the world also follows a similar trajectory. Thus the global average temperature increase is, on average 2.5^{o}C above the pre-industrial levels by the end of the century.

Table 3: Assumptions of heating and cooling degree days

	2020	2030	2040	2050
SPS1 – SPS3: – Heating degree days (RCP 2.6)	3190	3105	3054	3030
SPS1 – SPS3: – Cooling degree days (RCP 2.6)	177	193	198	196
SPS4: Heating degree days (RCP 4.5)	3182	3089	2997	2928
SPS4: Cooling degree days (RCP 4.5)	177	199	226	245

Source: CH2018 scenarios [7] *and EP2050+* [20]

The international fossil fuel prices also develop differently in the four storylines, depending on the assumed market integration. SPS1, which has the higher market integration among all storylines, displays the lowest international fossil fuel prices. In contrast, SPS2, which has regional conflicts and trade barriers, displays the highest international fossil fuel prices. SPS3 lies between SPS2 and SPS1 as it has fewer trade barriers than SPS2 but not the degree of market integration in SPS1. Finally, SPS4 presents an extrapolation of the current price trends. Table 4 summarises the price assumptions in the four long-term pathway scenarios.

Table 4: International fossil fuel prices assumptions

		2021	2030	2040	2050
SPS1					
	Steam coal ($2021/t)	120	52	48	42
	Natural gas ($2021/MBtu)	9.5	4.6	4.2	3.8
	Crude oil ($2021/barrel)	69	35	30	24
SPS2					
	Steam coal ($2021/t)	120	74	79	67
	Natural gas ($2021/MBtu)	9.5	10.3	12.0	10.1
	Crude oil ($2021/barrel)	69	87	102	97
SPS3					
	Steam coal ($2021/t)	120	62	57	53
	Natural gas ($2021/MBtu)	9.5	7.9	7.2	6.3
	Crude oil ($2021/barrel)	69	64	62	60
SPS4					
	Steam coal ($2021/t)	120	60	62	64
	Natural gas ($2021/MBtu)	9.5	8.5	8.9	9.2
	Crude oil ($2021/barrel)	69	82	89	95

Source: IEA WEO 2022 [11] *and own assumptions*

Sustainable exploitable renewable energy resources potentials remain the same in the four narratives. The potential exploitation rate is, however, based on the storyline's assumptions. For instance, SPS3, which emphasises reduced import dependence, would probably display a higher exploitation rate of domestic renewable resources than, e.g., SPS4, which is based on current trends. However, we do not pre-define the deployment rate of renewable energy technologies, as this will be one of the outcomes of the storylines. The assumed sustainable exploitable renewable potentials are given in Table 5. The ranges reported in the table express the uncertainty surrounding each resource. The four SURE narratives draw on these ranges based on their assumptions. The number in the parenthesis corresponds to the "reference" value.

Table 5: Sustainable exploitable renewable energy resources potential (common across storylines)

	2050
Hydropower excl. pump storage (TWh_e)	34.8 – 38.4 (36.4)
Solar PV rooftop (TWh_e)	30 – 50 (40)
Solar PV facades (TWh_e)	0 – 8 (4)
Solar PV alpine (TWh_e)	0 – 30 (3)
Wind turbines (TWh_e)	1.7 – 30 (4.3)
Biomass wet and solid (PJ)	100 – 113 (100)
Waste renewable and non-renewable (PJ)	74 (74)
Geothermal electric (TWh_e)	0 – 4.3 (2.1)

Source: SWEET CROSS data platform [19] *and EP2050+* [20]

Finally, Table 6 presents the assumptions on passenger and freight mobility demands. The SWEET CROSSDat assumptions are based on projections from Transport Outlook 2050 from ARE [21].

Table 6: Assumptions on passenger and freight demand

		2019	2030	2040	2050
SPS1,SPS3					
	Total passenger transport	**130.0**	**134.7**	**136.0**	**133.6**
	Motorised personal transport (Bpkm)	103.1	105.3	102.3	96.1
	Public road transport (Bpkm)	3.0	3.3	3.8	4.2
	Public rail transport (Bpkm)	23.9	26.1	29.9	33.3
	Total freight transport	**27.2**	**29.5**	**31.8**	**34.1**
	Freight road transport (Btkm)	17.1	17.4	18.4	19.3
	Freight rail transport (Btkm)	10.1	12.1	13.4	14.8
SPS2					
	Total passenger transport	**130.0**	**137.9**	**143.6**	**145.3**
	Motorised personal transport (Bpkm)	103.1	109.6	113.1	113.7
	Public road transport (Bpkm)	3.0	3.2	3.4	3.5
	Public rail transport (Bpkm)	23.9	25.1	27.1	28.1
	Total freight transport	**27.2**	**29.9**	**32.7**	**35.5**
	Freight road transport (Btkm)	17.1	18.6	20.9	23.2
	Freight rail transport (Btkm)	10.1	11.3	11.8	12.3
SPS4					
	Total passenger transport	**130.0**	**136.2**	**139.8**	**139.4**
	Motorised personal transport (Bpkm)	103.1	107.4	107.7	104.8
	Public road transport (Bpkm)	3.0	3.2	3.6	3.9
	Public rail transport (Bptm)	23.9	25.6	28.5	30.7
	Total freight transport	**27.2**	**29.7**	**32.1**	**34.7**
	Freight road transport (Btkm)	17.1	18.0	19.6	21.2
	Freight rail transport (Btkm)	10.1	11.7	12.5	13.5

Source: SWEET CROSS data platform [19]

4 Definition of shocks

4.1 Global and regional disruptive events for the energy system transformation

The SURE shock scenarios seek to assess disruptive events that can impact the energy system transformation. Such disruptive events may have different root causes and characteristics, such as energy supply interruptions due to geopolitical distortions, technological innovation, societal unrest, financial crises, political ideology swings, etc. According to [5], extremes relevant to the energy transition and system transformation must account for both transient and disruptive events. Given the multitude of these events, a literature review regarding risk report analyses at Swiss [4] and global scales [22] was performed to identify relevant events within the SURE consortium’s expertise.

Figure 9 shows that electricity outages and shortages are among the top 5 events in terms of likelihood or impact for Switzerland. When looking at the global landscape, extreme weather and financial crises also emerge as the top risks identified in the literature. Moreover, extreme weather events are also responsible for social unrest. According to the United Nations High Commissioner for Refugees, an annual average of 21.5 million people have been forcibly displaced by weather events, such as floods, storms, wildfires and extreme temperatures since 2008. These numbers are expected to increase, and global forecasts foresee up to 1.2 billion people who could be displaced due to climate change and natural disasters by 2050 [23]. National governments are starting to recognise climate migration as an issue that needs to be tackled.

In the field of energy policy, the current crisis in Europe that led to the development of the REPowerEU Plan brought to the discussion agenda for energy security in Europe the delay in the nuclear phase-out capacities in Europe [24]. In Switzerland, an initiative to lift the ban on new nuclear power was launched in August 2022[2]. These movements in both regions signalled a re-thinking on the timing of the exit from nuclear power, given increased concerns for the reliability of the energy services provision in times of distress.

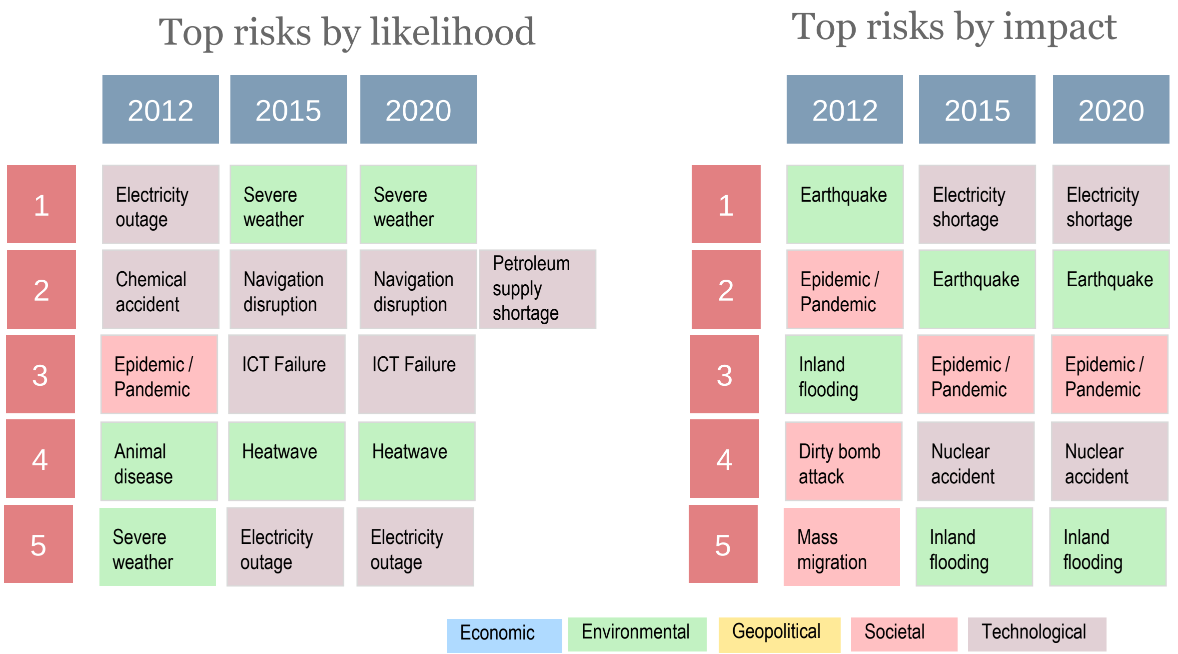

Figure 9: The evolving landscape of risks in Switzerland (based on FOCP[3] [4])

The above analysis indicated five areas where disruptive events can occur with high relevance to the long-term energy system pathways: economy, society, policy and environment. Based on the expertise of the SURE consortium and the stakeholder interactions during the 1st SURE Stakeholder Workshop in April 2022, five shocks were defined, as shown in Figure 10. From the themes of economy, environment, society and policy. These shocks are developed as scenario storylines, which determine the main attributes of the shocks, as stated in the introduction section.

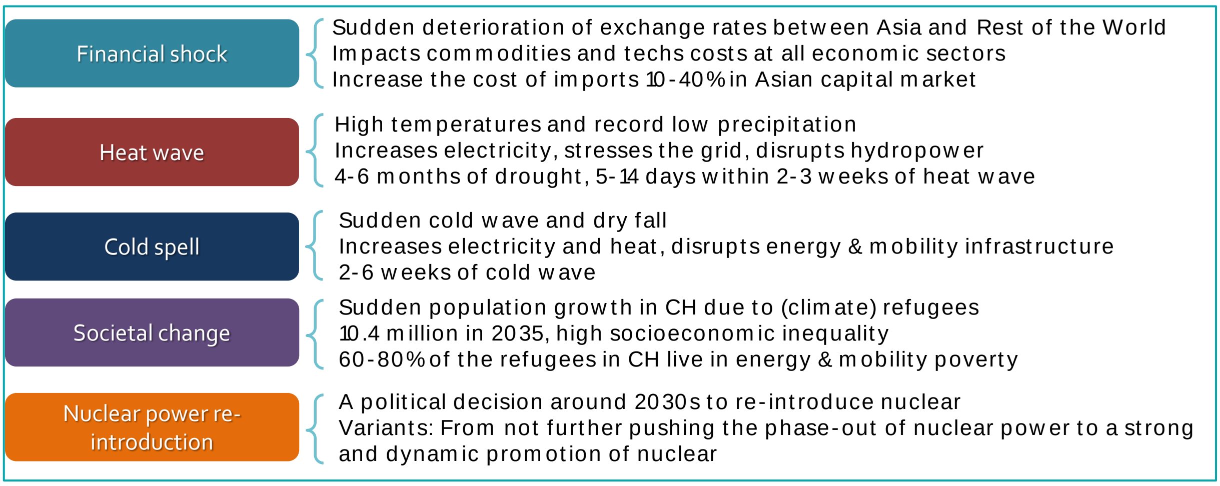

Figure 10: Main elements of the five overarching SURE Shocks Scenarios

2 See https://www.aargauerzeitung.ch/news-service/inland-schweiz/strommangel-initiative-fuer-neue-atomkraftwerke-offiziell-lanciert-ld.2335186

3 https://www.babs.admin.ch/de/publikservice/downloads/gefrisiken.html

In SURE, we abstain from assessing the shocks plausibility. Such an assessment requires resources and competences outside the SURE consortium, and it is usually based on Delphi methods and indicator-based approaches. Even if these methods had been employed, several factors could render a definitive conclusion on the likelihood of frequency the events among the experts who participated in Delphi and indicator-based approaches.

However, each shock is characterised by three intensities or escalation levels. This approach ensures that not only one but several possible event courses are considered. It is also followed in the Swiss National Risk Analysis [4]. A scenario is built for each intensity, low, medium, and high. A set of input parameters is used to characterise the different intensity levels for each shock and, where this is not endogenously captured from the SURE modelling framework, the magnitude of the impact on the energy system.

A challenge in defining the shock scenarios is their comparison regarding their impacts on the sustainability and resilience indicators. In the National Risk Analysis Report of Switzerland [4], the "major" intensity scenarios are compared. In the SURE framework, this is equivalent to comparing the "medium" intensity. However, we should acknowledge that the shock scenarios are very different to each other and multidimensional in their definition. Thus, the "medium" intensity of, e.g., the financial shock, might not be directly comparable with the "medium" intensity of the nuclear reintroduction shock. However, this discussion is more relevant regarding the Multi-Criteria Decision Analysis based on the impacts of the shocks on the sustainability and resilience indicators after quantifying these impacts. In the case of large differences, which constitute a particular shock as "cataclysmic" to others, a "normalisation" process of their impacts can be envisaged. Still, such a "normalisation" requires capturing non-linear relationships between shock intensities and impacts on indicators. The surrogate machine learning models developed in WP9 could help reveal these non-linear relationships.

4.2 Detailed description of the SURE Shocks Scenarios

In the following sections, the SURE shock scenarios are described in detail, including a reasoning to select these disruptive events, the related research and policy questions and the shocks' narratives. Fact sheets for each shock scenario are provided in the Appendix in section 7.

4.2.1 Financial shock: exchange rates deterioration with Asian economies

a. Selection criteria:

- Importance: Switzerland depends to a large extent on imports regarding the equipment/appliances required to decarbonise its energy system (wind turbines, electric cars etc.). An increase in import prices may have an adverse effect on firms' production costs and households' disposable income.

- Plausibility: Fluctuations in the exchange rate at the order of magnitude suggested by the shock have been observed historically.

b. Research and policy questions addressed:

- What would be the costs of decarbonising the energy system under different prices for final and intermediate products?

- How much is Switzerland dependent on imports and, in particular, from Asian countries, in performing its energy transition plan?

c. Narrative

The transition towards a low-carbon economy will impact production costs, trade balance, labour markets and consumer preferences. Decarbonisation is a complex process requiring system-wide changes impacting all sectors, firms, and households in Switzerland, creating challenges and opportunities. The massive uptake of low and zero-carbon technologies will impact the Switzerland economy and labour market, inducing large shifts from fossil fuels and carbon-intensive activities towards renewable energy sources and energy efficiency.

In this context, the ability of Switzerland's economy to adopt, install and produce green technologies is crucial for its competitiveness and economic growth. Since most of the equipment related to low-carbon technologies is imported, changes in the exchange rates may increase the cost of imported goods and products and negatively affect the transition by increasing total economic costs.

Following recent trends, Asian economies are projected to have a high share (driven by low prices) in producing low-carbon technologies globally. To consider the potential negative impacts of expensive imports of clean energy technologies, we simulate a scenario where a sudden deterioration in the exchange rate between the Asian economies (i.e., China) and the RoW (incl. Switzerland) affects the cost of imported goods. To examine the consequences of such a crisis in the Swiss economy, we assume three different intensities of the "financial shock" based on the historical fluctuation of the exchange rate between CHF and CNY:

1. Low: an increase in the cost of imports by 10% in the Asian capital market
2. Medium: an increase in the cost of imports by 20% in the Asian capital market
3. High: an increase in the cost of imports by 40% in the Asian capital market

Two "financial shocks" will be simulated, one in 2030 and one in 2045, to examine the impact in the near-term period (i.e., 2035) and the long-term period (i.e., 2050).

4.2.2 Environmental shock: heat wave

a. Selection criteria:

- The shock has been selected to analyse the robustness and the security of the energy supply of the Swiss energy system when extreme weather puts the energy system under stress by both leading to an increase in electricity demand and also leading to a de-crease in supply by hydropower plants and imports.
- The source of the shock is of environmental (i.e., weather) and technical nature. Although areas like economy, society and politics also play a role in the evolution of the shock, they are not the main drivers.
- The shock is designed such that multiple circumstances (energy use behaviours, energy availability, etc.) all add onto each other in a way that they make the shock most severe. There are no successful mitigation measures. Exceptions are (automatic) emergency actions that are triggered to secure short-term supply of energy, e.g., use of backups.
- The peak of the shock describes the point of highest stress and vulnerability of the energy system at which large blackouts can barely be prevented with today's existing emergency measures. Electricity, heat, and transport system do not collapse. However, future changes in infrastructure

b. Research and policy questions addressed:

- Is a future Swiss energy system robust against a period of extreme heat by always providing enough energy to satisfy the national demand? What are in this regard critical and vulnerable elements of the energy infrastructure?

- Which electricity and heat generation and storage technologies are needed to which ex-tend for the Swiss energy system to be sustainable and resilient against a heat wave? What are in this regard crucial elements of the energy infrastructure?

- Are there technical and political actions that need to be taken short-term and long-term to make the Swiss energy system robust and resilient against a severe heat wave, i.e., preventing blackouts and a (partial) collapse of the energy system?

Further research questions that can be addressed using the shock but are not directly related to the definition of the shock:

- What are the consequences for economy and society in a worst-case scenario where political calls for reductions in energy demand are ignored by companies and individuals?

- Over years, how often must a heat wave shock repeat to see change in policy and energy behaviours?

c. Narrative

Weather: Extremely high temperatures and record low precipitation

After a mild winter, central Europe records a historically warm and dry spring. Air and water temperatures increase further over the months, peaking in an extreme heat wave with average daily temperatures in the midlands above 25-30°C for up to 3 weeks in summer [25]. Between April and August, less than 40% of the average rainfall are recorded [26]. Water levels from rivers, lakes, and ground water are lower than average all over Switzerland. Many small rivers and some larger ones dry out, as the previous winter had low amounts of snow, resulting in little amounts of melting water. In early fall, water levels in rivers and hydro storage reservoirs are 20-30% of their average [26].

Increasing electricity demand for cooling and with energy supply shortage at the same time

Due to the heat wave, cooling demands increase, resulting in high use of electricity due to, e.g., air conditioning, and the transport capacity of transmission lines reduces [25]. Purchase and use of fans and supplementary air conditioners increase significantly. Additionally, at the start of the holiday season, thousands of international tourists heading towards Italy charge their electric vehicles at the fast-charging stations on both sides of the Gotthard.

Further, the low river water levels and the increasing water temperatures limit the electricity production from hydropower plants (reduced by 20-30% [26]), and some small plants that highly depend on melting water must be turned off. Similar situation applies to thermal power generation plants, including two nuclear plants in Switzerland (Beznau I and II) and nuclear or fossil fuel plants in neighbouring countries, as they need cold river water for cooling [27]. In addition, in the summer months are used for planned maintenance some other Swiss reactors.

The Swiss power grid faces stress and risk of outages

Imports of electricity are low. An electricity agreement between Switzerland and the EU has not yet materialized. Swissgrid must rely on bilateral agreements with the neighbouring countries, preventing an efficient grid operation. Unscheduled loop flows from France to Italy through Switzerland, increasing the already high market-based scheduled transit flows through Switzerland, cause a very uneven distribution of the Swiss transmission grid load, resulting in a few lines reaching their limits, while others are barely used. A more even distribution could be achieved using re-dispatch. The risk of load shedding or outages increases further as transformers overload due to the limited electricity supply ([25], [26]).

Following a transmission line outage in Germany, additional load flow is shifted to lines in Switzerland that have no room for temporary overloading. A cascade of line outages is triggered, that can barely be contained through emergency load shedding in Switzerland.

Forest fires and the drought have an impact on the vegetation, leading to even lower availability of water during the heat wave and biomass in the future years. At the end of the extreme heat wave in summer, consecutive thunderstorms with heavy rainfall cause floods as dry grounds cannot take up large amounts of rainfall. Dams must be opened to prevent or mitigate floods. Thus, most of the water cannot be stored in dams nor used by hydropower turbines as the run at full capacity already with smaller amounts of water. Additionally, thunderstorms can cause local disturbances in electricity supply, outages of mobile and landline telephony, and cancellation of public transport routes due to, e.g., floods, erosions. Lightning strikes damage control systems of electrical devices, transmission lines and roads.

The energy demand shifts from economy and public sector more to households

Several streets are blocked and train and tram lines are disturbed as the heat damages street surfaces, make rails tilt, and air conditioning of trains fail due to overload. The limited rail transportation and limited shipping due to too low river water levels lead to shortages of goods until alternative ways of transportation are organised [28]. In places, cold chains are interrupted which lead to an increase in food waste which again lead to higher financial losses for companies in the food industry and individuals. Due to the high electricity costs, the expenditures of companies in the industrial sector and in the service sector with low insulated offices increase. Some companies have to close their offices due to overloaded cooling systems. As a consequence, a significant number of people works from home and thereby further increase the residential electricity demand. The employees have to bear increased electricity costs as they work from home. Fans and supplementary air conditioners are sold out. Due to hot (home-)offices and workplaces, people work less efficient. Due to the intensity of the heat wave, private households ignore the call for reduced use of supplementary air conditioning, electricity and water use.

Secondary effects

The social impact is severe. Social unrest is hard to contain, especially in regions with high cooling demand and energy costs. Many people die due to the heat or from drowning. Pools, beaches and swimming areas next to rivers and lakes are overcrowded. The heat wave continues to afflict urban areas with poor natural ventilation.

The intensity of the shock and the time to fully recover depend on the severeness of cascading effects caused by heat wave and drought, e.g., number and length of load shedding, use of reserves, economic loss.

We should note that measures to mitigate impacts of heat wave and drought are deliberately not described in detail here, neither are consequences of blackouts.

4.2.3 Environmental shock: cold spell

a. Selection criteria:

- The shock has been selected to analyse the robustness and the security of energy sup-ply of the Swiss energy system when extreme weather puts the energy system under stress by both leading to an increase in electricity and heat demands and also leading to a decrease in supply by volatile electricity generation plants and imports.

- The source of the shock is of environmental (i.e., weather) and technical nature. Although areas like economy, society and politics also play a role in the evolution of the shock, they are not the main drivers.

- The shock is designed such that multiple circumstances (energy use behaviours, energy availability, etc.) all add onto each other in a way that they make the shock most severe. There are no successful mitigation measures. Exceptions are (automatic) emergency actions that are triggered to secure short-term supply of energy, e.g., use of backups.

- The peak of the shock describes the point of highest stress and vulnerability of the energy system at which large blackouts can barely be prevented with today's existing emergency measures. Electricity, heat, and transport system do not collapse. However, future changes in infrastructure of the Swiss energy system might put the energy sys-tem at higher risk of failure.

b. Research and policy questions addressed:

- Is a future Swiss energy system robust against a period of extreme cold by always providing enough energy to satisfy the national demand? What are in this regard critical and vulnerable elements of the energy infrastructure?

- Which electricity and heat generation and storage technologies are needed to which ex-tend for the Swiss energy system to be sustainable and resilient against a cold wave? What are in this regard crucial elements of the energy infrastructure?

- Are there technical and political actions that need to be taken short-term and long-term to make the Swiss energy system robust and resilient against a severe cold wave, i.e., preventing blackouts and a (partial) collapse of the energy system?

Further research questions that can be addressed using the shock but are not directly related to the definition of the shock:

- What are the consequences for economy and society in a worst-case scenario where political calls for reductions in energy demand are ignored by companies and individu-als?

- Over years, how often must a cold wave shock repeat to see change in policy and ener-gy behaviours?

c. Narrative

Weather: snowfall followed by freezing temperatures for up to six weeks

After a dry and cold fall, temperatures in central Europe fall and significant amounts of snow start to accumulate (in midlands up to 30cm [29]). At the beginning of an extreme cold wave in January, there is heavy snowfall of up to 80cm of fresh snow for 3-5 days [29]. In some areas, the snowfall becomes sleet that freezes on the ground, and winds cause snowdrifts. Following the days of snowfall, temperatures drop even further and lay on average around -10°C in the midlands and -20°C in the Alps for up to 6 weeks ([30], [31]). Switzerland records lowest temperatures in the midlands of -20°C and below -25°C in the Alps ([30], [31]).

Increasing electricity and heating demand with energy supply shortage at the same time

Due to the cold wave, electricity and heating demands increase. Motivated by recent gas supply risks, a significant share of heating is provided through electric heating and heat pumps, significantly increasing the electricity demand during these weeks. Since all neighbouring countries also face the cold and prioritize the supply of electricity and heat for their own populations, imports of electricity, gas and oil to Switzerland are low and their prices high. An electricity agreement between Switzerland and the EU has not yet materialized. Swissgrid must rely on bilateral agreements with the neighbouring countries, preventing an efficient grid operation. Unscheduled loop flows from France to Italy through

Switzerland, increasing the already high market-based scheduled transit flows through Switzerland, cause a very uneven distribution of the Swiss transmission grid load, resulting in a few lines reaching their limits, while others are barely used.

Water levels in rivers and hydropower reservoirs are low, and thus the electricity generation from run-of-river plants and large dams. Hydro storage reserves must be used for power generation [30]. There is low power generation from photovoltaics due to accumulated snow, and batteries (e.g., in cars) show lower capacity and faster discharging when exposed to low temperatures.

Some heating systems stop working due to overload or too low outside temperatures, e.g., heat pumps ([30], [32]). The purchase and use of comparatively inefficient supplementary electric heaters increase significantly. Supplementary heaters are also used more intensively by private households with oil and gas heating to reduce their consumption of oil and gas to compensate the high oil and gas prices that derive from the lower imports.

Local disturbances increase the risk of blackouts that must be prevented

Heavy weights of snow and ice cause damage and failures of power plants and distribution lines directly, and indirectly as snow and ice make trees and branches fall ([30], [32], [33]). In addition, there is an unexpected maintenance required in a Swiss nuclear power plant, reducing the amount of Swiss production. Results are lower electricity production and local overloads of power grids, which require a redispatch of electricity in the Swiss grid to prevent blackouts. Since electricity import is limited, only the Swiss power plants can be used to compensate the lacking power generation by increasing their regular production (i.e., using production capacity reserves). The shortage of electricity might call for rationed use of electricity and centralized management of power plants (OSTRAL) that goes along with limiting the free market for electricity. However, due to the intensity of the cold wave, private households ignore the call for rationed use of electricity and heating.

The energy demand shifts from economy and public sector more to households

Roads and railway lines are blocked, and signals, rail points, etc. stop working as they freeze [2]. In many places, public and private transport is unreliable and limited. Thus, people work from home and thereby further increase the residential energy demand. Road and rail conditions impact multiple activities, e.g., repair of grids or heating systems, emergency services, supply of goods, delivery of post. The shortage of goods causes panic purchases. Supplementary electric heaters are sold out. The economic situation can worsen with an increasing number in ill workforce and limited supply of goods in the economy sector. Due to the high energy costs, the expenditures of companies in the industrial sector increase. In comparison, the service sector is not impacted as significantly due to its generally lower energy demand and even lowered demands due to employees working in home-office. Instead, the employees have to bear increased energy costs as they work from home. The GDP decreases significantly.

If mitigation measures are not sufficient: technology and supply failures are the consequence

The cold wave and its consequences on the energy system increase the risk of failures across all energy sectors. Where heating systems stop working, buildings are at risk of cooling out, causing pipes to freeze and burst. Without electricity, gas and charging stations stop working and thus provoke limited use of vehicles. Due to the blocking and disturbances of roads and railway lines, public transport can collapse and private transport is limited in many places. Partial blackouts of power and telephony can be a caused by damages of distribution lines ([29], [30]). Further, temporal closures of public buildings as well as load shedding can be measures to react to the energy shortage.

Secondary effects

The social impact is severe. Social unrest is hard to contain, especially in regions with high heating demand and energy costs. People have to move to emergency shelters and some people die while the cold wave continues to afflict areas with poor heating systems and insulation.

The intensity of the shock and, by this, the time to fully recover depend on the severeness of cascading effects caused by the cold wave, e.g., amount and frequency of load shedding and blackouts, use of reserves, economic loss.

It should be noted that measures to mitigate impacts of the cold wave are deliberately not described in detail here, neither are consequences of blackouts.

4.2.4 Societal shock: refugee crisis

a. Selection criteria:

- The selection of this shock is based on the potential disruption to the energy system that can be triggered by a rapid growth in population. A rapid rise in the population could cause a hike in energy demand for which the Swiss networks might not be adequately prepared. Such an event could also engender the use of less efficient and sustainable supply technologies in the building and mobility sectors, thus hindering or delaying the achievement of national energy and climate goals by a target year.

- The shock is triggered by the arrival, within a short timeframe, of a high number of migrants and asylum seekers with diverse cultural and economic backgrounds. This shock was considered relevant, as already in 2021 it was estimated by the UNHCR that the global number of people subject to forced displacement reached nearly 89 million [34]. Also, according to the Institute for Economics & Peace estimations [23] «Over one billion people are at threat of being displaced by 2050 due to environmental change, conflict and civil unrest».

- The presence of migrants and refugees can have an impact on the economy. The impact can be positive, increasing local GDP and reducing unemployment rates, or can pose a detrimental stress on socio-political and economic national structures, if not appropriately addressed [35], [36].

- An inadequate and uncoordinated global response to refugee crises might generate socio-political disputes within the Swiss confederation as well as geo-political disputes on the EU and international scale. Such disputes could disrupt national and international economic and environmental agendas, as well as the availability of energy resources and technologies.

b. Research and policy questions addressed:

- What would be the repercussions on the Swiss energy system of a rapid intake of asylum seekers in years 2030-2035, which is equivalent to 5-9% of the Swiss population?

- How will the Swiss socio-political and economic system react to an unprecedented international refugee crisis demanding, under international accords, the integration of a mainly destitute and underprivileged population?

c. Narrative

We are in 2035 and the population in many countries worldwide has been largely affected by unprecedented anthropogenic humanitarian crises. Even though the pathway for the decarbonisation of the economy has been undertaken by many countries worldwide, and forecasts estimate that by the end of the century the average global temperature increase will remain below 2°C degrees, irreversible impacts of climate change have revealed themselves in all their gravity in many countries around the world. They have been detrimental to living conditions and triggered displacement or hampered return for those who have already been displaced. Drinking water has become even scarcer in many parts of the world. Crops and livestock struggle to survive, threatening livelihoods and in the previous five years conflicts for access to drinking water have broken out between countries that had previously been living under unstable peace relationships. In other countries, worsening living conditions have even triggered internal political conflicts, which in some cases developed in civil wars. In such conditions, in many countries worldwide seeking refuge abroad has been the only strategy for people to survive.

In the previous decade, refugee migration mostly occurred within the borders of the same country, from rural towards urban regions, or towards neighbouring countries. From 2030 onwards, instead, the latter are no longer able to host the refugees, and many are forced to migrate towards the European continent. In 2030, pushed by the UN Framework Convention of Climate Change (UNFCC), the 1951 UN Convention relating to the Status of Refugees (aka the “Geneva convention”) is extended such as to legally allow displaced people to ask for the “climate refugee status”, which thus adds on to the established “conflict refugee status”. Countries members of the Schengen Area, including Switzerland, agreed to host refugees and satisfy their basic needs, under a common responsibility sharing approach. Signatories of the treaty agreed on burden sharing percentages, and Switzerland was attributed a maximum yearly share of refugees equal to 2% of the 2030 country’s population, which had already reached 9.5 million, due to “regular” migration flow (on average, equal to 1% per year) and birth and mortality rate. Between 2030 and 2035, depending on the intensity of the worldwide crises and conflicts, the Swiss population swells by:

- Low: 5% increase, the population has reached 10 million inhabitants in 2035.
- Medium: 7% increase, the population has reached 10.2 million inhabitants in 2035.
- High: 9% increase, the population has reached to 10.4 million inhabitants in 2035.

The refugees are given temporary shelter and resources to cover their basic needs, including education, basic health services, language and capacity building courses to favour the integration of the new potential workforce in the local market. The related subsidies increase public expenditure and compel the Federal Council to use financial resources that had already been allocated to other sectors.

By 2035, some of the refugees (depending on the intensity of the shock) have managed to enter the Swiss job market and to become financially independent, thus also supporting growth of the Swiss economy and GDP. However, they are mostly given low-skilled jobs. The subsidies for those excluded from the job market, the heightened competition for low-skilled jobs, and the increase in demand for goods and services paves the way to socio-political tensions. Some political parties demand for Switzerland to abandon the treaty, and the traditional Swiss political system stability and governability are threatened.

The increase in the population leads to an unprecedented increase in the demand for food, goods, including building materials for houses for the refugees, and services, including mobility. Due to the low amounts of subsidies or earnings they receive, many refugees remain trapped in energy and transport poverty conditions. In such case, on the one hand the average per capita energy demand by refugees is lower than the per capita demand of the average Swiss citizens, since the refugees have lower individual purchase power and therefore a lower consumption rate of goods and services. On the other hand, as a large number of refugees are not able to afford new/retrofitted high performance housing, efficient appliances, and electric vehicles, their heating and mobility demand is characterised by higher shares of fossil fuels than average Swiss citizens. Such conditions not only hinder the achievement of personal wellbeing, but also create an obstacle towards achievement of the Swiss energy strategy and net-zero greenhouse gas emissions goals.

4.2.5 Political shock: nuclear power re-introduction

a. Selection criteria:

The selection of the shock was triggered by the re-entering of nuclear power in energy policy agenda in Europe. The REPowerEU Plan foresees a postponement to the nuclear power plants phase-outs, e.g., in Germany and France [24] to cope with the current energy crisis. Other European countries with existing nuclear power are planning for new constructions, e.g., Finland and the Unitied Kingdom, to meet their emissions reduction targets. And, others, are planning to introduce nuclear power into their energy system, e.g., Poland. In Switzerland, a "nuclear power initiative" was recently lunched[4]. Finally, the European Commission has recently labelled nuclear energy as "climate-friendly" and "sustainable". All these similar trends observed in Switzerland and Europe point to a "realistic political compromise" based on technological feasibility and attractiveness regarding a possible maintenance or increased share of nuclear power in their electricity mix.

b. Research and policy questions addressed:

- Would maintaining or increasing the share of nuclear power in Switzerland facilitate a sustainable and resilient energy transition? Is indeed nuclear an "easy way out" to the climate change mitigation?
- If the market get a signal from politicians that there will be no phase out of nuclear energy would it defer from investing in renewable energy? Would this create stranded assets of renewable power? Or, would this reduce the acceptance of renewable energy?

c. Narrative

We are in the late 2020s. The progresses towards the net-zero target are still slow, a majority support for stringent measures is still not "there", neither in the population nor in the government and the parliament. In particular, right-wing forces constantly and successfully use cost and risks arguments in political campaigns. At the same time, support for the energy targets as such remains high.

In this situation, a political party at the political centre/right proposes to follow the EU and other European countries and to re-consider nuclear phase-out. While already in the early 2020s a similar proposition to get rid of the "technology ban" had been discussed, in the context of uncertain geopolitical conditions related to energy security, it only received limited political success at that time. But now, a few years later, as the pressure for decarbonisation is still high as is the preference for energy independence (especially from energy produced in countries with unstable regimes, e.g., Russian gas and oil), nuclear energy is a welcome "way out".

The left/green parties oppose the re-introduction of the nuclear, but with the centre and right parties supporting it, a clear political majority in parliament accepts the according amendment to the Energy Law. Left-green parties collect enough signatures to bring the amendment at the ballot. However, also in the population, a majority casts a yes-vote. On the one hand, the proponents are successful in making the argument that the reliance on nuclear energy enables Switzerland to reach the energy targets

[4] See **https://www.srf.ch/news/schweiz/kernenergie-in-der-schweiz-initiative-fuer-neue-atomkraftwerke-wird-lanciert**

without much other effort. Moreover, it shows that many citizens perceive nuclear energy as something “well known”, a technology that has been used for decades without any relevant accident.

After this decision, different “intensities” of the shock can occur depending on how strong the “shift” towards the nuclear will be:

- **Low** – “partial phase-out”: Nuclear energy is part of the future energy mix, but the decision does not lead to a “dynamic” with strong popular support and a real push for this technology. This scenario actually does not require an explicit political decision to re-introduce nuclear energy but it is more the reflection of the implicit political consensus not to push ahead with the phase-out of nuclear energy. This is achieved by extending the planned lifetime of the current nuclear power plants, and means that, in contrast to the current scenarios, nuclear energy remains in the mix until 2050.

- **Medium** – “no phase-out”: This scenario reflects a political decision to allow for the construction of new nuclear power plants. The re-introduction triggers some dynamics at the technical, economic and societal level. Existing power plants continue to run and new nuclear power plants (including small modular reactors or micro reactors) can be built. Whether new nuclear power plants are actually constructed depends on market conditions, while there are no specific public support measures.

- **High**: In this scenario, the political decision triggers a strong dynamic in favour of nuclear energy. New technologies are developed, new plants are constructed (could include SMRs and Microreactors), nuclear energy becomes a main pillar of the CO_2-reduction by also covering most of the increased electricity demand. In this scenario, nuclear energy could also support the provision of high temperature heat for industry and to support H_2 production. The revival of nuclear power, in this scenario, is politically promoted and steered. This is done with subsidies but also by introducing advantageous policy conditions that allow for shortened lead-in times of the new nuclear reactors, i.e., by offering more favourable licensing and construction times. New power plants are built on the sites of today's nuclear power plants, namely in Aargau and Solothurn.

It is important to note that after the political decision has been taken, it takes some time for this shock to actually affect energy supply. In particular, political instruments like subsidies, new regulations etc., which might be necessary to get new nuclear power plants constructed, need to be introduced. Given that a relevant minority will always be against the re-introduction of nuclear energy, referendum votes will be very likely, especially in the medium and high intensity scenarios. Hence, the intensity of the shock not least depends on how strong the shift in popular support towards the nuclear will be. The stronger the “dynamic” towards nuclear energy (maybe fuelled by European countries shifting towards this energy source as well), the faster the evolvement of the shock can be.

5 References

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6 Appendix

6.1 Financial shock factsheet

6.1.1 Real life examples

Switzerland in 2021 imported goods amounting to 64 bn $ from China and India representing 17% of its total imports. Hence the exposure to currency risk from the Asian markets is significant (Table 7).

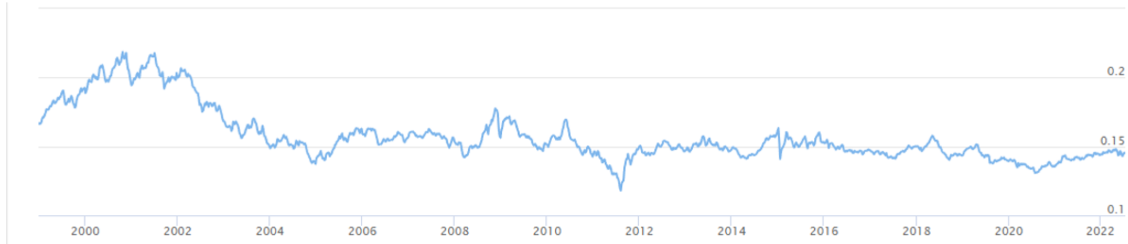
Table 7: Import dependency of Switzerland from the European, Asian and American markets

	Value of imports	Share in Swiss imports in 2021
United States	63.1 billion USD	16.6%
Germany	55.2 billion USD	14.5%
China	33 billion USD	8.7%
India	31.3 billion USD	8.2%
Italy	20.3 billion USD	5.3%
France	19.1 billion USD	5.0%

Historically the exchange rate has varied over the range that is suggested in the different scenarios (Figure 11). There is clear evidence that Chinese products will further increase their market share globally and in Swiss market in particular. In example, Chinese wind manufactures, with three companies in top 6 manufactures at 2022, increase their shares in the global market by reducing their unit cost of production as compared with the global average (Figure 12).

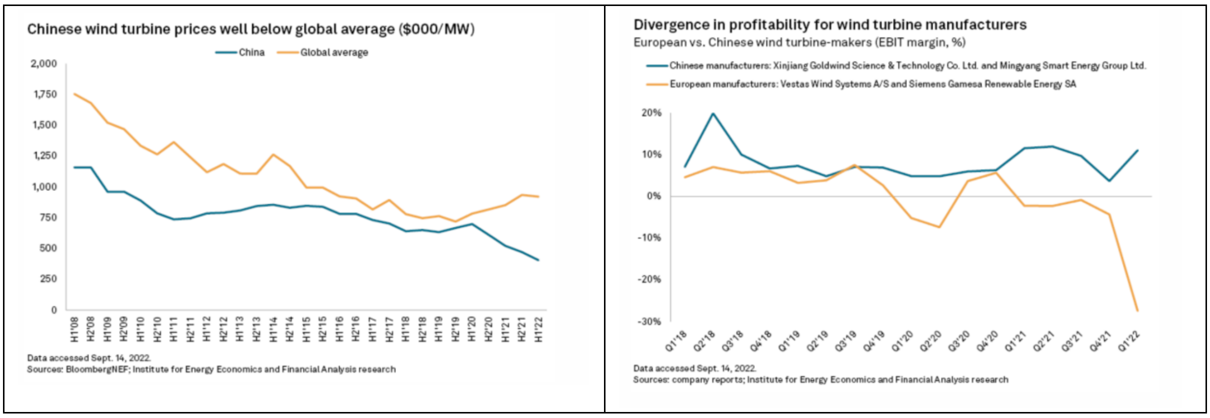
Real-life example:

The graph below presents the historical fluctuations in the exchange rate between the: CHF and CNY:



with an average exchange rate at 0.15 CHF/CNY, having a maximum value at: 0.22 CHF/CNY and a minimum value at: 0.12 CHF/CNY. In the period of 2002 to 2005 there was a deterioration of the Swiss currency from: 0.22 CHF/CNY to 0.14 CHF/CNY or 45% in logarithmic terms.

Figure 11: Exchange rate fluctuations between CHF and CNY in the last 20 years



Company	Location	Total Capacity (GW)
Vestas	Denmark	9.60
Siemens, Gamesa	Spain	8.79
Goldwind	China	8.25
GE	USA	7.37
Envision	China	5.78
MingYang	China	4.50

Figure 12: Chinese wind-turbine manufacturing

6.1.2 Change in the input parameters of the models

The following input is used by GEM-E3 to provide the macro-economic implications of the shock. The impacts on the energy system are quantified based on the updated macro-economic outlook from GEM-E3:

1. Low intensity: an increase in the cost of imports by 10% in Asian capital market
2. Medium intensity: an increase in the cost of imports by 20% in Asian capital market
3. High intensity: an increase in the cost of imports by 40% in Asian capital market

6.2 Heat wave shock factsheet

6.2.1 Real life examples and detailed shock specification

Definition of shock:
Heat wave* (peak: 1-3 weeks) + extended drought (developed over multiple months / half a year (spring-fall), peaking in summer): - Many small rivers and some larger ones dry out (as previous winter had low amount of snow and thus little amount of melting water) - High use of electricity due to high cooling demand (e.g., air conditioning), potentially causing instabilities in the grid and cuts in electricity supply - High demand at the electric vehicle fast-charging stations on both sides of the Gotthard - Reduced efficiency of transmission lines - Overloaded transformers lead to limited electricity supply - Thermal power generation plants shut down in late summer as there is not enough cold river water for cooling. - Low river water levels and increasing water temperatures limit the power production of run-of-river plants (up to -25%), hydro storages (-10%), and small plants that depend highly on melting water must be turned off - Planned maintenance some Swiss reactors - Unscheduled loop flows from France to Italy through Switzerland, increasing the already high market-based scheduled transit flows through Switzerland, cause a very uneven distribution of the Swiss transmission grid load - Due to the intensity of the heat wave, private households ignore the call for reduced use of supplementary air conditioning, electricity and water use. - No EU-CH electricity agreement - Limited electricity imports as neighboring countries have similar issues with shortage of electricity - Increase in electricity prices - Forest fires might damage power overhead lines and landline telephony, potentially causing local blackouts - Forest fires increase water scarcity and reduce biomass, droughts have impact on vegetation which again reduce availability of biomass - Blocked streets due to damage of street surface, and forest fires - Train and tram lines are partially interrupted or stopped due to tilted rails, etc. - Cancellation of several train connections as the air conditioning of some trains fail or stops working at high outside temperatures, or as there is not enough electricity available - Limited shipping as river water levels are too low for large ships, leading to some shortages of goods (short- and mid-term) until alternative transportation ways to ships are organized; imited transportation of goods (short- and mid-term) due to blocked and tilted rails (as mentioned above), cold chains are repeatedly interrupted leading to higher food waste and financial losses in the food sector

- The expenditures of companies in the industrial sector and in the service sector with low insulated offices increase due to the high electricity costs, some offices need to close due to overloaded cooling systems. Due to hot (home-)offices and workplaces, people work less efficient.
- Fans and mobile air conditioners are sold out

- At the end of the heat wave in summer: thunderstorms cause floods as dry grounds cannot take up large amounts of water
- Open run-of-river dams to prevent/mitigate floods, causing water being lost for power production

- (estimated) costs due to damages sum up to around 5-10 billion CHF

At the end of a heat wave within an extended drought:

Thunderstorm [BABS 2020 (Unwetter + Hagelschlag)]:

- Falling trees cause damage of power overhead lines, landline telephony, mobile network, potentially leading to local blackouts
- Lightning strikes damage control systems for heating/cooling/elevator/… causing local blackouts
- Flooded basements and underground garages cause damage of cars and other goods
- Blocked streets due to fallen trees, local floods, erosions, leading to cancellation of public transport routes (additionally some damaged buses and trains due to hailstorm)
- Overloaded mobile network due to increased number of calls and outages of radio transmission lines due to local power blackouts

High water and flood [BABS 2020 (Hochwasser)]:

- Blocked streets and railway lines due to floods, landslides, …, for which repairs can last for more than a year limited public transport
- Numerous supply lines (gas, water, power, TV, phone) are damaged, causing local blackouts and interruptions in supply

* MeteoSwiss defines a heat wave as of summer 2021 if the daily average temperature is above 25°C for a minimum of three consecutive days and warning level 3 is reached.

Impacts of drought can last for years (high intensity of drought: 2 years) [BABS 2020 (Trockenheit)].

Real-life examples:

June-Sept 2015, Europe, heat wave with temperatures above 40°C, in Vienna 18 days with temperatures above 35°C, drought period (but wet spring above-average which made it less impactful) [BABS 2020]

June-August 2003, Europe, summer with multiple heat waves and temperatures up to 42°C in CH [BABS 2020]

Spring to Fall 2018, CH, heat and extended drought, only 45% of the usual rainfall between April-August [BABS 2020 (Trockenheit)], lowered ground water and river levels, in June: municipalities call for reduced water use, in late summer / early fall: water levels 30-40% of normal [BABS 2020]

Summer 2018, CH, low water level of river Rhein, limited (up to forbidden) use of waterway for large ships (in October: cargo and hotel ships) [BABS 2020 (Einschränkungen Schiffsverkehr)]

Summer 1947, midlands CH, long heat period with extremely low precipitation, low levels of hydro storages lead to lower electricity production in November, causing cancellation of train connections (-5%) [BABS 2020]

Specification of shock

Source: Weather (low precipitation and high air and water temperatures)

When: Any year; spring to fall with peak in summer

Where: Switzerland and central Europe

Duration:
- extended drought develops over multiple months: half a year (spring-fall), peaking in summer
- wave of extreme heat (daily average temperature > 25°C) for 2 x 4-5 days within three weeks, with high temperatures (daily average temperature around 20°C) in the days in between

Intensity (provide metric): medium to high, depending on river and lake water levels, air and water temperatures, maintenance works in thermal power plants, timing (e.g., start of holiday season) and secondary effects, e.g., forest fires, social unrest.

Time to fully recover from the shock: depending on intensity and activity

The intensities of the shock scenarios below depend to a great extent on the economic/technological/political pathways in the decade previous to the shock and thus, the status (e.g., the infrastructure) of the energy system at the time of the shock.

Scenario 1: Low Intensity

When: any year; spring to fall with peak in summer

Where: Switzerland and neighbouring regions

Duration: 1 week (peak)
- extended drought develops over multiple months: 4 months (late spring – early fall), peaking in summer, some precipitation, but below average
- wave of extreme heat (daily average temperature > 25°C) for 4-5 days in the midlands

Intensity: lower river and lake water levels than average, lower electricity production from hydro power plants, increased cooling demand, during extreme heat: overloaded transformers, no EU-CH electricity agreement, low electricity imports, high electricity costs, call for reduced energy and water use lowers the demands only slightly

Time to fully recover from the shock:
- The shock is transient
- Time to recover: several weeks to months as there is sufficient precipitation after the heat wave and temperatures drop
- It takes 1 year for hydro storages to become normal

Scenario 2: Medium Intensity

When: any year; spring to fall with peak in summer

Where: Switzerland and countries in central and southern Europe

Duration: 2 weeks (peak)
- extended drought develops over multiple months: half a year (spring-fall), peaking in summer, low precipitation
- wave of extreme heat (daily average temperature > 25°C) for 5 days within two weeks with high temperatures (daily average temperature around 20°C) in the midlands

Intensity:
lower river and lake water levels than average, lower electricity production from hydro power plants (-15-20% for run-of-river, -5% for hydro storages), increased cooling demand, small forest fires, during heat wave: overloaded transformers, no EU-CH electricity agreement, limited electricity imports, several blocked streets, limited shipping for 1-2 months starting with heat wave, limited and less efficient work in economy, short periods in which some thermal power plants work limited or are shut down, unscheduled power loop flows from France to Italy through Switzerland, call for reduced energy use shows no effect

Time to fully recover from the shock: - The shock is transient - Time to recover: several months as the fall is rather dry and warm; in winter there is above average precipitation - It takes 1-2 years for hydro storages to become normal
Scenario 3: High Intensity
When: any year; spring to fall with peak in summer **Where:** Switzerland and countries in central and southern Europe **Duration:** 3 weeks (peak) - extended drought develops over multiple months: half a year (spring-fall), peaking in summer, very low precipitation (marking a historical record) - wave of extreme heat (daily average temperature > 25°C) for 2 x 7 days within three weeks, with high temperatures (daily average temperature around 20-25°C) for two weeks in between in the midlands **Intensity:** lower river and lake water levels than average (historic record), limited electricity production from hydro power plants (-25% for run-of-river, with small ones stopping completely, -10% for hydro storages), high cooling demand, several forest fires causing damage on power lines/landlines, during heat wave: overloaded transformers, limited electricity imports, several blocked streets, limited shipping for 3 months in summer/ fall starting with heat wave, limited transportation of goods and loss of food due to several limited cooling chains, limited and less efficient work in economy, 2-3 week period in which some thermal power plants are shut down, unscheduled power loop flows from France to Italy through Switzerland, the heat wave peaks in the beginning of the holiday season causing peak demands due to EV charging on both sides of the Gotthard, call for reduced energy use shows no effect, several local floods due to heavy thunderstorms after the heat wave **Time to fully recover from the shock:** - The shock is transient - Time to recover: one year as fall and winter are rather dry and warm; only in late winter and early spring there is above average precipitation - It takes 1-2 years for hydro storages to become normal

6.2.2 Change in the input parameters of the models

The following changes are provided as relative changes to the nominal scenario in Percent. Thereby, the impact can be scaled according to nominal scenario of future years.

Parameter	Scenario 1 (Low intensity)	Scenario 2 (Medium intensity)	Scenario 3 (High intensity)	Source / Comment
Run-of-River production	Change +5% in Winter, +0% in Spring, -10% in Summer and Fall	Change +15% in Winter, +0% in Spring, -30% in Summer and Fall	Change +25% in Winter, +0% in Spring, -50% in Summer and Fall	MeteoSchweiz, NCCS Schweizer Energiestatistik 2021 BABS More power in winter, less in summer
Hydro inflow (and potential annual production):	Change -10% in total energy over the entire year	Change -15% in total energy over the entire year	Change -20% in total energy over the entire year	Schweizer Energiestatistik 2021 Less total precipitation
Electricity Demand	Change + 10% in Summer + 0% in Fall (cooling, work from home, no consumer flexibility to reduce demand)	Change + 20% in Summer + 5% in Fall (cooling, work from home, no consumer flexibility to reduce demand)	Change + 30% in Summer + 10% in Fall (cooling, work from home, no consumer flexibility to reduce demand)	This depends on regional share on cooling devices and airconditioning (e.g. more in Ticino, less in Aargau)
PV, Wind production	Unchanged	Unchanged	Unchanged	PV not necessarily increased.
Gas demand	Unchanged	Unchanged	Unchanged	Mainly used in Winter
Conventional generation	-30% of nuclear (if still in the scenario)	-30% of nuclear (if still in the scenario)	-30% of nuclear (if still in the scenario)	Fish protection (river water for cooling too warm) Unexpected maintenance
Import capacities	Change of maximum import from DE -15% Change of maximum import from FR -30%	Change of maximum import from DE -20% Change of maximum import from FR -40%	Change of maximum import from DE -25% Change of maximum import from FR -50%	Higher loading of transmission lines of European neighbors, less line capacity available for Switzerland This occurs in particular if Switzerland is not part of the European FBMC

Transitflows	Change of transit/ loop flows from North to IT +10%	Change of transit/ loop flows from North to IT +20%	Change of transit/ loop flows from North to IT +30%	System Adequacy study 2021 More hours with high Transit towards Italy
Electricity cost	Change +10% (for end consumers in the following year)	Change +15% (for end consumers in the following year)	Change +20% (for end consumers in the following year)	More reserve measures undertaken to ensure / improve system security after the blackout (or the near miss of the blackout); impact on grid tariffs
Peak loading of critical transmission grid lines	Change +20%	Change +25%	Change +30%	During peak hours in summer
Peak loading of critical distribution grid lines	Change +10%	Change +20%	Change +30%	During peak hours in summer, high load in distribution system in critical locations (a lot of AC / housing)

6.3 Cold spell factsheet

6.3.1 Real life examples and detailed shock specification

Definition of shock:

Cold wave (six weeks of extreme cold)
+ heavy snowfall at the beginning of the cold wave*
+ accumulation of snow:

- High electricity and heating demand,
- Low PV generation,
- Low hydro storage levels, use of reserves
- Unexpected maintenance required in a Swiss nuclear power plant
- Unscheduled loop flows from France to Italy through Switzerland, increasing the already high market-based scheduled transit flows through Switzerland, cause a very uneven distribution of the Swiss transmission grid load.
- Damage, e.g., to local grids and transmission lines (caused by heavy snow, ice and falling trees), potentially causing reduced electricity supply, local blackouts of power and telephony (landline and mobile), and local overload of the power grid
- Due to the intensity of the cold wave, private households ignore the call for rationed use of electricity and heating.

- No EU-CH electricity agreement
- Limited imports of electricity, gas, and oil as neighbouring countries have similar shortage issues
- Increasing electricity, gas, and oil prices

- Some heating systems stop working due to overload and not able to work at low temperatures (heat pumps might not work at very low temperatures, or at least in backup mode (i.e., electric heating) [Vaillant 2022], which increases the electricity demand even more)
- Higher use of electricity due to supplementary electric heaters as many buildings are not designed for too low temperatures **
- Increased demand of new “mobile” electric heater that people want to buy
- Where heating systems stop, buildings become colder and pipes freeze or burst
- Lower battery capacity (80%) / faster discharge at low temperatures

- Risk of collapse of public transport (consequence: lower energy demand) due to blocked roads and railway lines, frozen points, signals, etc.

- Weather and road conditions complicate repairs and emergency services
- Shortage of goods in shops and supermarkets, delivery of goods and post is limited
- Industrial sector: potentially limited or stopped production due to limited/stopped transportation and absence of ill workforce
- All economy sectors: potentially limited work in economy but also public services (due to collapsed/limited public transport and lack of goods and higher energy prices), decreased GDP (up to -10%)
- If in the end of the winter season: potential lack of resources (e.g., de-icing salt) and thus extended period of icy roads
- Costs due to damages sum up to around 5-10 billion CHF

*Note: a combination of a strong cold wave and heavy snow fall is very rare for physical reasons, since very cold air can contain only very little moisture and thus only small snowfalls can from out of cold air [BABS 2020 (Kältewelle)]. Cloud temperatures must be around -4°C and -20°C, otherwise it is too dry [Planet Wissen 2020] However, extreme cold wave and heavy snow fall can be consecutive events, that occur within a short time window

**Note: There are cantons that already forbid new installations of electric boilers (e.g.: Kanton Solothurn 2017), thus impacts related to electric boilers in mid- to far-future energy systems might not be applicable

Potential cascading effects:

Power outage:

- Power outage can last 5-7 days ("extreme scenario") with complete regeneration/repairs up to 3-4 weeks [BABS 2020 (Stromausfall)], (indirect) impacts can last for more than a year

There are countless consequences of a power outage, e.g.:

- Mobile phone connection and landline telephony limited or collapsed
- Increased use of cars due to cancelled train connections, chaotic street transport also due to outage of traffic control systems
- Increased use of gas for heating and cooking
- Lack of gasoline since gas stations do not work without electricity

Limited availability of electricity:

- Shock with the highest aggregated economic damage
  [BABS 2020 (Strommangellage)]

There are measures in case of limited electricity production [BABS 2020 (Strommangellage)]:

- (Governmental) call to reduce electricity consumption in households and economy (after week 1, scenario "gross")
- Regulations for reduced electricity consumption (quotas) for specific areas/applications/households/economy/… and closure of public facilities, e.g., sport centres, pools, …, reduction in public transport, … (after week 3, scenario "gross")
- Centralized management of power plants (OSTRAL) (after week 3, scenario "gross"), and thus: stopped/limited electricity market
- Bi-/multi-lateral agreements on electricity exchange between countries
- Deliberate blackouts (after week 5, scenario "gross"), patterns of 4h
- Uncontrolled blackouts

Real-life examples:

Once-in-a-lifetime events:

Winter 1962/63: two months, CH and Europe: snowfall followed by temperature drops in the end of December, many days with average temperature below -5°C and even -10°C, Lake Constance and Lake Zurich froze, almost no data on economic damage or transport limitations

Nov-Dec 2005, DE (Münster area): heavy snowfall and strong winds created 15cm thick ice around power overhead lines and high voltage masts. 50 masts broke due to the heavy ice, resulting in blackouts for ~ 250,000 people up to one week

Feb 2021, Northern America, most severe in Texas: record low temperatures (-20°C) and one of the snowiest winters with millions losing access to power, many frozen or bursting pipes

Events with higher frequency:

2019, January (~ 2 weeks), pre-Alps in DE/AT: storm with heavy snowfall, snowdrifts caused road and railway line closures, valleys cut off (e.g., Salzburg: 40.000 people cut off)

2006, 5th/6th March, northern and eastern CH: heavy snowfall, road and railway line closures, collapse of public transport (trams/busses), emergency shelters for stranded people

2006, 16th January – 5th February, CH and Europe: cold wave with down to -34°C in Germany, limited public transport, 30.000 households without electricity

Specification of shock
Source: Weather (extremely cold temperatures and snowfall) **When:** Any year; fall to spring with peak in winter **Where:** Switzerland and central Europe **Duration:** up to six weeks in winter **Intensity (provide metric):** medium to high (see below) **Time to fully recover from the shock:** depending on dimension: power system (1-2 weeks), public transport (4-8 weeks), economy (months), refill of water reserves (1-2 years)

The intensities of the shock scenarios below depend to a great extent on the economic/technological/political pathways in the decade previous to the shock and thus, the status (e.g., the infrastructure) of the energy system at the time of the shock.

Scenario 1: Low Intensity
When: Any year; January/February after a cold and dry fall **Where:** Switzerland and neighbouring regions **Duration:** 2 weeks (peak) **Intensity (provide metric):** low water levels in rivers and hydropower reservoirs causing reserves to be used for power generation; limited electricity and gas imports; lowered availability of electricity, oil and gas; delayed access to goods; call for reduced energy use lowers the demands only slightly; high energy expenditures in population **Time to fully recover from the shock:** The shock is transient. Thus, there are no remaining implications on the energy system in the next winter.
Scenario 2: Medium Intensity
When: Any year; January/February after a cold and dry fall and accumulation of snow **Where:** Switzerland and central Europe **Duration:** 4 weeks (peak) **Intensity (provide metric):** low water levels in rivers and hydropower reservoirs causing reserves to be used for power generation; limited electricity and gas imports; limited availability of electricity and gas; periods of limited public transport; limited work in economy; limited/delayed access to goods, unscheduled power loop flows from France to Italy through Switzerland; call for reduced energy use shows no effect; high energy expenditures in population **Time to fully recover from the shock:** The shock is transient. Thus, there are no remaining implications on the energy system in the next winter.

Scenario 3: High Intensity
When: Any year; January/February after a cold and dry fall and accumulation of snow **Where:** Switzerland and central Europe **Duration:** 6 weeks (peak) **Intensity (provide metric):** low water levels in rivers and hydropower reservoirs leading to empty reservoirs; very limited electricity and gas imports; lack of electricity and gas; several emergency measures (OSTRAL) in place; periods of limited public transport; limited work in economy; unscheduled power loop flows from France to Italy through Switzerland; call for reduced energy use shows no effect; high energy expenditures in population **Time to fully recover from the shock:** The shock is transient. Thus, there are no remaining implications on the energy system in the next winter.

6.3.2 Change in the input parameters of the models

The following changes are provided as relative changes to the nominal scenario in Percent. Thereby, the impact can be scaled according to nominal scenario of future years.

Parameter	Relative Change Scenario 1 (Low intensity)	Relative Change Scenario 2 (Medium intensity)	Relative Change Scenario 3 (High intensity)	Source / Comment
Run-of-River production	Change -15% in Winter	Change -20% in Winter	Change -25% in Winter	Less water in winter
Hydro inflow (and potential annual production):	Unchanged	Unchanged	Unchanged	Schweizer Energiestatistik 2021 Delayed hydro inflow (later in spring), but same annual amount
Electricity Demand	Change + 0% in Summer + 30% in Fall / Winter	Change + 0% in Summer + 40% in Fall / Winter	Change + 0% in Summer + 50% in Fall/Winter	Heating via heat pumps, no potential to reduce demand This depends on the proliferation of heat pumps in the nominal scenario (e.g. in 2050 higher change than in 2025)
PV, Wind production	Change -10% in Winter	Change -20% in Winter	Change -30% in Winter	Snowfall reduces PV further, Wind not operational due to cold shock
Gas demand	Change +10% in Winter	Change +20% in Winter	Change +30% in Winter	Heating
Conventional generation	-30% of nuclear (if still in the scenario)	-30% of nuclear (if still in the scenario)	-30% of nuclear (if still in the scenario)	Unexpected maintenance
Import capacities	Change of maximum import from DE -20% Change of maximum import from FR -40%	Change of maximum import from DE -40% Change of maximum import from FR -60%	Change of maximum import from DE -50% Change of maximum import from FR -80%	Higher loading of transmission lines of European neighbors, less line capacity available for Switzerland This occurs in particular if Switzerland is not part of the European FBMC
Transitflows	Change of transit/ loop flows from North to IT +20%	Change of transit/ loop flows from North to IT +30%	Change of transit/ loop flows from North to IT +40%	System Adequacy study 2021 More hours with high Transit towards Italy
Electricity cost	Change +20% (for end consumers in the following year)	Change +25% (for end consumers in the following year)	Change +30% (for end consumers in the following year)	More reserve measures undertaken to ensure / improve system security (impact on grid tariffs) Higher overall prices for primary energy sources
Peak loading of critical transmission grid lines	Change +20%	Change +25% In addition outages of 1-2 alpine transmission lines due to freezing	Change +30% In addition outages of 3-5 alpine transmission lines due to freezing	Supply higher demand (for heating etc.)

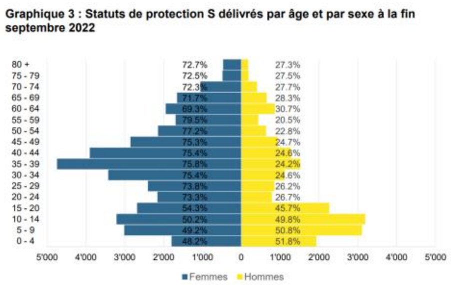
Parameter	Relative Change Scenario 1 (Low intensity)	Relative Change Scenario 2 (Medium intensity)	Relative Change Scenario 3 (High intensity)	Source / Comment
Peak loading of critical distribution grid lines	Change +40%	Change +45%	Change +50%	During peak hours in winter, high load in distribution system in critical locations (a lot of heating via Heat Pumps and new electric heaters)

6.4 Societal shock factsheet

6.4.1 Real life examples and detailed shock specification

Definition of shock:
- Sudden population growth -> 5-9% of the 2030 population over a 5-year period; - Difficulties in finding adequate temporary and/or permanent housing; - Launching language and capacity building courses to certify and integrate the new potential workforce in the local market; - Depending on the shock intensity, a different percentage of the refugee population is integrated in the job market. In any case, refugees remain trapped in energy and transport poverty conditions, which delay achievement of the energy transition and net zero climate goals; - Political instability and turmoil.

Facts and figures

Criteria	Info
General info about refugee permits	Types of permits for refugees in Switzerland: • F permit – Person recognised as a refugee but not granted asylum (temporary admission); • N permit – Person in ongoing asylum procedure; • S permit – A collective protection granted to a specific group for the duration of a serious threat, in particular in case of war; • B permit – Person recognised as a refugee and granted asylum; • C permit – Person recognised as a refugee who has been able to obtain a settlement permit, after having resided in Switzerland for a certain number of years on a refugee B permit and having fulfilled certain conditions, notably integration. (Source: https://asile.ch/procedure-dasile-permis-et-droits/permis/)
POP changes - current examples and future projections	Swiss law distinguishes between refugees who have been granted asylum (so-called B-permit) and refugees who are only temporarily admitted to Switzerland (F-permit). The vast majority of F-permit holders, over 96 per cent, remain durably in Switzerland. After five years, an F-permit holder may apply for a B-permit, provided that they meet a number of conditions. B-permit refugees have an enforceable right to family reunification with their pre-flight family members. F-permit refugees and F-permit holders have no such right. F-permit refugees and F-permit holders may not apply for family reunification before the expiry of a three-year period after the grant of their temporary admission (Motz,2017).
	Status of S-permit refugees in Switzerland in 2022  (Source: **https://www.sem.admin.ch/sem/fr/home/publiservice/statistik/asylstatistik.html**)
	In 2021 it was estimated by the UNHCR that the global forced displacement surpassed 84 million people. According to the calculations, Turkey, with a population of 84.3 million, is hosting 3.7 million refugees (≈4.4% of its population). In Central Europe Germany, with a population of approximately 83.2 million, hosted 1.2 million refugees (≈ 1.4% of its population). (Source: https://www.unhcr.org/refugee-statistics/#_ga=2.212273044.160016061.1668419216-727715489.1657715431)
	There could be 1.2 billion climate refugees by 2050 (Institute for Economics & Peace, 2022).
	Water scarcity affects roughly 40% of the world's population and, according to predictions by the United Nations and the World Bank, drought could put up to 700 million people at risk of displacement by 2030. (Source: **https://www.**bbc.com/future/article/20220912-are-drying-rivers-a-warning-of-europes-tomorrow)

The global north faces the opposite problem – a “top-heavy” demographic crisis, in which a large elderly population is supported by a too-small workforce. North America and Europe have 300 million people above the traditional retirement age (65+), and by 2050, the economic old-age dependency ratio there is projected to be at 43 elderly persons per 100 working persons aged 20–64. Cities from Munich to Buffalo will begin competing with each other to attract migrants.
(Source: **https://www.theguardian.com/news/2022/aug/18/century-climate-crisis-migration-why-we-need-plan-great-upheaval**)

Refugee integration expenditures (health, education and social services)

The Confederation pays the cantons lump-sum compensation for all asylum seekers and provisionally admitted persons who have been in Switzerland for less than 7 years.
Since 1 March 2019, the Confederation has been paying the cantons a lump-sum to cover the costs of emergency assistance, the amount of which varies according to the asylum procedure conducted and amounts to:

- 402 francs for persons subject to a Dublin procedure (index as at 31 October 2018);
- CHF 2516 for persons subject to an accelerated procedure (index as at 31 October 2018);
- CHF 6030 for persons who have been subject to an extended procedure, or whose provisional admission has been revoked (index as at 31 October 2018).

At the end of each calendar year, the SEM modifies the emergency aid rates for the following year on the basis of the national consumer price index.
(Source: **https://www.sem.admin.ch/sem/fr/home/asyl/sozialhilfesubventionen/bundessubventionen.html**)

The Confederation’s expenditure on asylum does not even represent 1% of GDP. The Confederation pays the cantons a lump sum of CHF 18,000 per year per person with a residence permit, as well as a one-off lump sum of CHF 6,000 per person for integration.
(Source: **https://www.amnesty.ch/fr/sur-amnesty/publications/magazine-amnesty/2017-1/suisse-couts-de-lasile-accueil-refugies#**)

Swiss welcome package: From Spring 2019, Cantons receive CHF 18’000 per refugee to cover services such as accommodation and care. They are also responsible for organising and paying for training courses. The goals include everyone securing a basic knowledge of a national language within three years. The goals:

- All recognised refugees and provisionally admitted persons have a basic knowledge of a national language three years after their arrival.
- 80% of refugee children who arrived in Switzerland before the age of four are able to make themselves understood in the language spoken in their place of residence when they start compulsory school.
- Five years after arrival, two-thirds of refugees and temporary residents aged 16-25 are in initial vocational training.
- Seven years after arrival, half of the refugees and temporary residents are permanently integrated into the labour market.
- After a few years, all refugees and provisionally admitted persons are familiar with Swiss customs and maintain contacts with the local population.

Based on an annual number of 11,000 recognised refugees and provisionally admitted persons, this process was estimated to generate additional costs for the Confederation of 132 million francs per year in the short term. However, calculations also show that for every franc invested, the public authorities will save up to four francs per person of working age in the long term thanks to the Integration Agenda**.** A calculation shows, for example, that adults aged 26-49 who enter working life more quickly thanks to the Integration Agenda will save the public sector an average of about CHF 90,000 per person. These measures are expected to not only relieve social welfare but also the training sector. The integration services currently provided by the training sector for this target group are not taken into account in the Integration Agenda.
(Sources: **https://www**.kip-pic.ch/fr/pic/agenda-integration/;
https://www.swissinfo.ch/eng/business/chf18-000-per-refugee_what-will-new-asylum-seeker-integration-funds-be-spent-on-/44092810)

Employment, higher or vocational education, GDP

Data regarding all working-age refugees who received subsidiary protection status and arrived in Switzerland from 1999 to 2013 (n = 22’159) indicate that, on average, the third-year employment rate was 15%. It could become 26% under AI algorithms aimed at matching allocation of refugees to cantons of residence based on their characteristics (Bansak et al., 2018).

In Switzerland, in 2022 48.5% of F permit owners had a lucrative activity, and 41.9% of refugees with a B permit. (Source: https://www.sem.admin.ch/sem/fr/home/publiservice/statistik/asylstatistik/archiv/2022/09.html)

F-permit holders encounter various obstacles in accessing the Swiss labour market, including restrictive employment laws during the asylum procedure, unreliable language courses, medical problems and the constant worry about the security and well-being of family members in the country of origin. After three years, approximately 20 per cent are employed (Motz, 2017).

Statistics for Switzerland:
Number of provisionally admitted persons (F permits) with gainful employment by canton as of 30.9.2022

	Total personnes admises provisoirement (incl. AP avec qualité de réfugié)				**Évolution par rapport au même mois d' l'année précédente**			**Durée de séjour > 6 et <= 7 ans**			
	Total	Personnes potentielle-ment actives (18 à 65 ans)	Personnes actives	Tau' d'activité	Personnes actives même mois d' l'année précédente	Evolution du nombre	Evolution du nombre de personnes	**Total**	Personnes potentielle-ment actives (18 à 65 ans)	Personnes actives	Tau' d'activité
Total	45,137	29,863	14,491	48.5%	14,915	-424	-2.8%	8,214	5,894	3,455	58.6%

(Source: **https://www.sem.admin.ch/dam/sem/de/data/publiservice/statistik/asylstatistik/2022/09/6-22-Effectif-AP-activ-f-2022-09.xlsx.download.xlsx/6-22-Effectif-AP-activ-f-2022-09.xlsx**)

Within two years of an influx of migrants, unemployment rates drop significantly and economic health increases. Asylum seekers also benefit economies, but their effects take longer to transpire — from three to seven years — and the boom is less obvious (d'Albis et al., 2018).

Table 1. Economic and fiscal Responses to migration shocks. Year 0 stands for the year of the shock. We set the size of a shock on the net flow of migrants or the flow of asylum seekers to 1 incoming individual per thousand inhabitants. For per capita, GDP, spending, and net taxes, we expressed the responses in percentage change; for the unemployment rate and fiscal balance/GDP, the responses are in percentage point change.

	Year 0	Year 1	Year 2	Year 5	Year 10
Increase in the flow of asylum seekers					
Spending per capita	0.28	0.33	0.34	0.58	0.24
Net taxes per capita	0.57	0.63	1.01	1.31*	0.20
GDP per capita	0.27	0.45	0.54	0.59*	0.13
Unemployment rate	−0.08*	−0.15*	−0.21*	−0.21*	−0.02
Fiscal balance/GDP	0.06	0.07	0.15	0.15	−0.01
Increase in the net flow of migrants					
Spending per capita	0.29*	0.49*	0.60*	0.33*	−0.02
Net taxes per capita	0.85*	1.11*	0.95*	0.19	−0.09
GDP per capita	0.17*	0.24*	0.32*	0.12	−0.05
Unemployment rate	−0.12*	−0.16*	−0.14*	−0.03	0.01
Fiscal balance/GDP	0.11*	0.11*	0.05	−0.04	−0.02

*Statistical significance at the 10% level.

Excerpt from d'Albis et al., 2018.

Among the 25 to 39-year-olds with roots in so-called MENAPT countries (a Danish category comprising the Middle Eastern and North African countries and Turkey), 48 % of men and 71 % of women have completed higher or vocational education. There is still a gap between this group and ethnic Danes of the same age - for whom the same statistics stand at 73 % for men and 81 % for women, however the gap has significantly narrowed over the last decade.
(Source: https://ec.europa.eu/migrant-integration/news/denmark-growing-number-refugee-and-migrant-descendants-complete-higher-education_en)

According to the IAB-BAMF-SOEP 2016 survey in Germany, low-skilled men and women account for more than 50% (EPRS, 2018).

In the US, immigrant employees account for 73% of the agricultural industry, 24% of the construction industry, 12.8% of the education workforce, 18% of health care workers, 21.8% of hospitality industry, 19.8% of professional services Less immigration causes labour shortages that eventually increase inflation. According to a recent report from Texas A&M University, increasing the number of immigrant farm workers can reduce food prices and raise wages.
(Source https://www.boundless.com/blog/immigration-could-help-lower-inflation/)

Based on 30 years data from 15 western European countries, within 5 years after an immigration spike, the asylum seekers can bring an increase in GDP/capita of 0-1%, and a percent point reduction in the unemployment rate of 0-0.4. Those effects are likely down to migrants increasing market demand, providing services, adding jobs and paying taxes. The study showed this economic activity far outweighs governmental costs of newcomers — that may be partly explained by the fact that immigrants tend to be young and middle-aged adults who are less reliant on state benefits (d'Albis et al., 2018).

General effects of climate change, national

More than 250 medical journals are calling for more climate justice for Africa. The continent has contributed little to the crisis but suffers disproportionately, says the editorial, which is published in prestigious journals such as the British Medical Journal, The Lancet and New England Journal of Medicine, as well as 50 African medical journals: "The acute and chronic effects of the climate crisis create problems such as poverty, infectious disease, forced migration, and conflict that spread through globalized systems. These effects affect all nations." (Atwoli et al., 2022).

Problems faced by immigrants in Switzerland

Residence permit, language, public authorities, socio-cultural integration (Kiselev et al., 2020).

6.4.2 Change in the input parameters of the models

Specification of shock
Source: see above **When:** The shock starts in 2030 and its effects are fully realised by 2035. **Where:** At the national level. **Duration:** Considering the uncertainties in climate change, wars, and natural hazard related displacement (ex: Syrian civil war duration – over 11 years), this could be a sudden and permanent increase in the population. **Intensity:** Depends on the intensity of the international crises, the mitigation measures and "welcome" packages, and social and political acceptance within Switzerland **Time to fully recover from the shock:** In 2035 (five years after the start of the shock) a new state that affects the energy demand and socio-economic disparities is reached, requiring to recalculate the energy resources required and the policy packages to be implemented in order to keep Switzerland on-track for the Net-Zero goal in 2050.

Scenario 1: Low Intensity
When: The shock starts in 2030 and its effects are fully realised by 2035. **Where:** At the national level. **Duration:** At least five years. **Intensity: Low:** - **Population increase** – 5%: in 2035 the population peaks to 10 million inhabitants. Increase in population wrt business as usual scenario forecast for 2035: 0.5 million inhabitants (refugees). On average, this is equal to a 0.1 million inhabitants population increase per year, for five years. - **Habitat** – Influx manageable for distribution in permanent structures and housing solutions in urban environments. In 2035, 50% of the refugees however mostly live in non energy-retrofitted houses, still heated by fossil fuels, and find themselves in energy poverty conditions. - **Transport** – in 2035, 50% refugees suffer of transport poverty (lack of affordability and accessibility). - **Resources** – import scarcity not significant. - **Domestic policy** – 50% of immigration is men and women with low skill/education accreditation but domestic policy includes courses in language and in labour sectors expected to have high demand in future (ex: health care). 50% immigrants integrate relatively easily in the workforce within 5 years. In 2035, their job allows them to enjoy comparable well-being conditions as Swiss citizens in low-to-mid-income classes. The remaining 50% immigrants remain excluded from the labour market and live under public assistance. - **Public expenditure** – If we stick to current public expenditure for each refugee, this would be the public expenditure (which we might assume to last only for five years after the refugees' arrival): 600 million CHF/year (18'000 CHF/year * 0.1 million refugees/year* 0.5 unemployed refugee share * 0.67 refugees/funding ratio based on the current situation). **Time to fully recover from the shock:** after five years, a new state that affects the energy demand and socio-economic disparities is reached, requiring to recalculate the energy resources required and the policy packages to be implemented in order to keep Switzerland on-track for the Net-Zero goal in 2050.

Scenario 2: Medium Intensity
When: The shock starts in 2030 and its effects are fully realised by 2035. **Where:** At the national level. **Duration:** At least five years. **Intensity: Medium:** - **Population increase** – 7%: in 2035 the population peaks to 10.2 million inhabitants. Increase in population wrt business as usual scenario forecast for 2035: 0.7 million inhabitants (refugees). On average, this is equal to a 0.14 million inhabitants population increase per year, for five years. - **Habitat** – Influx nearly manageable for distribution in permanent structures and housing solutions in urban environments. Need for new buildings to host some of the refugees. To limit direct construction costs, insulation materials only achieve minimum legal standards. In 2035, 60% of the refugees however mostly live in non energy-retrofitted houses, still heated by fossil fuels, and find themselves in energy poverty conditions. - **Transport** – In 2035, 60% refugees suffer of transport poverty (lack of affordability and accessibility). - **Resources** – food supply disrupted, fuel and energy cost increases. - **Domestic policy** – 60% of immigration is men and women with low skill/education accreditation. "Welcome package" is not adequately developed. Only 40% immigrants integrate relatively easily in the workforce within 5 years, however getting low-skilled jobs. In 2035, their job allows them to enjoy comparable well-being conditions as Swiss citizens in low-

income classes. A large share of the refugees (60%) remains unemployed, excluded from the labour market and living under public assistance.
- **Public expenditure** – If we stick to current public expenditure for each refugee, this would be the expenditure public expenditure (which we might assume to last only for five years after the refugees' arrival): 1'008 million CHF/year (18'000 CHF/year * 0.14 million refugees/year* 0.6 unemployed refugee share * 0.67 refugees/funding ratio based on the current situation).

Time to fully recover from the shock: after five years, a new state that affects the energy demand and socio-economic disparities is reached, requiring to recalculate the energy resources required and the policy packages to be implemented in order to keep Switzerland on-track for the Net-Zero goal in 2050.

Scenario 3: High Intensity

When: The shock starts in 2030 and its effects are fully realised by 2035.

Where: At the national level.

Duration: At least five years.

Intensity: High:

- **Population increase** – 9%: in 2035 the population peaks to 10.4 million inhabitants. Increase in population wrt business as usual scenario forecast for 2035: 0.9 million inhabitants (refugees). On average, this is equal to a 0.18 million inhabitants population increase per year, for five years.
- **Habitat** – Influx too high for distribution in permanent structure and housing solutions – use of temporary structures such as prefabricated "container-like" shelters during winter. Need for important investments in new buildings to host relevant shares of the refugees. To limit direct construction costs, insulation materials only achieve minimum legal standards. In 2035, 60% of the refugees live in non energy-retrofitted houses, still heated by fossil fuels, and find themselves in energy poverty conditions.
- **Transport** – In 2035, 60% refugees suffer of transport poverty (lack of affordability and accessibility).
- **Resources** – International commercial routes and supply of various materials and food are disrupted.
- **Domestic policy** – 60% of immigration is men and women with low skill/education accreditation. "Welcome package" is not adequately developed. Only 40% immigrants integrate relatively easily in the workforce within 5 years, however getting low-skilled jobs. In 2035, their job allows them to enjoy comparable well-being conditions as Swiss citizens in low-income classes. A large share of the refugees (60%) remains unemployed, excluded from the labour market and living under public assistance.
- **Public expenditure** – If we stick to current public expenditure for each refugee, this would be the expenditure public expenditure (which we might assume to last only for five years after the refugees' arrival): 1'296 million CHF/year (18'000 CHF/year * 0.18 million refugees/year* 0.6 unemployed refugee share * 0.6 refugees/funding ratio based on the current situation).

Time to fully recover from the shock: after five years, a new state that affects the energy demand and socio-economic disparities is reached, requiring to recalculate the energy resources required and the policy packages to be implemented in order to keep Switzerland on-track for the Net-Zero goal in 2050.

6.5 Political shock factsheet

Definition of shock:

After the decision to phase-out nuclear energy (Energy Strategy 2050), nuclear energy has been "politically dead" but also economically unattractive. The replacement of existing nuclear power plants through renewable energy production has been the main starting point for all political discussions about energy transition.

In this context, a political decision to re-introduce nuclear energy can be considered as a shock that impacts different levels and aspects of the energy transition:

- It would create a new technological option and could also trigger rapid technological development in the field (through investments in R&D)
- It would reduce the pressure to increase the share of renewables and, accordingly, the introduction of effective political measures promoting renewable energy production, on which currently important political conflicts exist, would become even more unlikely
- This could be backed by an increased popular support for nuclear energy (instead of renewables) since this option could be politicised and sold as "the easy way out" (no need for individual behavioural change, a "well-known" technology that "works", no dead birds…)
- This shock might become more likely in the context of persistent uncertain geopolitical conditions related to energy security.
- Eventually, this shock would change the future energy mix.

Real-life examples:

The EU commission has recently labelled nuclear energy as “climate-friendly”.
Great Britain wants to construct new nuclear power plants to reach the climate targets.

In the context of the current energy crisis, countries like Germany or France have kind of postponed their nuclear and coal phase-out. This is similar to what we describe in the low-intensity scenario.

The announcement of a new “nuclear power initiative” reflects the situation we describe in the medium-intensity scenario. https://www.srf.ch/news/schweiz/kernenergie-in-der-schweiz-initiative-fuer-neue-atomkraftwerke-wird-lanciert

Specification of shock

Source: Given the political lock-in regarding the energy transition, a political coalition of centre and right-wing parties form a political majority to delete the ban on construction of new nuclear power plants.

When: Before 2035! 2025-2030

Where: At the national level (nuclear energy is largely in the responsibility of the federal level)

Duration: This is a sort of “end-less” shock leading to a new “state” or triggering a change of path.

Intensity (provide metric): The intensity of the shock depends on the extent to which the “pure political decision” triggers a stronger or weaker dynamic:

- **Low:** Nuclear energy is part of the energy mix, but the decision does not lead to a “dynamic” with strong popular support and a real push for this technology. It is rather the political consensus not to push for the nuclear phase-out and let the current nuclear power plants run for longer.
- **Medium:** The re-introduction triggers some dynamics at the technical, economic and societal level. While existing power plants run for longer, new nuclear power plants could be built if market forces allow for.
- **High:** the political decision triggers a strong dynamic in favour of nuclear energy. New technologies are developed, new plants are constructed, nuclear energy becomes an important pillar of the CO2-reduction by also covering most of the increased electricity demand. Public support measures are taken to promote and steer the revival of nuclear energy.

Time to fully recover from the shock: No recovery, but a new state.

Scenario 1: Low Intensity

When: Before 2035! Decision taken 2025-2030

Where: At the national level

Duration: The decision as such is very short-term, but the dynamics triggered take years or decades.

Intensity (provide metric):
Low: Nuclear energy remains in the electricity supply mix as existing nuclear reactors continue to operate also beyond 2050. However, the ban in constructing new nuclear reactors remains. (partial phase-out)

Time to fully recover from the shock: Recovery in this case means stabilisation along another pathway -> to fine-tune above parameters, we could refer to the characteristics of the pathways.

Scenario 2: Medium Intensity

When: Before 2035! Decision taken 2025-2030

Where: At the national level

Duration: The decision as such is very short-term, but the dynamics triggered take years or decades.

Intensity (provide metric):
Low: New nuclear energy plants can be constructed (as of 2030) if the market conditions are favourable and capital financing from the investors is available. SMR as a technology is available. Existing power plants continue to run as long as they are safe, “no phase-out”.

Time to fully recover from the shock: Recovery in this case means stabilisation along another pathway -> to fine-tune above parameters, we could refer to the characteristics of the pathways.

Scenario 3: High Intensity
When: Before 2035! Decision taken 2025-2030? **Where:** At the national level **Duration:** The decision as such is very short-term, but the dynamics triggered take years or decades. **Intensity (provide metric):** **High:** New technologies are developed, existing nuclear power plants continue to operate as long as they are safe. SMR technology is commercially available. New plants are constructed (in Aargovia and Solothurn, where current power plans are sited), nuclear energy becomes a main pillar of the CO2-reduction by also covering most of the increased electricity demand. **Time to fully recover from the shock:** Recovery in this case means stabilisation along another pathway -> to fine-tune above parameters, we could refer to the characteristics of the pathways.

Input parameters for the models to support the narrative:

- Overnight investment cost for a 10-year lifetime extension of existing reactors, beyond the "normal" 50 years lifetime: 1100 CHF/kW
- Decommissioning cost of existing reactors: 900 CHF/kW
- Overnight investment cost for a new SMR reactor: 7000 EUR/kW
- Construction time of a new SMR reactor:
  - Medium intensity shock: 10 years
  - High intensity shock: 5 years
- Potential sites and maximum sizes of new nuclear reactors (both for Medium and High shocks):
  - Beznau (AG) - existing site: 1.6 GW ±20%
  - Niederamt (SO) - next to Gösgen: 1.6 GW ±20%

Political background for new sites: Generally, the acceptance of nuclear power plants is typically highest close to existing plants, which not least has economic reasons. Moreover, AG and SO still have running nuclear power plants. Hence, having a new one at these spots means just "business as usual". Therefore, these are the most likely places for new power plants.