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Authors		
Name	**Organisation**	**E-mail**
Jonathan Schwieger*	First Climate	jonathan.schwieger@firstclimate.com
Urs Brodmann	First Climate	urs.brodmann@firstclimate.com

*Lead author

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Hydrogen; CCS; H_2-CCS chain; business model; business case framework; carbon price; climate policy; Switzerland; CO_2 Act; avoided emissions; carbon removals

Abstract

This report presents the application of the ELEGANCY WP3 business case assessment framework to the Swiss case study and resulting business model considerations for delivering low-carbon hydrogen in Switzerland's transport sector. The targeted application of the business case framework finds that key system-level investment barriers specific to the Swiss case study are primarily of policy and regulatory nature. In particular, regulatory drivers, market governance and sector coordination figure as prominent areas to address to foster large scale development of low-carbon H_2 production and end-use in the transport sector, as well as associated CO_2 transport and storage services.

In this context, the Swiss climate policy framework provides opportunities to incentivize the large-scale delivery and use of low-carbon hydrogen. Carbon pricing instruments in place enable the climate benefit of H_2-CCS chains to be monetized in three different instances along the pathway from H_2 production to end-use: emissions avoided at production (i.e. from fossil fuel feedstocks), carbon removals at production (i.e. from biogenic feedstocks with CCS), displacement of transport fuels (e.g. diesel fuel in trucks). The authors find that in each case the policy basis is in place, with applicable precedents sometimes available, but that important limitations exist. Furthermore, this framework is also found to deliver sufficiently high carbon prices for CO_2 storage in Switzerland, whereas adoption of the legislative package currently under revision would be needed to raise carbon prices sufficiently to enable CO_2 export and storage in the North Sea.

TABLE OF CONTENTS

Page

ABBREVIATIONS

ATR	Autothermal Reforming
BECCS	Bioenergy with Carbon Capture and Storage
CPG	CO_2 Plume Geothermal
DAC	Direct Air Capture
EAC	Energy Attribute Certificate
FOEN	Swiss Federal Office for the Environment
GHG	Greenhouse Gas
HFCEV	Hydrogen Fuel Cell Electric Vehicles
HRS	Hydrogen Refuelling Station
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ITMO	Internationally Transferred Mitigation Outcome
LCA	Life Cycle Assessment
LSVA	Performance-related heavy vehicle charge (*Leistungsabhängige Schwerverkehrsabgabe*)
PEM	Polymer Electrolyte Membrane
RE	Renewable Energy
RED	Renewable Energy Directive
SFOE	Swiss Federal Office of Energy
SMR	Steam Methane Reforming
SCCER	Swiss Competence Center for Energy Research
VPSA	Vacuum Pressure Swing Adsorption

1 INTRODUCTION AND OBJECTIVES

Work Package 3 (**WP3**) of ELEGANCY has developed a business case assessment framework applicable to any H_2-CCS case study or project to facilitate the development of suitable business models. WP3 has focused on providing the methodology, tools and guidance necessary to identify key barriers and gaps and determine the appropriate business model which works in the specific context of the country, rather than providing a recommendation on the ideal business model. The framework is therefore flexible and allows for customized use to fit the needs and stage of a project.

This Milestone report tests the WP3 business case framework on the ELEGANCY WP5 Swiss case study with the intention of delivering practical insights for policymakers in accelerating large-scale deployment of H_2-CCS chains in Switzerland. The report is structured in three parts:

I. **Overview of the business case framework and the scope of the Swiss case study:** the contents of the WP3 framework are presented and the focus of the Swiss case study described, along with a review of key results from Swiss WP5 project partners;
II. **Preliminary application of the business case framework to the context of the Swiss case study**: The tools and methods of WP3 are applied to the Swiss case study to identify market failures, business drivers, policy gaps and investments barriers;
III. **Considerations on business model configurations for the Swiss case study and applicability of carbon pricing instruments:** Options for delivering hydrogen for use to Switzerland are discussed along with the relevance of existing carbon pricing instruments for these business models.

The third section is particularly focused on identifying synergies with Switzerland's existing climate policy framework. Indeed, to deliver on the case study's goal of contributing to decarbonizing the transport sector by using clean H_2 with CCS – and contribute to the achievement of Switzerland's intended net-zero emission target by 2050 – business cases will need to account for the cost premium of producing this carbon-neutral/negative energy carrier. Carbon finance approaches and market mechanisms present opportunities for the private sector to monetize emission reductions – and ideally negative emissions – resulting from a broad uptake of clean H_2 in the transport sector. The present assessment therefore aims to evaluate in particular the applicability of existing carbon policy instruments in Switzerland at enabling this large-scale transformation of the transport sector.

2 CONTEXT

2.1 Business case framework (WP3)

2.1.1 Summary

The vision of ELEGANCY includes not only technical and scientific objectives, but also an ambition to investigate regulatory, commercial and market issues around H_2-CCS chains in order to accelerate their deployment. Within this scope, Work Package 3 (WP3) has developed a publicly available business case framework to identify and select suitable business models for H_2-CCS projects.

The framework comprises an assessment methodology, Excel-based analytical and visualization tools, as well as guidance papers, and is applicable to H_2-CCS projects broadly. A full description of the elements and approach of the framework are detailed in the relevant reports of WP3.[1] This section provides a high-level summary of the methodology and tools.

2.1.2 Methodology

The overall methodology developed by WP3 to select business models for H_2-CCS opportunities is presented in Figure 2-1. The process is divided into four distinct steps, from the definition of the case study scope to the selection of appropriate business models. A business case can be defined and assessed once a business model is selected. The ELEGANCY business case assessment methodology (presented in report D3.3.4) is therefore applied to business models chosen through the process described herein. As business model preferences can change with changing business contexts as well as with the maturity of a project, the combined selection and assessment process is iterative.

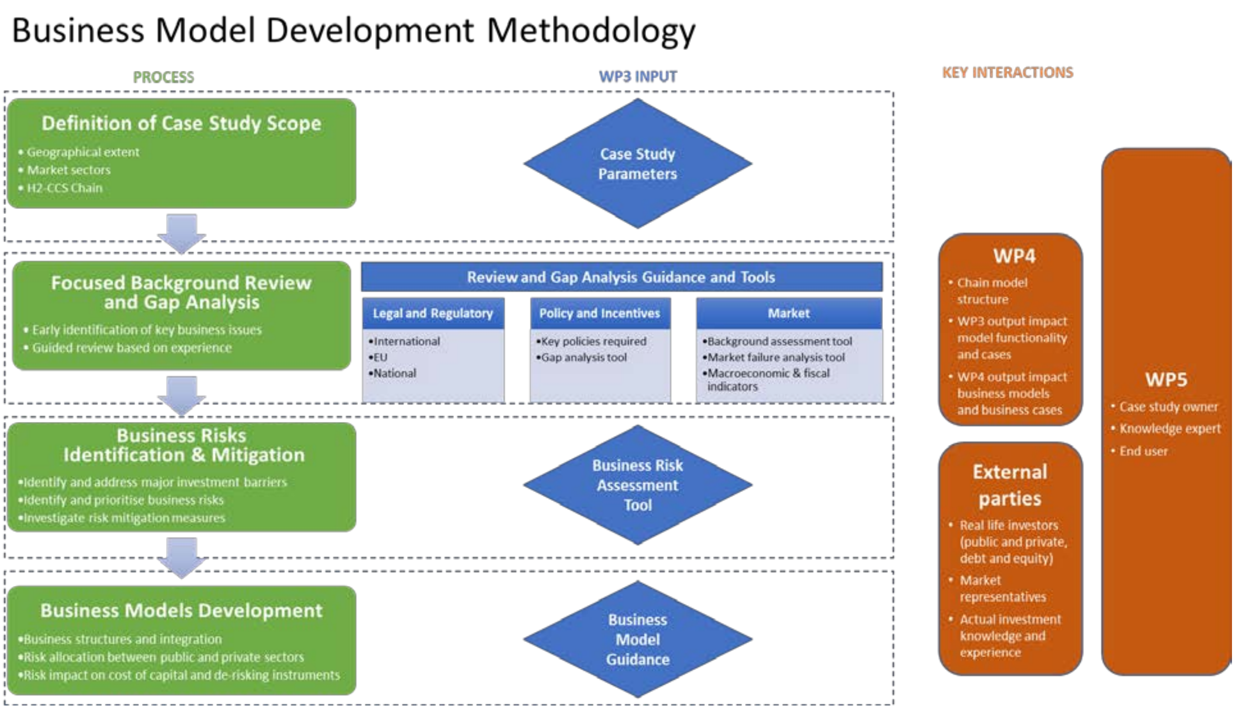

Figure 2-1: Business model development methodology. (Source: Sustainable Decisions Limited)

[1] ELEGANCY publications: https://www.sintef.no/projectweb/elegancy/publications/.

Step 1: *Definition of the scope of the particular H_2-CCS chain for the relevant case study*

The process commences with an initial focus on the specific H_2-CCS chain technical sub-components, business segments, and associated market sectors of main interest, the geographical extent (including industrial hubs, production facilities, storage areas, end-users, cross-border interactions, etc.), and market potential.

First Climate and Sustainable Decisions have created a standardised framework for any case study lead organisation to use in this first step that matches the needs of the scope definition exercise described above. This framework comprises the technology elements and market sectors, a H_2-CCS chain business tree, and an extensive set of potentially relevant case study parameters (described in Report D3.2.1). This framework and analysis are to be used side-by-side with the scenarios and quantitative estimates of market potentials undertaken in Work Package 5, Task 5.1 Interfaces, and reported in D5.1.1.

Step 2: *Focussed market background review and gap analysis*

The purpose of this second step is to guide an overall assessment of the market background for any case study in preparation for the third step of understanding the investability and handling of major business risks. The major barriers and business risks that are faced by potential developers and financiers in the H_2-CCS business chain have been identified by stakeholders to be non-technical, and robust economic scrutiny is essential for any large-scale infrastructure investment. Investing in, and delivering, low-carbon hydrogen using CCS at scale requires an understanding of the risks associated with government policy, market development, and regulatory frameworks.

A set of spreadsheet tools has been designed and produced, based on the project development experience gained over a number of years in countries such as The Netherlands, Norway and UK, to facilitate a simple high-level analysis of the major drivers for each of the H_2-CCS chain market sectors and business segments. The market background includes the legal and regulatory environment, the market fundamentals and applicable market failures, key macroeconomic drivers, the policy status and financial support mechanisms. An important aspect of this assessment method is the requirement to include thinking and review of the interactions between different market players reflected in the H_2-CCS chain business segments.

Step 3: *Business and investment risk identification and mitigation*

Based on the information gathered during step 2, the third step is to identify and quantify the major business risks that impact the level of investment potential for each of the market sectors and business opportunities from both a public and a private sector perspective. A bespoke risk assessment spreadsheet tool has been designed by Sustainable Decisions (Report D3.3.2 Appendix A.2) that can be applied to any individual or bundled business opportunities along the H_2-CCS chain selected from the standardised business tree.

Section 2.4 of report D3.3.2 describes the risk assessment methodology in more detail. In summary, assessable risks are divided into:

A. Investment barriers: these are circumstances or facts that raise the risk of detrimental investment outcomes to an unacceptable level for any type of investor. Generally, these barriers will affect multiple segments along the chain, or the whole chain, and require a ‘system view’ and multi-party (often in collaboration with government) approach to mitigation measures. These barriers need to be addressed in priority for any investment to be possible; and
B. Major business risks: these are risks that impact cost, revenue, liabilities, financing, schedule and therefore the risk/return equation for a final investment decision (FID). Individual businesses will generally be capable of mitigating these operational risks through familiar technical, commercial, insurance and other standard measures.

This step facilitates an early identification and prioritisation of risks to be addressed by a case study lead organisation and guide the subsequent communication and conversations with potential private investors and public/government organisations.

Step 4: *Business model development*

The fourth step in the method focuses on how to remove the investment barriers and mitigate business risks and to select appropriate business models for any given case study. Chapters 4-7 of Report D3.3.2 deal with the principles and elements used in the methodology. Report D3.3.3 completed the methodology with a description of the business model selection process, its relationship with preparing and assessing a business case, and a business model selection tool. When applied to case studies, the outcome will be the development of a number of viable commercial structures and business models, investigating the potential investor mix and the allocation of risks between those investors for each of the market opportunities, the de-risking mechanisms required from the financial and carbon markets and from the EU and national governments.

2.1.3 Toolkit

The content of the ELEGANCY Business Case Development Toolkit is presented in Figure 2-2 and comprises the various spreadsheets developed to accompany the business development methodology and steps described previously. The toolkit uses heatmaps and matrices for the display of complex data and information relationships to assist in visualizing the results.

The toolkit is made available for any case study lead organisation to use towards identifying key investment issues for the project and applicable commercial structures. As every case study or project is different, both in scope and level of maturity, the tools are intended to be flexible and customizable to suit specific purposes.

The toolkit is released under the Creative Commons Attribution NoDerivs (CC BY-ND). It can be found on the ELEGANCY website at:

https://www.sintef.no/projectweb/elegancy/programme/wp3/business-case-development-toolbox/

Process step:	Available tools:	What is assessed?
Business Context	Market background assessment	Country context (macroeconomic, fiscal, climate policy), market players and interactions, business drivers
	Market failures analysis	Presence of market failures, extent of the market failures
	Policy and financial support gap analysis	Availability of relevant policies and financial support, level of policy implementation
	Policy needs heatmap	Demand intensity for relevant policies, gaps in policy coverage
Business Risk Identification & Assessment	Risk assessment	Investment barriers and business risks, impacts of the risk, quantification of the risks, mitigation measures
	Risk mitigation heatmap	Demand intensity for risk coverage, availability and types of risk mitigation measures, gap in risk mitigation coverage
Business Model Development	Business model selection	Business model drivers, potential business models at system and individual sector level, engagement and collaboration between public sector and private sector
Business Case Development & Assessment	Business case definition and assessment	Business case definition and assessment (strategic rationale, financial costs & benefits, economic value & benefits, commercial delivery, technical delivery, outcome management)

Figure 2-2: ELEGANCY WP3 Business Case Development Toolkit. (Source: First Climate)

2.2 Swiss case study (WP5)

2.2.1 Objective of the case study

The Swiss case study is led by ETH Zurich with contributions from PSI, Climeworks, and First Climate. It aims to demonstrate the key role of H_2 and CCS in addressing the following three challenges:

1) Enabling the efficient generation of emission-free hydrogen – including from biomethane – as a means to **decarbonize the transport sector**;
2) preparing the way for a CO_2 storage site and thereby advancing **sustainable geo-energy processes**; and
3) paving the way for solutions that can remove CO_2 from the atmosphere, i.e. enable **negative CO_2 emissions**.

2.2.2 Scope of the case study

Transport currently accounts for 24% of global CO_2 emissions.[2] In Switzerland, where electricity is mainly generated from hydropower and nuclear, as much as 40% of total domestic emissions in 2018 (including international aviation and shipping) are transport-related.[3] The mobility sector is the one causing the highest greenhouse gas emissions in Switzerland and is among the few energy-related sectors with emissions higher than in 1990.

Reducing these emissions has been challenging in the past and is currently achieved via offsetting. By the end of 2020, 10% of the transport fuel related emissions are to be compensated through domestic emission reduction credits. The revised Swiss CO_2 Act – proposed by the Federal Council in 2017 and undergoing parliamentary debates in both Chambers as of August 2020 –

[2] IEA (2020): Tracking transport 2020. https://www.iea.org/reports/tracking-transport-2020.

[3] Federal Office for the Environment FOEN (2020): Switzerland's Greenhouse Gas Inventory 1990-2018.

foresees to raise the domestic compensation requirement to at least 15%, with higher thresholds also possible depending on the outcome of the revisions.[4]

In aggregate, the draft CO_2 Act foresees a total offsetting requirement of up to 90% by 2030 where the balance to the domestic requirement would need to be covered through offsets from international projects. Given the uncertain supply of such offsets beyond 2030 and the Paris goals, it is generally recognized that further reductions through technology switch and behavioural change are key for transport decarbonization in the medium and long term.

Using hydrogen in fuel cell vehicles – especially for heavy transport such as lorries and buses – may be a promising technology option. However, such fuel cell vehicles can only contribute to decarbonization of the transport sector, if hydrogen production does not cause any substantial greenhouse gas (GHG) emissions. The case study uses natural gas and organic feedstock as a starting point for hydrogen production:

- Natural gas and biomethane would be reformed in a steam reformer with CO_2 capture, applying newly developed (VPSA) technology for the single cycle purification of hydrogen and CO_2;
- Solid biomass would be gasified, after which the product gas is to be cleaned of contaminants and CO_2 and hydrogen purified (with CO_2 capture), likely also with the VPSA technology.

By using biomass as a feedstock for producing H_2 with CO_2 capture, net-negative emissions are achieved – provided the captured CO_2 is stored permanently. Other approaches for removing CO_2 from the air are also considered, i.e. direct air capture (DAC), where Switzerland demonstrates the worldwide first commercial direct air capture plant. Enabling such negative emission technologies is critical for Switzerland's plans to achieve net-zero carbon emissions by 2050. While this long-term target is indicative and not enshrined in the revisions to the Swiss CO_2 Act (which covers the period until 2030), it is a declaration of intent by the Swiss Federal Council to meet the internationally agreed target highlighted by the Intergovernmental Panel on Climate Change (IPCC) of limiting global warming to a maximum of 1.5°C when compared with the pre-industrial era.[5]

The value chain in the case study is complemented with a full hydrogen and CO_2 transmission network, and hydrogen refuelling stations (HRS). The investigation of CO_2 storage sites is also undertaken, alongside the development of deep geothermal energy, as recommended by the Swiss Energy Strategy 2050 and the Swiss roadmaps for CCS[6] and deep geothermal energy development[7]. Accordingly, multiple storage options are considered: storage in a saline aquifer in Switzerland; exporting the CO_2 to countries with high storage capacities in depleted oil and gas fields (e.g. in the EU); putting it to use in CO_2 plume geothermal (CPG) energy generation, whereby the CO_2 is simultaneously stored and used as a working fluid for geothermal electricity

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[4] Swiss Parliament (2020): Totalrevision des CO2-Gesetzes nach 2020, Sommersession 2020. https://www.parlament.ch/centers/eparl/curia/2017/20170071/N3%20D.pdf.

[5] Federal Council (2019): Federal Council aims for a climate-neutral Switzerland by 2050. https://www.admin.ch/gov/en/start/documentation/media-releases.msg-id-76206.html.

[6] Mazzotti, M., Burdet, A., Curdin, C., Diamond, L., Häring, M., Leu, W., . . . Zappone, A. (2013): Roadmap for a CCS pilot project in Switzerland. Bern, Switzerland: Swiss Federal Office of Energy.

[7] Evans, K., Wieland, U., Wiemer, S., & Giardini, D. (2014): Deep Geothermal Energy R&D Roadmap for Switzerland. Zurich, Switzerland: Swiss Competence Center for Energy Research - Supply of Electricity.

production cycles. For this reason, the case study also favours the decarbonization of Swiss building stock, which accounts for another 24% of total CO_2 emissions in Switzerland,[8] through increased use of geothermal energy replacing natural gas.

2.2.3 Key messages from interim modelling results

Techno-economic modelling performed by Swiss consortium partners (i.e. ETH, PSI) at the energy system level has provided key insights to date into H_2 and CCS technology deployment pathways to decarbonize the Swiss energy system, including the transport sector. Modelling activities have compared two core scenarios: continuation of existing trends (baseline scenario) and achievement of the goals of the Swiss energy and climate strategy, i.e. net zero emissions in 2050 (climate scenario).[9] In each scenario, the full Swiss energy system from resource supply to energy end uses is considered – factoring in interconnections with energy import / export partners (i.e. EU) – within a least-cost optimization framework over a multi-decade time horizon.

Coupled with this technical modelling, assessments of life cycle impacts of various combinations of hydrogen and CCS technologies were also performed. Various impact categories were considered, including climate change (i.e. CO_2e), but also ecosystem quality, human health, and resources.

Key qualitative outcomes of relevance for the application of the business case framework are summarized in the next sections.

2.2.3.1 H_2 production

Switzerland will likely be required to develop low-carbon domestic hydrogen production capabilities, such as renewable energy electrolysis but in particular from biological sources (e.g. biomass gasification, biomethane reforming). Indeed, achieving net-zero emissions for the country in 2050 requires deploying at scale negative emissions technologies capable of delivering permanent removals of CO_2. Only then may emissions from ‘hard to abate’ sectors such as cement (approx. 4% of domestic emissions in 2018)[10] be balanced out. Life cycle assessments (LCA) results of H_2 production from biomethane confirm negative emissions are achievable using CCS, on the order of -0.3 to -0.5 tCO_2e/MWh H_2.[11]

Enabling domestic ‘carbon negative’ hydrogen production for use in the transport sector, but also possibly in other sectors such as industry, can therefore play a critical role in Switzerland’s decarbonization strategy. In the alternative, relying exclusively on imports of H_2 from the EU or beyond will likely provide at best a carbon neutral energy carrier but will not deliver negative

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[8] Federal Office for the Environment (2020): Climate: In Brief. https://www.bafu.admin.ch/bafu/en/home/topics/climate/in-brief.html.

[9] Variants of the climate scenario were also examined in the modelling, comprising different socioeconomic development levels (e.g. GDP and population growth), different hydrogen market support schemes and structures (e.g. supply measures such as subsidies in H_2 supply infrastructure, or H_2 demand boosting measures such as taxes on fossil fuels), and different H_2 technology developments (e.g. increased learning via (worldwide) R&D infusions). The ranges reported in this section incorporate the variations due to these different socioeconomic, market and technology development conditions. More details regarding the context of the variants and the relevant analysis can be found in the corresponding deliverable D5.3.6.

[10] Indirect emissions from cement production. Cf footnote n°3.

[11] See Report D5.3.1, also published as Antonini, C., Treyer, K., Streb, A., van der Spek, M., Bauer, C., Mazzotti, M. (2020): Hydrogen production from natural gas and biomethane with carbon capture and storage – a techno-environmental analysis. Sustainable Energy Fuels, 2020, 4, 2967.

emissions for Switzerland's GHG inventory as any negative emissions generated would presumably be accounted abroad, unless the import of H_2 is coupled with the import of carbon credits (Internationally Transferred Mitigation Outcomes, ITMOs) generated through capture and permanent storage of biogenic CO_2 (see Section 4.2.2).

Biogenic feedstocks face, however, supply constraints as domestic biomass availability is limited. For instance, the theoretical maximum production potential of biogas from agricultural biomass and renewable waste in Switzerland is estimated at 6.6 TWh, of which only 3.7 TWh could be practically and cost-effectively fed into the gas grid.[12] In comparison, current natural gas demand amounts to 30 TWh.[13] Supplying hydrogen in Switzerland will thus require deploying a portfolio of production technologies, including biomass gasification and biomethane reforming, as well as fossil methane reforming and renewable energy electrolysis. By 2050, in a net-zero scenario, hydrogen production capacities are estimated to be 10-20 TWh/a.

The scale (i.e. capacity) and location of individual production units deployed will need to accommodate for the specifics of the various technologies, feedstock availability and regional variability of H_2 demand. The modelling factors in an evolution in the production mix until 2050 to account for changing conditions such as the tightening emissions budget, leading to a move from steam methane reforming (SMR) in 2030-2040 to greater prevalence of renewable energy electrolysis by 2050. Thus, H_2 production may start as centralized but become more decentralized over time.

2.2.3.2 H_2 demand

Overall, H_2 is anticipated to account for a rather small portion of final energy consumption across all sectors in Switzerland in 2050 (approx. 10%). In the transport sector specifically, modelling results show expected H_2 consumption accounting for 20-40% of energy requirements (the balance comprises primarily electric vehicles and biofuels-based vehicles). However, the mobility sector will be responsible for 50% of hydrogen demand in Switzerland by 2050, the rest stemming from other sectors modeled (i.e. residential & commercial building heat, industry).

2.2.3.3 CO_2 storage

Uncertainty remains regarding the underground storage capacity for CO_2 in Switzerland, and whether structures capable of storing large amounts (>10 $MtCO_2$) are present. The modelling therefore considers an overall domestic potential of 50 $MtCO_2$ with limited storage by 2050 (~1-2 $MtCO_2$).

To store the CO_2 resulting from hydrogen production – but also captured from other sources (e.g. industry, DAC) to ensure sufficient removals for achieving the 2050 net-zero target – Switzerland will need to rely on transport infrastructure in the EU to access storage hubs abroad such as in the North Sea. The majority of total CO_2 captured domestically – amounting to 9-12 $MtCO_2$/a in 2050 – will therefore need to be stored abroad in this way.[14] Of this total, CO_2 captured from hydrogen production is estimated at 2-3 $MtCO_2$/a in 2050.

[12] E-CUBE Strategy Consultants (2018): Einspeisepotenzial von erneuerbarem Gas in das Schweizer Netz bis 2030. https://www.endk.ch/de/ablage/dokumentation-archiv-muken/BiogazSuisse_Rapport_D.pdf.

[13] Energie Zukunft Schweiz (2019): White Paper Erneuerbare Gase – Ziel 2030: Anteil erneuerbarer Gase 30% im gasversorgten Wärmemarkt für Gebäude, (1) Aktuelle Herausforderungen. https://energiezukunftschweiz.ch/de/Knowhow/News/Newsaktuell/2020-02-03-white-paper-serie.php.

[14] Panos, E., et al. (2020) to be published.

3 PRELIMINARY APPLICATION OF THE BUSINESS CASE FRAMEWORK

3.1 Scope of framework application

The ELEGANCY WP3 business case framework and associated toolkit is made available as a structured but flexible and customizable resource to H_2-CCS project proponents. The scope of its application to a specific project is intended to be tailored to fit with the project's characteristics. For projects already in planning stage, e.g. with initial feasibility plans and targets, stakeholder maps, and/or financial analyses, a full application of the framework is encouraged to merge public and private sector perspectives on allocation of risk mitigation responsibilities, business model preferences, and alignment of the project with the defined business case. Conversely, for case studies at earlier or conceptual stages of development, such as the Swiss case study, the framework is well-suited to assist in forming a view of existing barriers and gaps and navigating initial business model considerations.

A targeted application – as opposed to a full application – of the business case framework has therefore been favoured in the context of the Swiss case study. Business drivers, market failures and policy gaps for decarbonizing the road transport sector are assessed using the toolkit. A focus is also placed on developing an initial understanding of critical investment barriers[15], in order to form a view on the investability of this proposition. As opposed to business risks, which can generally be mitigated by individual businesses through familiar technical, commercial, insurance and other standard measures, investment barriers affect the H_2-CCS chain at a system level (i.e. across several elements of the chain) and cannot typically be mitigated by the private sector alone. These barriers need to be addressed in priority for any investment to be possible.

Based on these assessments and the interim modelling results by Swiss case study partners (see Section 2.2.3), indicative business model configurations are then sketched. These configurations illustrate different scenarios for delivering the H_2-CSS chain in Switzerland.

3.2 Business context

3.2.1 Business sectors

To visualize the elements of the H_2-CCS chain covered by the Swiss case study, we use the ELEGANCY WP3 flow sheet described in Report D3.2.1. This flow sheet, presented in Figure 3-1 below, highlights the various business options (infrastructure services and end-use markets) along the H_2-CCS value chain. Activities on the left-hand side represent the supply side, while the use-cases on the right-hand side represent the demand side. The two sides are connected by the logistics network for natural gas, hydrogen, and CO_2. All activities are within the country's national borders and commodity flows can either stem from or end in other European countries, or countries outside Europe.

The Swiss case study (hatched green highlights in Figure 3-1) focuses primarily on low-carbon H_2 production from biogenic feedstock to enable negative CO_2 emissions. The primary intended end-use market for H_2 is in the mobility sector, with domestic transport and distribution of hydrogen to refuelling stations. CO_2 on the other hand, is in large part exported with some minor domestic storage/utilization. In summary, the H_2-CCS business sectors covered are:

[15] Cf Section 2.1.2 for a description of the two types of assessable risks (investment barriers and business risks) considered in the business case framework methodology.

- H_2/CO_2 end-use markets:
  - H_2 use in road freight & passenger transport sector
  - CO_2 use as working fluid for geo-energy applications with storage potential
- H_2/CO_2 infrastructure services:
  - Centralized & decentralized production of H_2, by
    - reforming of natural gas or biomethane with/without CCS
    - gasification of biomass with/without CCS
    - renewable energy (RE) electrolysis
  - (H_2 import from other European countries)
  - H_2 transport (pipeline/rail/road) & distribution to end-users (hydrogen refuelling station network)
  - Intermediate (intra-seasonal) storage of H_2
  - Direct air capture of CO_2
  - CO_2 transport (pipeline/rail/road) for export and storage in other European countries
  - Domestic permanent geological storage of CO_2

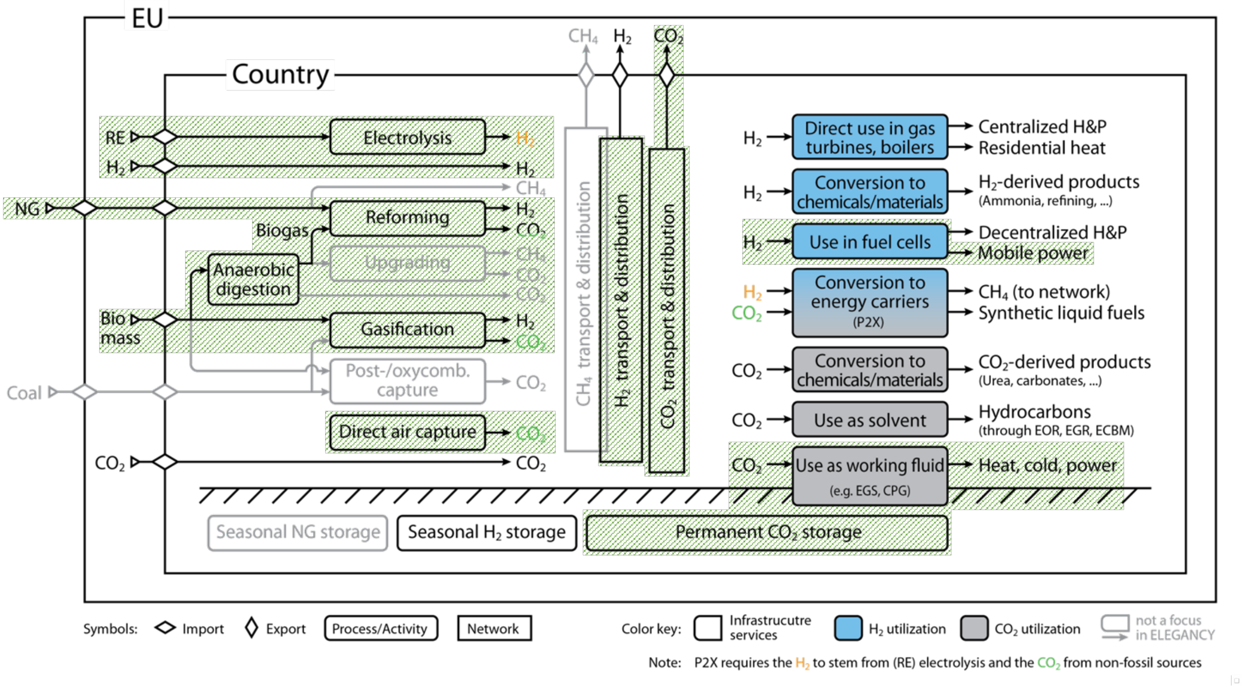

Figure 3-1: H_2-CCS chain flow-sheet: scope of ELEGANCY project and scope of the Swiss case study (hatched green highlights). (Source: First Climate)

3.2.2 Business drivers and market failures

In Report D3.2.1, we applied two tools in the ELEGANCY business case framework – “Market Background Assessment” and “Market Failures” – to the Swiss case study as an initial assessment of the current business context. Inputs to complete the tools were obtained through discussions with ELEGANCY project partners and select external participants. The following sections recap the outcomes of these assessments. For more detailed information beyond the highlights presented, see the D3.2.1 report.

3.2.2.1 Business drivers

The Market Background Assessment tool aims to facilitate a qualitative assessment of the prevailing business drivers for the H_2-CCS chain business sectors of a given case study. The assessment of business drivers provides valuable insights into prevailing market dynamics (or lack thereof) for a specific H_2-CSS chain segment – basis upon which further background assessment tools in the toolkit can build to identify market failures and policy gaps.

A summary of the results from the application of the tool is provided in Table 3-1, and the list of business drivers considered are listed in Box 3-1. Currently, H_2 utilization in the mobility space – although very limited to date – can be seen as primarily driven by social preferences (e.g. environmental or sustainability consciousness). Some regulatory drivers are also noteworthy, such as the exemption from performance-related heavy vehicle charges (LSVA) for heavy vehicles with electric propulsion (including H_2 fuel cells vehicles), and, to a lesser extent, vehicle emission standards, which are to be strengthened as part of the ongoing revisions to the CO_2 Act. In terms of the H_2 and CO_2 infrastructure services, the few niche markets present (e.g. hydrogen refuelling stations, hydrogen from RE electrolysis, direct air capture of CO_2) are similarly driven by stakeholder preferences but also anticipation of future markets and technological advances.

Table 3-1: Level of maturity of relevant H_2-CCS business sectors in Switzerland at present, and key drivers of these business sectors. (Source: market background assessment tool: First Climate; content for Swiss case study: collected by First Climate)

H_2-CCS business sectors	**Maturity**	**Key business drivers for currently active sectors**
H_2/CO_2 end-use markets:		
H_2 in mobility	**Niche**	Environmental consciousness and social preferences of users, climate and energy policy
CO_2 as working fluid in CPG	**Not present**	n/a
H_2/CO_2 infrastructure services:		
H_2 production (reforming, gasification) w/ CCS	**Not present**	n/a
H_2 production by RE electrolysis	**Niche**	Anticipation of future markets, stakeholder commitments
H_2 transport & H_2 distribution to end-users (HRS)	**Niche**	Anticipation of future markets, stakeholder commitments, climate and energy policy
H_2 storage (intra-seasonal)	**Not present**	n/a
CO_2 direct air capture	**Niche**	Anticipation of future markets, stakeholder commitments, technological advances
CO_2 transport	**Not present**	n/a
CO_2 domestic geological storage	**Not present**	n/a

Box 3-1: List of business drivers considered.

- Price for H_2, CO_2 products or services
- Commodity price fluctuations
- Fiscal advantages
- Carbon pricing mechanisms
- Other regulations (e.g. technical standards)
- Stakeholder commitments
- Clustering
- Technological advances
- Anticipation of futures markets
- Environmental consciousness of consumers
- Social acceptance/preference

3.2.2.2 Market failures

ELEGANCY WP3 has defined a number of generic market failures with the potential to impede the development of H_2-CCS markets. The Market Failures tool is designed to facilitate an identification of relevant market failures and to assess the severity of their effect, impact or consequence on the market or business segment targeted in the H_2-CCS chain. A key focus of the project should then be on addressing the areas with the greatest market failures.

A summary of the results from the application of the Market Failures tool is provided in Table 3-2, illustrating the market failures that were found to be of importance (see definitions of these market failures in Box 3-2).[16] As expected for the Swiss case, the analysis aptly captures the broad absence of H_2/CO_2 end user markets and infrastructure services in the country. Indeed, with the exception of niche markets for H_2 distribution and use for mobility as well as pilot installations on the direct air capture side, the heat map is unequivocal: missing markets are critical market failures across the board. Completing the picture, CO_2 price signals are currently assessed as insufficient in scope (i.e. type of activities covered) and level to stimulate swift and broad adoption of H_2/CO_2 storage technologies. Of note as well is the respondents' perception that coordination failure and knowledge spillover in H_2-CCS infrastructure is an inhibitor of investment in the sector.

Box 3-2: Definition of relevant market failures.

Missing market: No demand/market exists for the goods or services, thus creating a lack of price signals and preventing investment or even business interest in the activity.

Coordination failure: Investment and business activities are dependent on synchronised or coordinated planning, design, financial investment decisions and construction in other related activities in order to mitigate counterparty or stranded asset risk. No coordination results in no market activity.

Negative externality: Insufficient carbon price signal exists to effectively value the environmental impact of emissions and as a consequence impacts negatively investment interest in low carbon technologies or market-making activities.

Location immobility: H_2-CCS infrastructure is highly location dependent (e.g. geological storage of H_2 and CO_2, pipeline corridors, industrial clusters) - this is a significant cost constraint for broader deployment. The free market won't deliver beyond locational preferences without government intervention.

[16] In a few cases, results shown differ from those in Report D3.2.1 as the ratings were refreshed to account for new developments since the D3.2.1 was published.

(Definition of relevant market failures, continued)

Knowledge creation spillover: There is a significant risk that third parties and competitors can benefit from the investment made by first movers and innovators in both end-user markets and across the H_2-CCS chain, thus creating disincentives for taking risks in the early investment and market-making activities

Table 3-2: Key market failures in the Swiss case study and their extent. Rating are from low to high in terms of the severity of their effect, impact or consequence on the market or business segment in the H_2-CCS chain. (Source: market failures assessment tool: Sustainable Decisions Limited; content for Swiss case study: collected by First Climate)

H_2-CCS business sectors	**Market failures**				
	Missing market	**Coordination failure**	**Negative externality (low -priced CO_2)**	**Location immobility**	**Knowledge creation spillover**
H_2/CO_2 end-use markets:					
H_2 in mobility	medium	high	high	low	medium
CO_2 for CPG	high	low	medium	medium	medium
H_2/CO_2 infrastructure services:					
H_2 production (reforming, gasification) w/ CCS; H_2 production, RE electrolysis	high	high	high	medium	high
H_2 transport	high	high	high	low	medium
H_2 distribution to end-users (HRS)	medium	high	high	low	medium
H_2 storage, intra-seasonal	high	high	high	high	medium
CO_2 DAC	medium	high	high	medium	high
CO_2 transport	high	high	high	medium	high
CO_2 storage	high	high	high	high	high

3.2.3 Policy needs

The remaining business context tools ("Policy Gap Analysis Tool" and "Policy Needs Heatmap") enable an assessment of the policy landscape relevant to H_2-CCS chains and a visualization of priority policy needs for delivering the case study. These tools were applied – resulting in the heatmap displayed in Figure 3-2 – following a desk-based review performed by the authors of the existing domestic climate and energy policy as well as latest commercial developments in the most relevant sectors (H_2 infrastructure services, CO_2 infrastructure services, H_2 end-use market in the mobility sector). The main policy gaps displayed in the heatmap below constitute barriers to private sector investment and should be a key focus for government intervention.

Through its carbon and energy policy, Switzerland pursues a technology-neutral approach to achieve its climate ambition. Policies are in place to promote a low-carbon transition in the transport sector but without actively singling out hydrogen over other technologies. To date, these instruments (e.g. CO_2 compensation requirement for importers of fossil transport fuels, LSVA, vehicle emission standards) have not directly led to significant activity in the hydrogen mobility sector – but some commercial activity is starting to materialize. A notable private sector initiative is driven by the H_2 Mobility Switzerland Association, which brings together key stakeholders with the aim of rolling out an HRS network supplied by domestic green hydrogen production and a fleet of Hyundai fuel cell electric trucks (target of 6 operational stations and 50 trucks by the end of 2020[17]). The truck fleet will qualify for exemption from the LSVA, thus improving their cost-competitiveness against internal combustion engine (ICE) trucks. This initiative is encouraged by public authorities, but not mandated in coordination with an official national deployment strategy. Indeed, in contrast to the EU, or its neighbours, Switzerland has not developed a hydrogen strategy or deployment plan as a roadmap for long-term planning and coordination.[18]

On the CCS infrastructure side, development of the sector also faces policy needs. Namely, the Swiss CO_2 Act is generally silent on geological storage of CO_2 and only refers to sinks from timber used in construction. The CO_2 Act is however currently under revision and in its new form may alleviate some of these restrictions. Underground storage of CO_2 also lacks a clear and self-contained "CCS" regulatory framework, akin to the EU's CCS Directive. Coverage of relevant topics (e.g. permitting) is currently fragmented and spread among various Acts and Ordinances, or not regulated at all.[19] Beyond these critical investment barriers, further targeted policies are also needed, e.g. funding for pilot and demonstration projects.

At the international level, rules for transfers of negative emissions would be needed if Switzerland were to claim any biogenic carbon sequestration realized in third-party countries (e.g. Norway) towards its domestic GHG inventory. Currently, the rulebook for transfers of emission reduction under Art. 6 of the Paris Agreement is still under development, especially for the centralized channel under Article 6.4. Other EU- and international-level policy needs – such as clarifying the regulatory framework for cross-border transfers of CO_2, for instance through a commonly agreed interpretation of the *Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal* and its application to CO_2 transport – are covered in the regulatory and legal background in D3.2.1 and D3.1.1.

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[17] H_2 Mobility Switzerland Association (2020): https://h2mobilitaet.ch/en/bertrand-piccard-launches-hydrogen-electric-mobility-in-switzerland/.

[18] EU's "Hydrogen Strategy" (2020): https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12407-A-EU-hydrogen-strategy.

Germany's "National Hydrogen Strategy" (2020): https://www.bmbf.de/files/bmwi_Nationale%20Wasserstoffstrategie_Eng_s01.pdf.

France's "Hydrogen Deployment Plan for Energy Transition" (2018): https://www.ecologique-solidaire.gouv.fr/sites/default/files/Plan_deploiement_hydrogene.pdf.

[19] Federal Office of Energy (2013): Roadmap for a Carbon Dioxide Capture and Storage pilot project in Switzerland. https://docplayer.org/25675589-Roadmap-for-a-carbon-dioxide-capture-and-storage-pilot-project-in-switzerland.html.

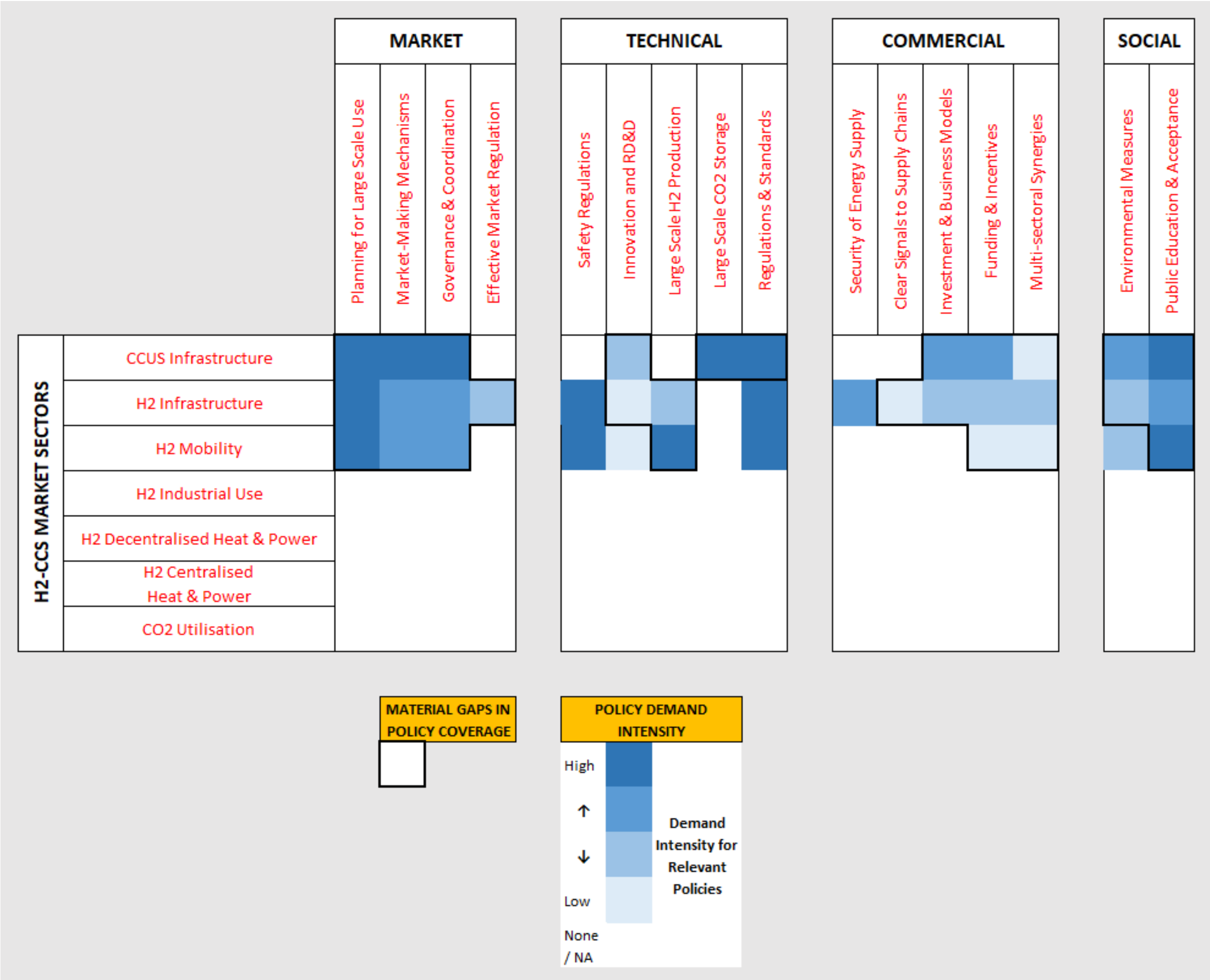

Figure 3-2: Policy needs heatmap for the Swiss case study. (Source: policy needs heatmap tool: Sustainable Decisions Limited; content for Swiss case study: collected by First Climate)

3.3 Investment barriers

Based on the business context assessment and an understanding of business drivers, market failures, and policy needs relevant to achieving the Swiss case study's goals, we derive a list of key system-level barriers inhibiting large-scale commercial activity in H_2-CCS chains in Switzerland.

For this purpose, the framework of the "Risk Assessment Tool" is partially applied, limited only to an identification of investment barriers[20]. A more detailed use of the tool (e.g. assessment of business risk, quantification of the risks, identification of mitigation measures) is beyond the scope of this preliminary application of the toolkit but could be warranted at a later stage beyond the ELEGANCY project once the Swiss case study has been refined to concrete sets of actions and outcomes.

The tool defines several risk/barrier categories, of which the relevant one for the assessment are described in Box 3-3. Using this categorization, we find that key investment barriers specific to the Swiss case study are primarily of policy and regulatory nature. The list below encapsulates

[20] Cf Section 2.1.2, Step 3, for a definition of investment barriers.

these prominent areas where government interventions would be required to facilitate market creation and enable self-sustaining markets for hydrogen mobility and CCS.

- Political, policy and social:
  - Uncertainty around Switzerland's non-binding 2050 net-zero emissions goal prevents firm commitments to negative emissions technologies;
  - In its current form the Swiss CO_2 Act is silent on technical carbon sinks and as a result the related Ordinance does not allow technical sinks as mitigation measures;
  - Lack of harmonized and self-contained regulation for carbon capture and storage providing a basis for activities such as commercial site selection, permitting, etc.;
  - No publicly driven long-term planning and coordination for hydrogen sector development in Switzerland;
  - Uncertainty as to whether Switzerland intends to accept international transfers of negative emissions generated through CO_2 removals (e.g. related to biogenic CO_2 captured in and exported from Switzerland);
  - Temporary policy incentives such as exemption of H_2-propelled vehicles from distance-related charges (LSVA) should be replaced by permanent incentives such as a sufficiently high carbon price.
- Technical and physical:
  - Uncertainty regarding the underground storage capacity for CO_2 in Switzerland, and whether structures capable of storing large amounts (>10 $MtCO_2$) are present.
- Market and commercial
  - Missing markets for domestic CO_2 capture, transport and geological storage;
  - Missing (or only niche) markets for hydrogen mobility and low-carbon H_2 production.

Box 3-3: Definition of relevant risk/barrier categories.

Political, policy and social risks: These risks derive from both the legitimate actions of authorities exercising their legislative functions in the interest of the public (policy/regulatory risks), and illegitimate and discriminatory acts by authorities and citizens, and political violence and instability

Technical and physical risk: These risks derive from the physical characteristics of the assets and/or the surrounding environment.

Market and commercial risks: These risks derive from the action of markets and commercial counterparties, the economic value of the output (price, volume) and the financial dimension (cost and availability of capital, liquidity)

4 BUSINESS MODEL CONSIDERATIONS FOR THE SWISS CASE STUDY AND APPLICABILITY OF EXISTING CARBON PRICING INSTRUMENTS

4.1 Overview of business model configurations for H_2 production

The application of the WP3 business case framework to the Swiss case study has identified key system-level issues and bottlenecks facing deployment of H_2-CCS chain elements in Switzerland. In particular, regulatory drivers, market governance and sector coordination figure as prominent areas to address to foster large scale development of low-carbon H_2 production and end-use in the transport sector, as well as associated CO_2 transport and storage services. In certain elements of the chain, private sector-led efforts have been successful to date in initiating niche commercial activities, namely Climeworks' direct air capture plant and H_2 Mobility's roll out of a fleet of Hyundai fuel cell electric trucks and a HRS network supplied by domestic green (renewable energy electrolysis) hydrogen production. However, to achieve Switzerland's stated net-zero ambitions by 2050, accelerated deployments will be critical.

The Swiss climate policy framework comprises a robust set of complementary instruments, in place since 2008, which play an important role in this regard. Through a price on emissions avoided or removed, the cost premium of clean H_2 could be compensated and the competitiveness of this technology improved. Pricing instruments regulate all – but to varying extents – high emitting sectors in Switzerland: emissions from stationary installations in the industrial and building sector are covered by a carbon levy on heating fuels or, where applicable, an emissions trading system, whereas fuel consumption in the transport sector is subject to an offsetting requirement placed on importers of fossil transport fuels. Additional policies include vehicle emission standards, petroleum tax relief for biogenic fuels, as well as an exemption from performance-related heavy vehicle charges (LSVA) for heavy vehicles with an electric propulsion. Together, these seek to incentivize a technology-neutral transition to a low-carbon economy.

Fitting with the WP3 business case framework theme of business model selection, but yet in a departure from the formal methodology, we assess in this chapter how these existing technology-neutral climate policy and carbon pricing instruments specifically support the large-scale delivery and use of low-carbon hydrogen in the Swiss case study or where gaps exist to be effective in this sense. From the system-level focus in Chapter 3, we therefore move to considering specific elements of the chain in this chapter.

To do so, we first develop a logical view of possible pathways for delivering hydrogen to Switzerland's transport sector. A flow-chart format is used for this representation with four decision points (see Figure 4-1):

i. **Location of H_2 production:** in Switzerland or abroad;
ii. **Type of H_2 production process:** fossil feedstock reforming/gasification, biogenic feedstock reforming/gasification, renewable energy electrolysis;
iii. **Use of carbon capture:** yes or no;
iv. **Location of CO_2 storage:** in Switzerland or abroad (e.g. EU/EEA).

These "business model configurations" cover the spectrum from full dependence on third-party countries for delivery of H_2 to full self-sufficiency. While they portray the production of H_2, they do not distinguish between transport or distribution modes of hydrogen nor of CO_2 (i.e. road/rail/pipeline). Each option also comes with various levels of climate impacts from the perspective of Switzerland's GHG emissions inventory: climate-negative (i.e. resulting in GHG emissions), net-zero (i.e. no net GHG emissions), and climate-positive (i.e. negative emissions generated).

When overlaid with constraints of the existing business context (see sections 2.2.3 and 3.2) it becomes clear that no single business model configuration will suffice but that several configurations will need to be operational simultaneously. For instance, H_2 production from biogenic feedstock with CCS is the only technology capable of delivering negative emissions but availability of domestic biomass is limited in Switzerland and it will need to be complemented in the medium-term by other H_2 production routes.

Consideration is also given to the use of H_2 later in this chapter.

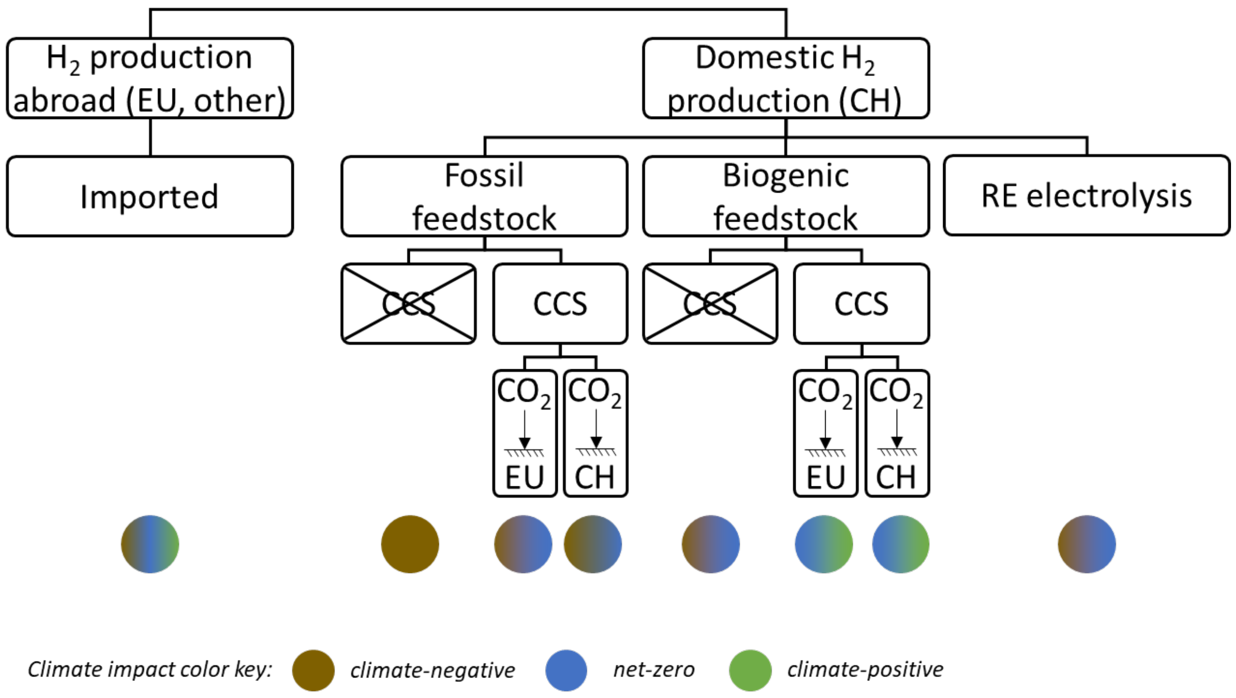

Figure 4-1: Business model configurations for H_2 production in the Swiss case study, including location of production (in Switzerland or abroad), type of production process (fossil feedstock reforming, biogenic feedstock reforming/gasification, renewable energy electrolysis), use of carbon capture (yes/no) and location of CO_2 storage (in Switzerland or in the EU). Climate impact of each configuration is indicated using the color key provided, and color combinations denote an impact range. (Source: First Climate)

4.2 Carbon pricing instruments for monetizing avoided emissions and carbon removals from H_2 production and end-use

4.2.1 Avoided emissions in stationary installations with fossil fuel combustion

Fossil fuel combustion in stationary installations is fully regulated under the Swiss CO_2 Act. This includes domestic H_2 production from fossil feedstocks – such as natural gas reforming facilities (steam methane reforming (SMR) or autothermal reforming (ATR)) – regardless of whether CCS is applied. At present, only a handful of small-scale reforming units for H_2 production are found in Switzerland. For instance, the Swiss chemical industry, clustered around Basel and in the upper Valais valley, has its own SRM facilities but produce way below the ktpa-scale (e.g. BASF in Kaisten). No commercial nor pilot projects have demonstrated such a plant coupled with CCS in Switzerland to date.

If the installed production capacity is above 25 tonne H_2/day, the facility is regulated by the Swiss emissions trading system (product benchmark: 8.85 tCO_2/tonne H_2)[21]. As of January 2020, the Swiss ETS is linked with the EU ETS and carbon prices are mirrored (approx. 25 EUR/tCO2 as of July 2020). Below this threshold capacity, the plant's fuel consumption would be subject to the carbon levy (currently at 96 CHF/tCO_2, equivalent to 90 EUR/tCO2 as of July 2020).

With the addition of CCS, the climate impact of H_2 produced from fossil feedstock is reduced to near climate neutrality, depending on the technology used. Capture rates modelled in the ELEGANCY project for SMR with CCS are approx. 60% as CO_2 in the flue gas of the steam production is not captured, while ATR with CSS can reach up to 98%.[22] The complication from a business model perspective stems in this case from the monetization of the CO_2 captured and sequestered, and the claiming of avoided emissions.

While IPPC guidelines are available for accounting carbon capture and storage in national inventories[23], the existing legal framework in Switzerland (CO_2 Act) is generally silent on carbon sinks besides those generated through harvested wood products. The issue of CCS and geological storage was debated in the development stage of the legal framework in 2008 but was not pursued.[24] CO_2 captured and sequestered in geological formations (irrespective of storage site location, i.e. in Switzerland or abroad) is therefore not regulated per se by Switzerland's climate policy instruments. If the revised CO_2 Act currently under negotiation at the Swiss Parliament were to explicitly allow for technical sinks, as was strongly recommended by the Risk Dialogue Foundation's white paper commissioned by FOEN[25], different pricing mechanisms could be envisaged to reward the capture and sequestration of CO_2:

- A reimbursement of the CO_2 levy for CCS activities would effectively price the avoided emissions of fossil CO_2 at the level of the levy. This would require CCS to become an accepted technology for operators to meet their individual CO_2 targets adopted in exchange for such reimbursement, which is not the case under the current CO_2 Act.[26]

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[21] Swiss CO_2 Ordinance, Annex 6 & Annex 9: https://www.admin.ch/opc/en/classified-compilation/20120090/index.html.

[22] See Report D5.3.1, also published as Antonini, C., Treyer, K., Streb, A., van der Spek, M., Bauer, C., Mazzotti, M. (2020): Hydrogen production from natural gas and biomethane with carbon capture and storage – a techno-environmental analysis. Sustainable Energy Fuels, 2020, 4, 2967.

[23] IPCC (2006): Guidelines for National Greenhouse Gas Inventories, Volume 2 (Energy), Chapter 5: Carbon Dioxide Transport, Injection and Geological Storage. https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.

[24] In its proposal of 2009 for the CO_2 Act currently in place, the Swiss Government indicated an intention to propose regulation for CCS in due course if conditions for the application of this technology in Switzerland were met. See Swiss Federal Council (2009): Botschaft über die Schweizer Klimapolitik nach 2012.

[25] Risk Dialogue Foundation (2019): The role of atmospheric carbon dioxide removal in Swiss Climate Policy. https://www.risiko-dialog.ch/projekt/stakeholderdialog-cdr/.

[26] Geological CO_2 storage is not currently an accepted emission reduction measure for this purpose as defined in the Swiss CO_2 Ordinance. See FOEN (2019): CO_2-Abgabebefreiung ohne Emissionshandel. https://www.bafu.admin.ch/bafu/en/home/topics/climate/info-specialists/climate-policy/co2-levy/exemption-from-the-co2-levy-for-companies/non-ets-exemption-from-the-co2-levy--step-by-step.html.

- Under the ETS, CCS would lower the needed number of allowances to be surrendered by the installation operator as effective emissions are reduced. This would either decrease the number of allowances that an operator would have to purchase or increase any surplus in gratis allowances available for sale in the market. In either case, pricing the avoided emissions at the allowance price. To allow for this, CCS would need to be an eligible measure for emissions abatement under the Swiss ETS. Considering such measures are not eligible under the current CO_2 Act for CO_2 levy reimbursement (see previous bullet) or as domestic offsetting projects (see Section 4.2.2), this suggests they likely also would not qualify under the Swiss ETS. This appears to be a departure from the EU ETS, to which the Swiss ETS was formally linked as of January 2020, where CCS is an eligible abatement measure and where the capture, transport and storage of CO_2 are activities explicitly covered by the scheme.[27]

When considering the location of CO_2 storage, the accountability of these avoided emissions towards Switzerland's GHG inventory may become a contended point. According to the IPCC, a sink is defined as "any process, activity or mechanism that removes a greenhouse gas (GHG), an aerosol or a precursor of a GHG or aerosol *from the atmosphere*".[28] Capture and storage of carbon from fossil feedstocks does not meet this definition and as a result avoided emissions from CCS are to be reported – according to IPCC Guidelines for National Greenhouse Gas Inventories – in the sector in which the capture takes place.[29]

With anticipated captured CO_2 volumes in Switzerland as modelled in the Swiss case study of 9-12 MtCO2/a by 2050 and only 1-2 $MtCO_2$ of domestic storage potential exploitable by that date (see Section 2.2.3.3), Switzerland will need to export most of its CO_2 for storage abroad. According to the IPCC national inventory guidelines, the location of the CO_2 capture appears decisive for accounting purposes for CCS of fossil CO_2, and Switzerland would thus be entitled to claim the climate benefit towards its GHG inventory (in the form of lower emissions of fossil CO_2), even if storage is abroad.[30] In the authors' view, arrangements should nevertheless be made in this case to ensure that no double counting of avoided emissions occurs.

[27] For the list of activities covered by EU ETS, see Annex 1 of Directive 2009/29/EC (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0029). For Switzerland's ETS, see the list of activities in Annex 6 of the Swiss CO_2 Ordinance (https://www.admin.ch/opc/fr/classified-compilation/20120090/index.html).

[28] IPCC (2014): Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar5/syr/.

[29] Cf footnote 23, page 5.7: "Emissions (and reductions) associated with capture should be reported under the IPCC sector in which capture CO_2 takes place (e.g. Stationary Combustion or Industrial Activities)."

[30] Cf footnote 23, page 5.20: "CO_2 may be captured in one country, Country A, and exported for storage in a different country, Country B. Under this scenario, Country A should report the amount of CO_2 captured, any emissions from transport and/or temporary storage that takes place in Country A, and the amount of CO_2 exported to Country B. Country B should report the amount of CO_2 imported, any emissions from transport and/or temporary storage (that takes place in Country B), and any emissions from injection and geological storage sites."

Box 4-1 Summary of existing policies and gaps.

- ✓ Existing policy framework in place to regulate fossil fuel use in H_2 production (i.e. CO_2 levy, emissions trading), thereby inherently incentivizing the switch to production routes with lower carbon intensities.
- × Swiss CO_2 act is generally silent on technical sinks, leading to an absence of guidelines on CCS.
- × No apparent mechanisms available (e.g. CO_2 levy reimbursement, accounting in ETS) to incentivize or compensate installation operators for capture and storage of CO_2, but this may change under the revised CO_2 Act for the period 2021–2030.

4.2.2 Carbon removals in stationary installations with biogenic feedstock use

Substituting fossil fuels with 100% biogenic feedstock (biomethane, biomass) in the reforming/gasification step eliminates any carbon costs at production stage as it renders the combustion process fully climate neutral in accordance with the established GHG methodologies. From a lifecycle perspective, the climate impact of the hydrogen produced from biogenic feedstock becomes also close to climate neutral (provided the biomass comes from sustainable harvest) and, with the addition of carbon capture and storage, has the potential to become climate-positive, i.e. deliver negative emissions. Indeed, Swiss case study LCA results confirm negative emissions are achievable using bio-energy CCS (BECCS), on the order of -0.3 to -0.5 tCO_2e/MWh H_2.[31]

The accounting of these carbon removals toward Switzerland's GHG inventory is however not straightforward. First, as stated previously, the current legal basis for climate policy is generally silent on technical sinks, irrespective of whether these are avoided emissions or removals. Secondly, it is not evident that removals of biogenic CO_2 captured in Switzerland and stored abroad would also be reflected in the Swiss inventory. Indeed, carbon removals through BECSS may qualify as sinks under IPCC definition and be accounted in the inventory of the storing country. To claim and account for these removals if the biogenic carbon is stored abroad, Switzerland may have to rely on emissions trading instruments such as the EU-ETS or Article 6 of the Paris Agreement.

It is uncertain today whether Switzerland intends to accept international transfers of negative emissions generated through CO_2 removals (e.g. related to biogenic CO_2 captured in and exported from Switzerland). The rulebook for transfers of emission reduction under Art. 6 of the Paris Agreement is still under development, especially for the centralized channel under Article 6.4. Regarding transfers via bilateral agreements under Article 6.2, the rules are also not finalized but progress has been made by certain prospective buyer and seller countries to initiate pilot activities. Switzerland is in fact among a few countries with a stated intent to procure ITMOs[32] and the Swiss Federal Office for the Environment is currently engaged in negotiations with several foreign countries – primarily in Latin America and Africa – for such purchases, despite the absence of

[31] Cf footnote 22.

[32] Canada, Japan, Liechtenstein, Monaco, New Zealand, Norway, South Korea, Switzerland and Sweden. World Bank Group (2019): State and Trends of Carbon Pricing 2019. http://documents.worldbank.org/curated/en/191801559846379845/State-and-Trends-of-Carbon-Pricing-2019.

formalized rules. Given these developments, in the view of the authors, the elements required for such bilateral transfers of ITMOs from CO_2 removals under Article 6.2 are largely in place.

Assuming storage were to occur in Switzerland, pricing these biogenic carbon removals could in principle be achieved through baseline and credit mechanisms. Indeed, in international voluntary carbon markets, experiences exist with crediting of carbon removals, although exclusively focused on biological sink projects such as afforestation, biochar or wooden building material.[33] Similarly, in Switzerland's domestic compliance offset mechanism, a program based on harvested wood products has been implemented. Technical sinks, however, are formally excluded as a technology for offset projects by the current Swiss CO_2 Ordinance. Provided this regulatory barrier regarding eligibility is resolved, projects could benefit from the comparatively high carbon prices in the Swiss market, where typical prices paid are around 100 CHF/tCO_2 (approx. 95 EUR/tCO_2) with a cap at 160 CHF/tCO_2 (approx. 150 EUR/tCO_2).

It should be noted as well that the domestic compensation mechanism is driven by an offsetting requirement placed on importers of fossil transport fuels (10% in 2020, at least 15% by 2030 per current status of ongoing CO_2 Act revisions). As the transport sector progressively decarbonizes to net zero emissions and fossil fuel imports decrease, offsetting requirements will diminish. Thus, this mechanism is not necessarily a stable source of funding in the long term.

Box 4-2 Summary of existing policies and gaps.

- ✓ No final rulebook for international transfers of ITMOs through bilateral agreements under Art. 6.2 of the Paris Agreement, nevertheless Switzerland is pioneering piloting activities and the authors consider the elements required for transfers of CO_2 removals to be in place.
- ✓ High carbon prices under domestic compliance baseline and credit mechanism
- × Technical sinks not allowable as domestic compensation projects.
- × Driver of compensation requirement (i.e. fossil fuel imports) may not be stable source of funding long term as the transport sector decarbonizes.

4.2.3 Avoided emissions from end-use

In addition to emissions avoided or removed at stationary installations producing low carbon hydrogen, climate benefits also materialize in the use phase of this energy carrier. Used in vehicles, hydrogen would usually displace diesel or gasoline consumption from internal combustion engines given the current vehicle fleets.

Precedent exists in Switzerland for monetizing the climate benefit of low-carbon transport fuels. Several domestic compensation projects are registered under Switzerland's compliance offset mechanism, which deliver emission reduction credits (so-called "attestations") to fuel importers for biofuels brought into the Swiss transport market. This carbon finance mechanism complements the petroleum tax relief (up to 0.75 CHF/l) granted to biofuels sold in Switzerland that meet certain ecological and social requirements. Finally, fossil fuel importers also benefit from a lower absolute offsetting requirement due to reduced petroleum fuel imports. Together, these incentives compensate for the cost premium of biofuels over conventional fossil transport fuels.

[33] For example, Puro.earth, the world's first voluntary carbon removal marketplace. https://puro.earth/.

An additional incentive is available to end-users of H_2 in freight transport, namely the exemption from performance-related (i.e. distance-dependant) heavy vehicle charges (LSVA) for heavy vehicles with an electric propulsion. This exemption applies to both battery and fuel cell electric vehicles, such as the truck fleet currently being rolled out by the H_2 Mobility Switzerland Association in collaboration with Hyundai. This benefit is claimable by vehicle (fleet) owners rather than suppliers of H_2.

A compensation approach similar to the one currently used for biofuels can be envisioned for low-carbon hydrogen used as transport fuel. Critical to the implementation of such a scheme are clear eligibility requirements for hydrogen to qualify as *low carbon*. For biofuels, the Mineral Oil Tax Act outlines specific conditions to be met in order to guarantee a high ecological and social benefit beyond Swiss borders (or rather absence of harm, e.g. the production of the raw materials must not require a change in the use of land with a high carbon stock or high biological diversity).[34]

A similar legal basis does not currently exist for low-carbon hydrogen. This leaves significant discretion to the ministries involved in administering the attestation mechanism under the CO_2 Act (FOEN in collaboration with Swiss Federal Office of Energy (SFOE)). For example, it is not currently evident whether electricity used for hydrolysis in Switzerland would need to come from renewable sources for the resulting H_2 to be eligible for attestations, nor what would be the quality requirements in respect of H_2 imported from abroad, if any. This comes down to the question whether, or under which circumstances, the GHG accounting of attestation projects in Switzerland needs to consider emissions occurring outside the country and / or from sources that are themselves subject to a carbon tax or CO_2 emissions cap.

This legal basis would in particular be needed as delivery routes of low-carbon hydrogen exhibit a range of possible climate impacts (see Figure 4-1):

- **Domestic H_2 production with fossil feedstock and CCS**
  Despite the capture and storage of emitted CO_2, steam methane reforming is not a fully climate neutral solution. To ensure sufficient ecological benefit, criteria on minimum carbon capture rates or upstream climate impact reduction may be required.

- **Domestic H_2 production with biogenic feedstock**
  Biogenic feedstocks are prevalent energy carriers in Switzerland. Biomass accounts for 5% of final energy consumption in Switzerland, and up to 8% at household level.[35] Also, some of the largest domestic gas distributors already blend between 5% and 20% of biogas in their standard consumer gas products. [36]

  To meet this growing domestic demand for biogas in Switzerland, a share of the blended biogas is understood to originate in the EU and the import to Switzerland via the gas grid covered through international Energy Attribute Certificates (EAC) for renewable gases. EAC schemes are common practice globally for tracking renewable energy claims of electricity purchases (e.g. Guarantees of Origin (GOs) in the EU, Renewable Energy

[34] Swiss Mineral Oil Tax Act, Art. 12b. https://www.admin.ch/opc/fr/classified-compilation/19960320/index.html.

[35] Federal Office of Energy (2019): Schweizerische Gesamtenergiestatistik 2019. https://www.bfe.admin.ch/bfe/en/home/supply/statistics-and-geodata/energy-statistics/overall-energy-statistics.html.

[36] Energie Zukunft Schweiz (2019): White Paper Erneuerbare Gase – Ziel 2030: Anteil erneuerbarer Gase 30% im gasversorgten Wärmemarkt für Gebäude, (1) Aktuelle Herausforderungen. https://energiezukunftschweiz.ch/de/Knowhow/News/Newsaktuell/2020-02-03-white-paper-serie.php.

Certificates (RECs) in North America). In the EU, guarantees of origin are formally defined in the Union's Renewable Energy Directive (RED).[37] For renewable gases, a patchwork of schemes exist, but without any formal EU-level legal background existing until 2018. Since then, the EU's revised RED has extended the coverage of GOs to renewable gases and a harmonization of certification schemes for renewable gases is under way with a consultation opened in May and June 2020 for the revision of the EU's EN16325 standard on guarantees of origin (GOs).

While used nowadays for voluntary ecological claims by Swiss gas distributors, transfers of renewable gas GOs between the EU and Switzerland in parallel to imports via the European gas grid are not presently accountable towards domestic national climate targets. Depending on the country of origin and the legal framework applicable there, the imported biogas differs in its ecological added value, which has not yet been reflected in Swiss legislation.[38] Allowing for such accounting in the Swiss GHG inventory may be contingent on the adoption of the formal institutional framework agreement currently under negotiation between Switzerland and the EU.

- **Domestic H_2 production from renewable energy electrolysis**
  Climate neutrality at production is clear with this route, provided a renewable electricity source is used. This benefit is likely sufficient for domestic compensation purposes, however when considered over the full lifecycle the situation may differ.

- **Imported H_2**:
  As an alternative to domestic production, Switzerland may rely on imported H_2 produced in the EU or beyond. For this purpose, either a dedicated H_2 grid would be needed as blending in the natural gas grid is not an option due to high purity requirements for use as a transport fuel, or the H_2 is to be delivered by road/rail/ship. From an emissions accounting perspective, the imported hydrogen would technically be climate-neutral for Switzerland's GHG inventory as any emissions generated (e.g. from natural gas reforming, or from the electricity mix if H_2 is produced via electrolysis) would be attributed to the producing country's inventory. Whether this is in practice sufficient – without a confirmation that the production route itself is low-carbon – to demonstrate meaningful and additional emission reductions under the Swiss compensation mechanism and overcome carbon leakage considerations is unclear.

  Proof of the low-carbon nature could be obtained through EACs. The EU's revised RED specifically intends to set the basis for including hydrogen from "renewable sources" under the coverage of GOs for renewable gases.[39] A pilot certification system and registry for renewable hydrogen GOs has also been set up with the first GOs issued in 2018.[40] Whether claims beyond carbon neutrality (i.e. negative emissions) would be possible through this or other renewable gas schemes is another question.

[37] EU Directive 2009/28/EC, Article 15.

[38] Cf footnote 36.

[39] EU Directive 2018/2001. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32018L2001.

[40] https://www.certifhy.eu/.

Box 4-3 Summary of existing policies and gaps.

- ✓ Existing precedent for fossil transport fuel displacement as domestic compensation project, enabling H_2 in transport to be awarded carbon credits ("attestations").
- ✓ Complementary incentives in place, such as the exemption from performance-related heavy vehicle charges (LSVA) for heavy vehicles with an electric propulsion (incl. fuel cell propulsion).
- × No clear basis (legal or in guidance form) for what type of hydrogen would be considered to have a sufficiently high ecological added value to qualify for a domestic compensation project. The following table provides an indicative assessment of the need for further clarity around the ecological benefit of different H_2 production routes.

Delivery route		**Ecological benefit**
Domestic production, fossil feedstock with CCS		Unclear – CO_2 capture rate influences total emissions avoided
Domestic production, biogenic feedstock	Biomass of domestic origin	Clear
	Biomass of foreign origin	Unclear – Quality of biomass/biogas and need for certification
Domestic production, renewable energy electrolysis		Clear
Imported H_2		Unclear – Impact of production method abroad

4.3 Indicative carbon price requirements

4.3.1 Scope of the assessment

A sufficiently high carbon price could provide the incentive needed to cover the cost premium of low-carbon or renewable hydrogen. Using technical and cost data on hydrogen production processes from the energy system modelling in the Swiss case study as well as select sources external to ELEGANCY, we estimate the price levels required for this purpose.

The levelized H_2 production cost (in CHF/kg H_2) is modelled based on unit costs for capital investment, fuel costs (i.e. natural gas, biomass, electricity), maintenance and, where applicable, capture, transport and CO_2 storage costs. A selection of key assumptions is presented in Table 4-1 and full details are available in Appendix A.

- Technology cost figures (including CO_2 capture, where applicable) are current and based on International Energy Agency (IEA)[41] and Swiss Competence Center for Energy Research (SCCER) [42] data. A capture rate of 90% is assumed for H_2 production with CCS.

[41] IEA (2019): The Future of Hydrogen. https://www.iea.org/reports/the-future-of-hydrogen.

[42] Swiss Competence Center for Bioenergy Research (SCCER BIOSWEET) and Joint Activity Scenarios and Modelling (JASM).

It should be noted that as these technologies mature significant cost reductions can be expected.

- Natural gas[43], biomass[44] and electricity[45] costs used are representative average values for these energy carriers in Switzerland. In the case of electricity, energy costs are distinguished from fees and transmission charges.
- CO_2 transport costs are derived from IPCC's Special Report on CCS[46] for the capture volumes expected in Switzerland (9-12 MtCO2/a in 2050, see 2.2.3.3). For pipeline transport within Switzerland, a distance of 500 km is assumed with a cost range of 3-7 CHF/tCO_2 (5 CHF/tCO_2 midpoint). For storage abroad, such as in the North Sea, transport via onshore pipeline (1'000 km) followed by offshore pipeline (1'000 km) is assumed. The cost range obtained in this case is 17-30 CHF/tCO_2 (23 CHF/tCO_2 midpoint).
- CO_2 storage costs are based on Zero Emissions Platform (ZEP)[47] analysis. Domestic storage in a geological formation of roughly the expected overall potential for Switzerland (50 MtCO2/a, see 2.2.3.3) is estimated to cost 15 CHF/tCO_2. For offshore storage, a generic site of a similar size is considered and with costs of 25 CHF/tCO_2.

Carbon pricing is applied where GHG emissions are generated or removed from the combustion of feedstocks. If the feedstock is fossil-based (e.g. natural gas), carbon pricing is applied on the net emissions released to the atmosphere and increases the production cost of hydrogen. For biogenic feedstock (e.g. biomass), the carbon removed generates a financial return and lowers the production cost of hydrogen.

As uncertainties surrounding input values can be large, carbon prices shown in the assessment are indicative.

Table 4-1 Selection of key assumptions.

Model input		**Data source**
Natural gas reforming technology		IEA (2019): The Future of Hydrogen
Biomass gasification technology		SCCER BIOSWEET + SCCER JASM
Electrolysis technology		IEA (2019): The Future of Hydrogen
Natural gas price		Swiss Federal Price Monitor
Price excl. CO_2 levy	40 CHF/MWh	
Electricity price		Swiss Federal Electricity Commission
Base price	69 CHF/MWh	
Transmission charges & fees	75 CHF/MWh	

[43] Swiss Federal Price Monitor: http://gaspreise.preisueberwacher.ch/web/index.asp?l=0.

[44] SCCER and JASM data platform: https://data.sccer-jasm.ch/.

[45] Swiss Federal Electricity Commission: https://www.strompreis.elcom.admin.ch/Map/ShowSwissMap.aspx.

[46] IPCC (2005): Special Report on Carbon Dioxide Capture and Storage, Chapter 4 Transport of CO_2. https://www.ipcc.ch/report/carbon-dioxide-capture-and-storage/.

[47] ZEP (2011): The costs of CO_2 storage, post-demonstration CCS in the EU. https://www.globalccsinstitute.com/archive/hub/publications/119816/costs-co2-storage-post-demonstration-ccs-eu.pdf.

Biomass price		SCCER and JASM Data Platform
Domestic wood	36 CHF/MWh	
Cost of CO_2 transport		IPCC (2005): Special Report on CCS
Onshore pipeline (500 km)	5 CHF/tCO_2	
On/offshore pipeline (2000 km)	23 CHF/tCO2	
Cost of CO_2 storage		ZEP (2011): The Costs of CO_2 Storage
Onshore (approx. 40Mt CO_2)	15 CHF/tCO_2	
Offshore (approx. 40Mt CO_2)	25 CHF/tCO_2	
Reference H_2 production cost		IEA (2019): Future of Hydrogen
Natural gas SMR, EU, no CCS	1.7 CHF/tCO_2	

4.3.2 Onshore storage in Switzerland

Previous sections of this report have highlighted the high uncertainty around large-scale domestic geological storage potential and the high likelihood that Switzerland would have to rely on international storage sites for its captured CO_2. Despite this key outcome of the Swiss case study, storing CO_2 in Switzerland may demonstrate important cost advantages. This assessment therefore distinguishes between H_2 production with storage in Switzerland and with storage abroad.

For domestic CO_2 transport and storage, we assume a combined cost of 20 CHF/tCO_2 (5 plus 15 CHF/tCO_2), compared to 48 CHF/tCO_2 for offshore storage in the North Sea (23 plus 25 CHF/tCO_2). While these cost figures take into account certain aspects specific to the Swiss case study (i.e. distance to storage sites, expected capture volumes, overall storage potential) and are thus a useful basis for comparison, they remain highly generic for both onshore and offshore storage. The authors therefore caution against a more detailed interpretation of the results beyond first order considerations discussed here.

The results of the assessment are presented in Figure 4-2, chart A), for three different technology options deployed in Switzerland: natural gas reforming, biomass gasification and electrolysis with renewable electricity (alkaline and polymer electrolyte membrane (PEM)). The “baseline” hydrogen production cost for each technology – i.e. excluding CCS and carbon costs – increases gradually when moving from natural gas SMR (2.26 CHF/kg H_2) to biomass gasification (4.40 CHF/kg H_2) and electrolysis (8.56-10.58 CHF/kg H_2). In the latter case, for electrolysis co-located with renewable energy production and avoiding grid charges and other fees, costs fall to 4.67-6.29 CHF/kg H_2. For comparison, the IEA reference for H_2 production costs from natural gas in the EU is also provided (1.70 CHF/kg H_2).

When applying a sufficiently high price carbon, technology alternatives with CCS become competitive against their baseline cases. At a price on fossil fuel combustion of approx. 95 CHF/tCO_2, the total cost of hydrogen from natural gas SMR increases to a level where it is comparable for both processes with CCS and without CCS (3.15 CHF/kg H_2). Similarly, at an attestation price level for carbon removals of 30 CHF/tCO_2, CCS costs for biomass gasification are balanced out by carbon revenues and total hydrogen costs are equivalent to the baseline technology (4.40 CHF/kg H_2).[48] Above these prices, technologies with CCS could thus be considered more economically attractive propositions and enable the added climate benefits associated with it.

With the support from attestations, carbon revenues from biomass gasification with CCS could potentially also bring down total hydrogen cost to levels comparable with natural gas reforming. Attestation prices of approx. 100 CHF/tCO_2 and 120 CHF/tCO_2 could deliver comparable hydrogen costs as SMR in Switzerland and the EU, respectively (see Figure 4-2, chart B)).

Existing carbon prices in Switzerland are, for the most part, able to achieve these levels. The CO_2 levy on fossil heating fuels is already at the 95 CHF/t CO_2 mark and attestation prices of 120 CHF are common for projects registered under the domestic compensation scheme. At 25 CHF/tCO_2 in recent months, allowances prices under the EU ETS (linked to the Swiss ETS) are however well below and would be currently insufficient to incentivize a move away from standard natural gas SMR.

[48] A lower carbon price is found to be needed in this case as the cost differential between the baseline technology and with carbon capture added is smaller for biomass gasification than natural gas reforming (note: different data sources are used for these two technologies). In addition, carbon cost effects in the baseline case are eliminated when using biogenic feedstock.

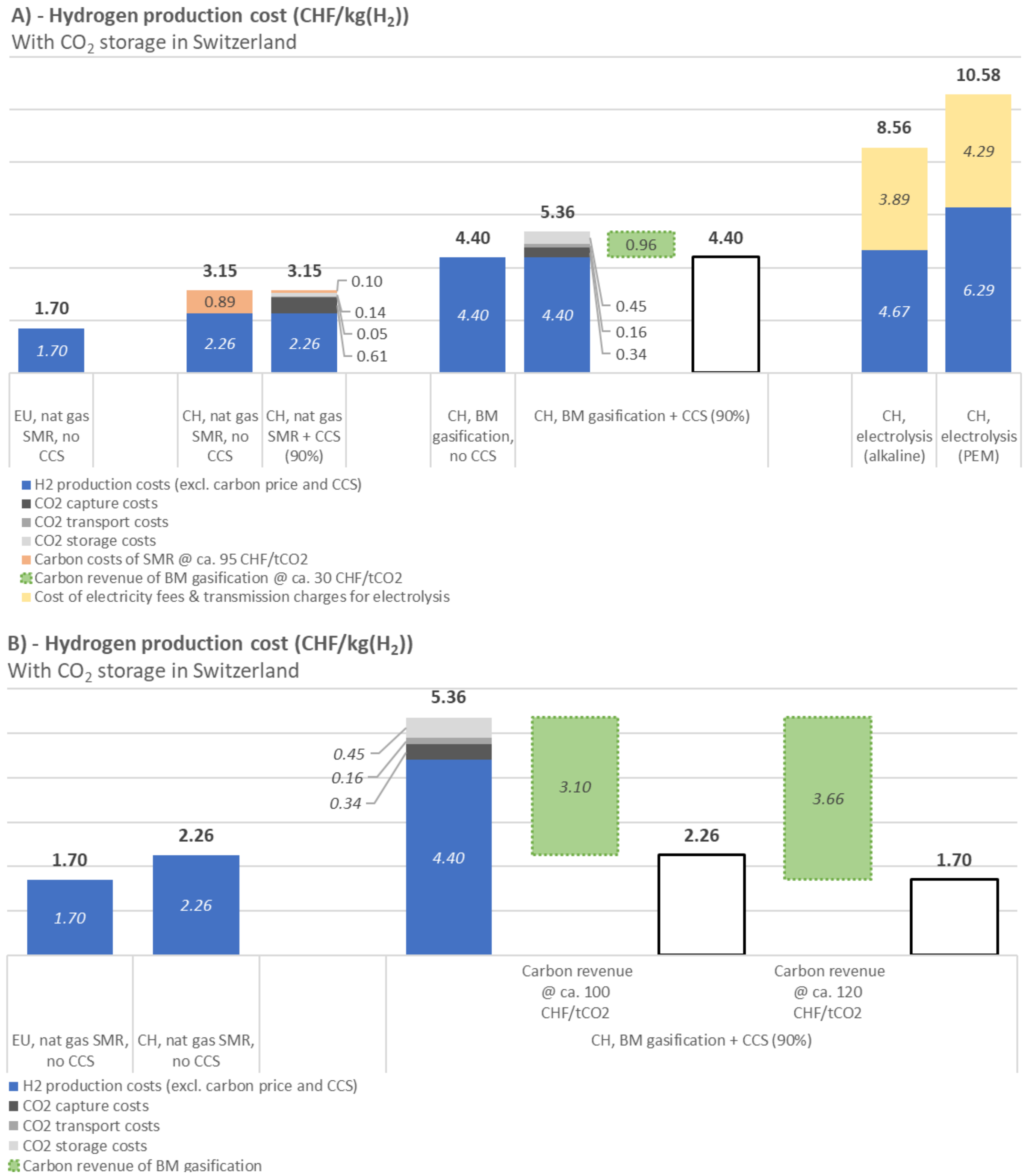

Figure 4-2 Levelized production cost of H_2 (CHF/kg H_2) produced in Switzerland through different routes, including steam methane reforming ("nat gas SMR") with and without CCS, biomass gasification ("BM gasification") with and without CCS, renewable energy alkaline and PEM electrolysis. Production costs in the EU using natural gas reforming without CCS are provided as reference. Where CCS is applied, a 90% capture rate is considered, and CO_2 is assumed to be stored in Switzerland. Carbon pricing is applied as cost for natural gas SMR and as revenue for biomass gasification with CCS. Charts A) and B) depict impacts of different carbon price levels. For more details, see Appendix A. (Source: First Climate)

4.3.3 Offshore storage in the North Sea

With higher costs for transport and storage of CO_2, a scenario with storage in the North Sea increases the H_2 cost differential between technologies with and without CCS (see Figure 4-3, charts A) and B)). Carbon price levels needed to incentivize natural gas reforming with CCS rise to approx. 125 CHF/tCO_2, from 95 CHF/tCO_2 with storage in Switzerland. Similarly, to promote negative emission with biomass gasification, a price level of 65 CHF/tCO_2 would be required, from 30 CHF/tCO_2 previously. Finally, prices of 130 to 145 CHF/tCO_2 would enable a switch from baseline natural gas SMR to biomass gasification with CCS, as opposed to 100 to 120 CHF/tCO_2 in the section above.

These price levels are generally at the limits of those currently available from Switzerland's carbon pricing instruments. Indeed, the CO_2 levy is currently caped at 120 CHF/tCO_2, while attestations are limited to 160 CHF/tCO_2 by regulation but in practice seldom above 140 or 150 CHF/tCO_2. These are also above any implemented carbon pricing policy in other countries.[49]

However, under the proposed revisions to the Swiss CO_2 Act, debated currently in Parliament, two important modification are foreseen:

1. An increase of the ceiling price for the carbon levy from 120 CHF/tCO_2 to 210 CHF/tCO_2;
2. An increase of the maximum price for emission reductions under the domestic compliance compensation scheme, from 160 CHF/tCO_2 to 320 CHF/tCO_2.

If adopted, the revised framework would broadly be able deliver the prices needed to incentivize CCS with storage in North Sea: a carbon levy of close to 125 CHF/tCO_2 would be within reach and prices of 130-145 CHF/tCO_2 could be payable for removals under compensation projects. Aside from the prices themselves, the new policy framework would of course need to have addressed the regulatory gaps highlighted in Section 4.2.

49 World Bank Group (2019): State and trends of carbon pricing 2019. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/191801559846379845/state-and-trends-of-carbon-pricing-2019.

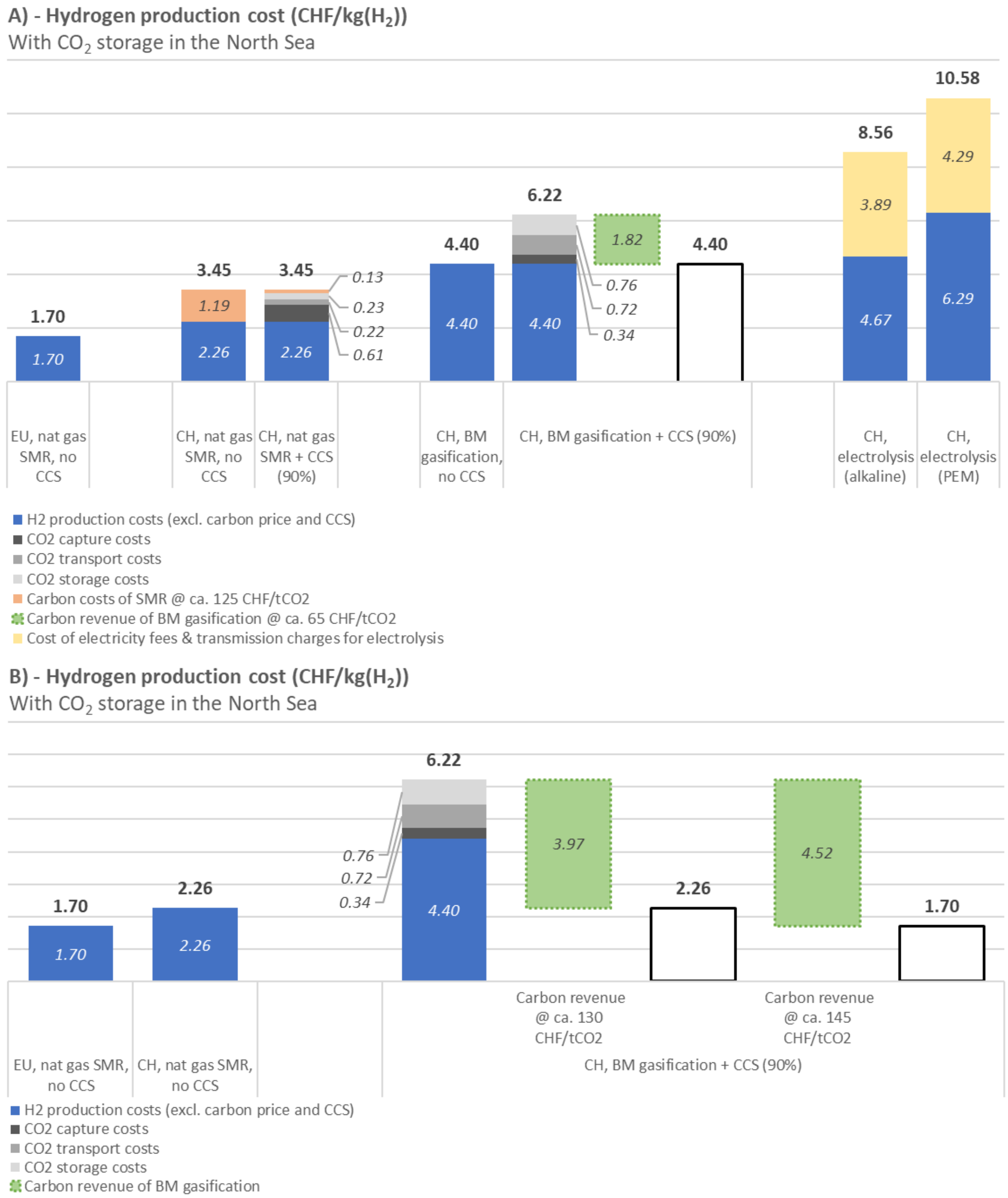

Figure 4-3 Levelized production cost of H_2 (CHF/kg H_2) produced in Switzerland through different routes, including steam methane reforming ("nat gas SMR") with and without CCS, biomass gasification ("BM gasification") with and without CCS, renewable energy alkaline and PEM electrolysis. Production costs in the EU using natural gas reforming without CCS are provided as reference. Where CCS is applied, a 90% capture rate is considered and CO_2 is assumed to be stored in the North Sea. Carbon pricing is applied as cost for natural gas SMR and as revenue for biomass gasification. Charts A) and B) depict impacts of different carbon price levels. For more details, see Appendix A. (Source: First Climate)

5 CONCLUDING REMARKS

Current use of hydrogen as an energy carrier in Switzerland's economy is limited, both in the transport sector as well as other high GHG-emitting sectors. Forays into commercial deployments have mainly been in the form of niche activities, the most prominent of which is spearheaded by the H_2 Mobility Association involving the targeted roll-out of 6 hydrogen refuelling stations and a fleet of 50 HFCEV trucks by the end of 2020. On the CCS side, private sector efforts are all but limited to Climework's DAC plant. As such, the vision of the Swiss case study in ELEGANCY to deploy H_2-CCS technology to decarbonize the transport sector and deliver negative emissions is ambitious and, if successful, potentially transformative.

The early-stage market environment of the Swiss case study – in contrast to more advanced H_2-CCS developments in other ELEGANCY countries the likes of Norway and the UK – is well suited to the application of the WP3 business case framework in order to identify key system-level barriers and gaps and navigate initial business model considerations. The assessments conducted, using a subset of the full toolkit clearly highlight regulatory drivers, market governance and sector coordination as priority areas to address to foster large scale development of low-carbon H_2 production and end-use in the transport sector, as well as associated CO_2 transport and storage services. Indeed, the general absence of a guiding hydrogen strategy at national level, unclear regulatory framework for CCS, and missing domestic markets for both H_2 and CCS are limiting factors to large-scale investment.

In parallel to the absence of needed H_2- and CCS-specific support, Switzerland has a robust climate policy framework with carbon pricing instruments in place since 2008 to foster impactful low-carbon development. While technology-neutral, these instruments cover all high-emitting sectors (i.e. transport, industry, building) and provide valuable financial incentives to domestic emission reduction activities.

The policy framework provides opportunities to monetize the climate benefit of H_2-CCS chains in three different instances along the pathway from H_2 production to end-use: emissions avoided at production (i.e. from fossil fuel feedstocks), carbon removals at production (i.e. from biogenic feedstocks with CCS), displacement of transport fuels (e.g. diesel fuel in trucks). The authors find that in each case the policy basis is in place, with applicable precedents sometimes available, but that important limitations exist. A summary of the assessment is provided in Table 5-1.

Table 5-1 Applicability of existing carbon pricing instruments to help bridge the cost premium of low-carbon H_2 and incentivize large-scale H_2-CCS deployment, while accounting avoided emissions or removals towards Switzerland's GHG inventory. Color key for rating: green = carbon pricing framework is generally place and sufficient to incentivize the climate benefit; orange = elements of the carbon pricing framework are in place to incentivize the climate benefit but important gaps exist. (Source: First Climate)

Low-carbon H_2 production route	**Climate benefit**		
	Avoided emissions at H_2 production	**Carbon removals at H_2 production**	**Avoided emissions at H_2 end-use**
Domestic production, fossil feedstock with CCS		(not achievable with this production route)	
Domestic production, biogenic feedstock, without CCS		(not achievable with this production route)	
Domestic production, biogenic feedstock, with CCS			
Domestic production, renewable energy electrolysis		(not achievable with this production route)	
Imported H_2	(not applicable, H_2 produced outside Switzerland)	(not applicable, H_2 produced outside Switzerland)	

The following instruments are in place to incentivize low-carbon H_2 production:

- Emissions trading, or at smaller scale a CO_2 levy, cover stationary emissions from H_2 production;
- Attestations delivered under Switzerland's compliance offsetting scheme:
  - Use of H_2 as transport fuel is potentially eligible for attestations today, in addition to other incentives (e.g. exemption from LSVA);
  - Of the policy instruments in place today, only attestation could directly incentivize BECCS (subject to amending scope of attestation instrument and pricing).

The relevant limitations related to the direct applicability of these carbon pricing instruments to H_2-CCS chains are listed below. Addressing these is of high importance to ensure this policy framework supports an increase in the speed and scale of H_2-CCS deployment in Switzerland.

- Regulatory uncertainty:
  - Legal basis for permitting technical sinks – both avoided emissions and carbon removals – as mitigation measures is missing, prohibiting these activities from being eligible for CO_2 levy refund, accounted under the ETS, and generating attestations;

    - Basis – legal or in guidance form – defining the sources of hydrogen considered to have a sufficiently high ecological added value to qualify for domestic compensation projects is missing, for hydrogen produced in Switzerland but also if imported;
    - Driver of compensation requirement (i.e. fossil fuel imports) may not be a stable source of funding for avoided or negative emissions in the long term as the transport sector decarbonizes.
- Insufficient price signal:
    - Current price levels of the carbon levy and compensation mechanism are not fully sufficient for incentivizing H_2 production with CCS (natural gas reforming or biomass gasification) if CO_2 is stored abroad such as the North Sea, however proposals in the ongoing revisions to the Swiss CO_2 Act will raise these prices to needed levels once adopted;
    - Under the Swiss ETS, linked with the EU system since January 2020, current prices are far too low to drive adoption of CCS technology with natural gas SMR irrespective of CO_2 storage location. Future allowance prices in the Swiss ETS will depend on European policies to strengthen GHG abatement targets and the associated tightening of the emissions cap in the EU ETS.

APPENDIX

A. Data and assumptions for assessment of carbon price requirements

Color Key for Inputs:
Source: IEA (2019): The Future of Hydrogen
Source: IPCC (2005): SRCCS
Source: ETH/PSI
Source: CH specific inputs
Source: ZEP (2011): The costs of CO2 storage
Variable

Inputs	Unit		Source
Exchange rate, 2017	*CHF/USD*	0.98	Swiss Federal Tax Administration
Natural gas price (CH)	*USD/GJ(NG)*	11	Swiss Federal Price Monitor
Natural gas carbon content (CH)	*tCO_2/GJ(NG)*	0.060	Swiss Federal Office for the Environment
Biomass price	*USD/GJ(biomass)*	10	SCCER and JASM Data Platform
Biomass carbon content	*tCO_2/GJ(biomass)*	0.112	ETH/PSI: Litterature review
Electricity price (CH), base	*USD/GJ(el)*	19	Swiss Federal Electricity Commission
Electricity price (CH), fees & charges	*USD/GJ(el)*	21	Swiss Federal Electricity Commission
Carbon transport (CH)	*USD/tCO2*	5	IPCC
Carbon storage onshore (CH)	*USD/tCO2*	15	ZEP
Carbon transport (NO)	*USD/tCO2*	24	IPCC
Carbon storage offshore (NO)	*USD/tCO2*	25	ZEP
Hydrogen price, EU (Nat gas, no CCS)	*USD/kg(H_2)*	1.73	IEA

Units: USD2017 constant prices

Tech description:	Unit	Storage in Switzerland: Natural gas reforming — No CCS	Storage in Switzerland: Natural gas reforming — With CCS	Storage in North Sea: Natural gas reforming — No CCS	Storage in North Sea: Natural gas reforming — With CCS
Total Investment Cost	*USD/kW(H_2)*	910	1680	910	1680
Discount Rate	*%*	8.0%	8.0%	8.0%	8.0%
Lifetime	*Years*	25	25	25	25
FOM cost	*USD/kW(H_2)/yr*	42.8	79.0	42.8	79.0
VOM cost	*USD/GJ/yr*	0.0	0.0	0.0	0.0
Avail. Factor	*%*	95%	95%	95%	95%
Efficiency	*%*	76%	69%	76%	69%
Fuel Price	*USD/GJ(fuel)*	11	11	11	11
Carbon Content	*tCO2/GJ(fuel)*	0.060	0.060	0.060	0.060
Carbon Price	*USD/tCO_2*	95.3	95.3	127.1	127.1
CO2 capture rate	*%*	0%	90%	0%	90%
Fixed Costs	*USD/GJ(H_2)/yr*	4.3	7.9	4.3	7.9
Fuel Cost	*USD/GJ(H_2)/yr*	14.9	16.4	14.9	16.4
Carbon Cost	*USD/GJ(H_2)/yr*	7.5	0.8	10.1	1.1
Total Production cost	*USD/GJ(H_2)/yr*	26.7	25.1	29.2	25.4
Total Production cost, excl. T&S	***USD/kg(H_2)***	**3.20**	**3.01**	**3.50**	**3.04**
carbon cost share	*USD/kg(H_2)*	0.90	0.10	1.21	0.13
balance	*USD/kg(H_2)*	2.29	2.91	2.29	2.91
Total production cost, incl. T&S (CH)		**3.20**	**3.20**		
CO_2 transport cost	*USD/kg(H_2)*	0.00	0.05		
CO_2 storage cost (onshore)	*USD/kg(H_2)*	0.00	0.14		
Total production cost, incl. T&S (NO)				**3.50**	**3.50**
CO_2 transport cost	*USD/kg(H_2)*			0.00	0.22
CO_2 storage cost (offshore)	*USD/kg(H_2)*			0.00	0.24

Units: USD2017 constant prices		Storage in Switzerland			
Tech description:		**Biomass gasification**			
	Unit	**No CCS**	**With CCS**	**With CCS**	**With CCS**
Total Investment Cost	*USD/kW(H_2)*	2880	2990	2990	2990
Discount Rate	*%*	8.0%	8.0%	8.0%	8.0%
Lifetime	*Years*	25	25	25	25
FOM cost	*USD/kW(H_2)/yr*	144.0	149.5	149.5	149.5
VOM cost	*USD/GJ/yr*	0.0	0.0	0.0	0.0
Avail. Factor	*%*	95%	95%	95%	95%
Efficiency	*%*	43%	39%	39%	39%
Fuel Price	*USD/GJ(fuel)*	10	10	10	10
Carbon Content	*tCO2/GJ(fuel)*	0.112	0.112	0.112	0.112
Carbon Price	*USD/tCO_2*	0.0	31.6	102.4	120.7
CO2 capture rate	*%*	0%	90%	90%	90%
Fixed Costs	*USD/GJ(H_2)/yr*	13.8	14.3	14.3	14.3
Fuel Cost	*USD/GJ(H_2)/yr*	23.5	25.8	25.8	25.8
Carbon Cost	*USD/GJ(H_2)/yr*	0.0	-8.1	-26.3	-31.0
Total Production cost	*USD/GJ(H_2)/yr*	37.3	32.1	13.9	9.2
Total Production cost, excl. T&S	***USD/kg(H_2)***	**4.47**	**3.85**	**1.67**	**1.11**
carbon cost share	*USD/kg(H_2)*	0.00	-0.97	-3.15	-3.71
balance	*USD/kg(H_2)*	4.47	4.82	4.82	4.82
Total production cost, incl. T&S (CH)		**4.47**	**4.47**	**2.29**	**1.73**
CO_2 transport cost	*USD/kg(H_2)*	0.00	0.16	0.16	0.16
CO_2 storage cost (onshore)	*USD/kg(H_2)*	0.00	0.46	0.46	0.46
Total production cost, incl. T&S (NO)					
CO_2 transport cost	*USD/kg(H_2)*				
CO_2 storage cost (offshore)	*USD/kg(H_2)*				

Units: USD2017 constant prices		Storage in North Sea			
Tech description:		**Biomass gasification**			
	Unit	**No CCS**	**With CCS**	**With CCS**	**With CCS**
Total Investment Cost	*USD/kW(H_2)*	2880	2990	2990	2990
Discount Rate	*%*	8.0%	8.0%	8.0%	8.0%
Lifetime	*Years*	25	25	25	25
FOM cost	*USD/kW(H_2)/yr*	144.0	149.5	149.5	149.5
VOM cost	*USD/GJ/yr*	0.0	0.0	0.0	0.0
Avail. Factor	*%*	95%	95%	95%	95%
Efficiency	*%*	43%	39%	39%	39%
Fuel Price	*USD/GJ(fuel)*	10	10	10	10
Carbon Content	*tCO2/GJ(fuel)*	0.112	0.112	0.112	0.112
Carbon Price	*USD/tCO_2*	0.0	60.1	130.9	149.2
CO2 capture rate	*%*	0%	90%	90%	90%
Fixed Costs	*USD/GJ(H_2)/yr*	13.8	14.3	14.3	14.3
Fuel Cost	*USD/GJ(H_2)/yr*	23.5	25.8	25.8	25.8
Carbon Cost	*USD/GJ(H_2)/yr*	0.0	-15.4	-33.6	-38.3
Total Production cost	*USD/GJ(H_2)/yr*	37.3	24.8	6.6	1.9
Total Production cost, excl. T&S	***USD/kg(H_2)***	**4.47**	**2.97**	**0.79**	**0.23**
carbon cost share	*USD/kg(H_2)*	0.00	-1.85	-4.03	-4.59
balance	*USD/kg(H_2)*	4.47	4.82	4.82	4.82
Total production cost, incl. T&S (CH)					
CO_2 transport cost	*USD/kg(H_2)*				
CO_2 storage cost (onshore)	*USD/kg(H_2)*				
Total production cost, incl. T&S (NO)		**4.47**	**4.47**	**2.29**	**1.73**
CO_2 transport cost	*USD/kg(H_2)*	0.00	0.73	0.73	0.73
CO_2 storage cost (offshore)	*USD/kg(H_2)*	0.00	0.77	0.77	0.77

Units: USD2017 constant prices

Tech description:	**Unit**	**RE electrolysis** Alkaline	PEM
Total Investment Cost	*USD/kW(el)*	900	1,450
Total Investment Cost	*USD/kW(H_2)*	1,406	2,500
Discount Rate	*%*	8%	8%
Stack lifetime	*Operating hours*	90,000	60,000
Full load hours	*Hours*	5,000	5,000
Lifetime	*Years*	18	12
FOM cost	*USD/kW(el)/yr*	13.5	21.8
VOM cost	*USD/GJ/yr*	0.0	0.0
Avail. Factor	*%*	57%	57%
Efficiency	*%*	64%	58%
Fuel Price (base price)	*USD/GJ(el)*	19.5	19.5
Fuel Price (fees & transmission charges)	*USD/GJ(el)*	21.1	21.1
Carbon Content	*tCO2/GJ(el)*	0.0	0.0
Carbon Price	*USD/tCO_2*	0.0	0.0
Fixed Costs	*USD/GJ(H_2)/yr*	9.1	19.6
Fuel Cost (base)	*USD/GJ(H_2)/yr*	30.4	33.6
Fuel Cost (fees & transmission charges)	*USD/GJ(H_2)/yr*	32.9	36.3
Carbon Cost	*USD/GJ(H_2)/yr*	0.0	0.0
Total Production cost	*USD/GJ(H_2)/yr*	72.5	89.6
Total Production cost	***USD/kg(H_2)***	**8.70**	**10.75**
carbon cost share	*USD/kg(H_2)*	0.00	0.00
electricity fees & transmission charges	*USD/kg(H_2)*	3.95	4.36
balance	*USD/kg(H_2)*	4.74	6.39