CGES
Coalition for Green
Energy & Storage

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Materials Science and Technology

The TAPIR framework

A new tool to assess climate and energy demonstration projects

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Disclaimer

Statements and views expressed in this report are solely those of the authors and do not imply endorsement by the CGES initiative or any of its partners.

The TAPIR assessment framework was initially developed during the evaluation of demonstration project proposals for the CGES initiative during 2023. However, the framework was further developed during the elaboration of this report. Therefore, the framework's version presented in this report does not exactly correspond to the one used to evaluate proposals submitted to the CGES project.

Credits

- Front page image by Martin Adams. Link: https://unsplash.com/photos/white-windwmill-oz4rQXuQaTU
- Figure 4 was adapted from a prior CGES publication. Author: Ivan Savicev, EPFL

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ABOUT CGES

The Coalition for Green Energy and Storage (CGES) is an association of scientific, industrial, and philanthropic stakeholders who have joined efforts to contribute to solving Switzerland's climate and energy crises. In June 2023, CGES was launched under the leadership of the Swiss Federal Institutes of Technology (ETH Zürich and EPFL), the Paul Scherrer Institute (PSI), and the Swiss Federal Laboratories for Materials Science and Technology (Empa). Today, over thirty organizations support the initiative.

The purpose of the association is the creation of a public-private platform to promote the development of seasonal energy storage projects, thereby strengthening the stability, security, and resilience of the Swiss energy system. Initially, CGES focused on carbon capture and carbon-neutral fuels: two critical technologies for reducing emissions and storing and using renewable energy.

CGES aims to build several "catapults" across Switzerland: megawatt scale technology demonstration platforms that will help launch innovation ecosystems around green energy and storage technologies. Catapult proposals were developed by scientific and industrial partners in coordination with the CGES team and submitted to the Catapult Assessment Workstream for evaluation in December 2023. The Catapult Assessment Workstream analyzed the proposals and presented the results to the CGES board to facilitate the decision-making process using an earlier version of the framework presented in this report.

EXECUTIVE SUMMARY

Addressing the climate and energy crises is an urgent priority. As emissions rise and energy supplies become less secure, governments and industries seek new solutions that can be deployed quickly and at scale. Synthetic fuels stand out as promising substitutes for fossil fuels that need minimal infrastructure changes and solve storage issues often raised by intermittent energy sources. However, their current production levels fall far short of the volumes required to achieve net-zero emissions. Additional efforts to speed up the development of synthetic fuels and of other climate and energy technologies are needed. As a central part of these efforts, demonstration projects provide practical proof of a new process or device's impact and viability, and help launch innovation ecosystems that eventually lead to the technlogy's commercialization.

The Coalition for Green Energy and Storage (CGES) brings together stakeholders focused on accelerating the development of a climate-neutral and secure energy system in Switzerland by building several demonstration projects across Switzerland.

The challenge of choosing demonstration projects

Choosing demonstration projects that address the climate and energy crises is a complex task that requires answering difficult questions about a new process or product's growth potential in a context of deep uncertainty.

- **Growth potential**: What is the project’s ability to achieve technological and economic viability and foster innovation ecosystems within its regional context?
- **Deep uncertainty**: How will the multiple early-stage technologies in the project evolve?

Existing technology assessment frameworks offer valuable tools but often fall short of addressing these two questions due to either a generic approach that overlooks local contexts or a narrow, often quantitative approach, to a single project or technology.

The TAPIR Assessment Framework

The Technology And Project Impact and Readiness (TAPIR) assessment framework was developed to fill this gap. Initially designed for the CGES initiative, TAPIR provides guidelines to assess demonstration project proposals for solutions to the climate and energy crises. It integrates both project and technology-level assessments, combines qualitative and quantitative data, and considers the global and regional context, allowing it to answer growth potential questions under deep uncertainty.

TAPIR’s ultimate goal is to support evidence-based discussions on which projects and technologies to prioritize by assessing demonstration projects and their technologies, helping compare project proposals, and enabling future project evaluations.

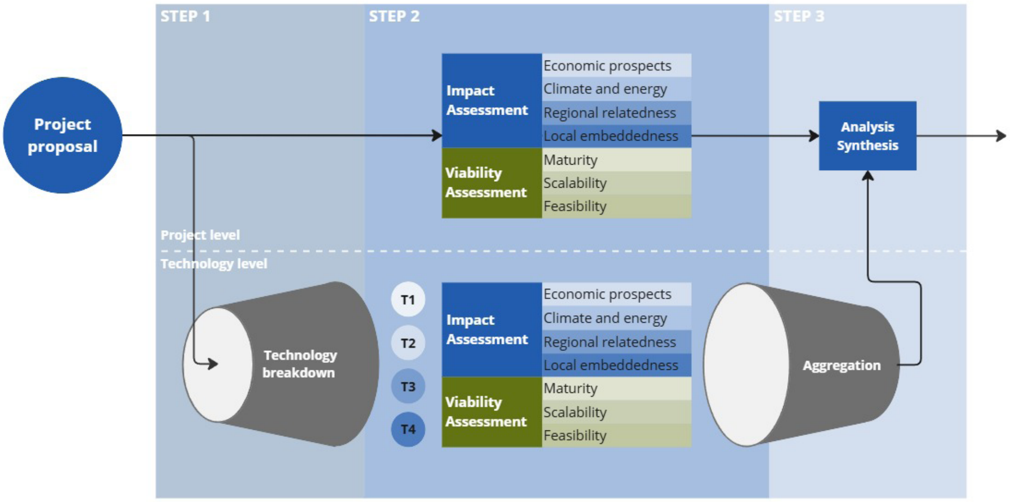

Figure 1. The TAPIR assessment framework's schematic representation. Source: Authors' elaboration.

As shown in Figure 1, applying TAPIR to a project involves three key steps:

1. **Technology breakdown:** Identifying the project's different technologies through a hierarchical technology breakdown, so they can be evaluated individually.
2. **Impact and viability assessment:** Combining quantitative and qualitative data with expert opinions to evaluate the project and its technologies along impact and viability criteria.
3. **Synthesis of analysis:** Aggregating and summarizing results at the project level to provide easily accessible information to decision-makers.

An optional fourth step, **a scale-up analysis**, can be added to gain further insights.

This report illustrates the application of TAPIR to an anonymized demonstration project proposal submitted to the CGES initiative.

Why use TAPIR?

TAPIR has two main advantages over similar tools. Its integrated assessment of the project and its technologies facilitates answering growth potential under uncertainty more completely than with project feasibility studies and technology assessment frameworks, and its standardized methodology enables consistent, fact-based comparisons across projects.

TAPIR provides a new tool for decision-makers, including governments and philanthropies, who want to prioritize demonstration projects with the potential to become new solutions for the climate and energy crises. Conceived within the CGES initiative, it aspires to support future decision-makers, helping address some of the most difficult and urgent challenges of our time.

1. INTRODUCTION

Developing and commercializing new solutions for the climate and energy crises has never been more urgent. As global emissions continue to rise, the opportunity to limit global warming is rapidly closing (1,2). At the same time, an increasingly unstable world has put energy security at the top of governments' agendas (3). In response, over a hundred governments have committed to reaching net zero emissions and securing their energy supplies. However, some of the solutions they need are not available yet (4,5).

One example of such solutions is synthetic fuels. Synthetic fuels are combustible substances produced with low carbon emissions that can replace fossil fuels with minimal changes to the existing infrastructure and end-use devices. They can be used in many applications, both stationary and mobile, and are expected to play a key role in sectors where electrification is difficult, such as aviation. The International Energy Agency (IEA) estimates that synthetic fuels based on hydrogen must supply 37% of aviation's final energy use in 2050—equivalent to 7.2 million barrels of oil per day—to achieve net-zero emissions (6). However, synthetic fuel production today, mainly in scattered pilot plants, is equivalent to around 1.2 *thousand* barrels of oil per day (7)[1]. Bridging this gap requires additional efforts to develop and commercialize new technologies.

Demonstration projects can help develop new devices and processes, by providing practical proof of their technical, economic, environmental, and social feasibility. They can also accelerate their commercialization, by being the starting point of innovation ecosystems. However, choosing which demonstration projects to support is a challenging task. Investors, philanthropists, companies, and governments must assess and compare multiple proposals and answer critical questions about growth potential under deep uncertainty.

A project with high growth potential means that it is not only viable and has positive impacts on the climate and energy crises, but also that it can help launch innovation ecosystems that eventually lead to the commercialization of the device or process. Assessing which demonstration projects meet this criterion is not straightforward. Multiple factors must be considered to avoid projects with devices and processes that never achieve technological and economic viability, create new environmental problems, or are blocked by public opposition. The regional context of the projects must also be taken into account, such as the availability of resources and their alignment with existing economic activities, to assess their potential to launch innovation ecosystems.

Uncertainty is a key difficulty when assessing demonstration projects, particularly those composed of multiple technologies. At the early stages of development of a technology, there are many different variations that compete for resources and investment until a dominant design emerges, which then concentrates resources and investment, marking the shift to its growth phase (8). Before a dominant design emerges, there is a lot of uncertainty about how technology variations may evolve, and there is a lack of data, particularly quantitative data, about the technology variations.

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[1] In their 2050 net-zero emissions scenario, the IEA expects aviation to use 15 exajoules (EJ) per year. In energy terms, this is equivalent to around 358.2 million tons of oil equivalent (Mtoe) per year (1 EJ = 23.88 Mtoe) or about 7.2 million barrels of oil equivalent per day (1 million barrels of oil per day = 49.8 Mtoe). The amount of oil required to deliver this final energy would be larger due to conversion inefficiencies.

Despite a vast literature on innovation, there are few studies about assessing demonstration project proposals that help answer these questions. One commonly used tool is technology assessment frameworks (TAFs). First developed in the 1970s in the United States, TAFs provide guidelines to evaluate technologies along a set of criteria most commonly related to their potential impact and viability. In 1978, the U.S. Energy Research and Development Administration published one of the first TAFs applied to demonstration projects (9). TAFs have become widely used since then. For example, the EU published a TAF for grid infrastructure projects in 2016 (10), and in 2018, the Institute for Global Environmental Strategies published a TAF for projects supporting behavior changes for sustainability (11). Although they provide useful tools, their scope is too narrow to answer growth potential and uncertainty questions about demonstration projects for climate and energy that comprise multiple technologies. More recently, in 2023, the Indian Center for the Study of Science, Technology and Policy published a TAF that focuses on clean energy and mobility technologies, combines qualitative and quantitative data, and considers multiple factors (12).

Although it can be applied to climate and energy technologies, using it to compare specific projects and answer growth potential questions can be difficult because it mainly considers the technology level and overlooks the project level.

For all these reasons, there is a gap in the literature about how to assess demonstration project proposals for climate and energy technologies that can answer growth potential under deep uncertainty.

To help address this challenge, this report presents the Technology And Project Impact and Readiness (TAPIR) assessment framework. TAPIR provides guidelines to assess demonstration project proposals for climate and energy technologies and answer questions about their growth potential, by including multiple criteria at the technology and project levels that consider the regional context of the projects and uncertainty, combining qualitative and quantitative data. TAPIR was developed by the authors in 2023 for the CGES initiative, but it can be used in other contexts to inform the selection of demonstration projects for climate and energy technologies.

The remainder of the report explains the objectives of the TAPIR assessment framework (Section 2) and its methodology (Section 3). The TAPIR assessment framework is described in Section 4 and applied to an example project proposal in Section 5. Its advantages and limitations are discussed in Section 6, and conclusions and paths for future research are provided in Section 7.

2. OBJECTIVES

The TAPIR assessment framework provides a guideline to evaluate demonstration projects for climate and energy technologies based on a set of criteria related to their potential impact and viability both at the technology and project levels.

TAPIR was developed in the context of the CGES initiative, where an early version was used to assess how well demonstration project proposals aligned with the initiative's goal of accelerating the development and deployment of solutions to the climate and energy crises that can scale up rapidly and cost-competitively and help launch innovation ecosystems that eventually lead to technology commercialization.

Within this context, the objectives of the TAPIR assessment framework are to:

- Assess demonstration projects and their technologies,
- Facilitate comparisons across project proposals.

Ultimately, TAPIR aims to support evidence-based discussions on project prioritization.

3. METHODS

The TAPIR assessment framework combines qualitative and quantitative methods to capitalize on complementary data sources and provide comprehensive and nuanced assessments.

Mixed methods are necessary because demonstration projects often include multiple technologies at early stages of development, with little or no available data about their performance and cost. Mixed methods can incorporate various data sources, ranging from quantitative estimates in the scientific literature to qualitative insights from industry experts, to gain a better understanding of the technology's potential impact and viability than it would be possible with only one type of data.

The TAPIR assessment framework combines the following methods:

- **Technology breakdown:** a hierarchical approach to categorize and organize the technological components of a project, breaking down complex technology systems into smaller, manageable subareas.
- **Multicriteria assessment:** an evaluation of factors influencing a project's and a technology's impact and viability using quantitative and qualitative indicators based on desk research and directed literature review.
- **Expert opinion elicitation:** surveys of industrial and scientific experts with specialized experience and knowledge about the technologies in the projects.
- **Techno-economic modeling:** quantitative evaluation of process performance and cost through simplified engineering models of the project.
- **Scenario analysis:** quantitative and qualitative assessment of different future scenarios for scaling up the project's technologies.

Data were collected through directed literature reviews, desk research, surveys, and targeted expert interviews. Sources included scientific and grey literature, expert networks within and beyond the CGES initiative, and open-access databases like the IEA's ETP Clean Energy Technology Guide (5). Other data sources are found in the text.

4. FRAMEWORK DESCRIPTION

This section describes the TAPIR framework's structure and assessment steps. In the TAPIR framework, projects are evaluated in three steps: technology breakdown, impact and viability assessment, and analysis synthesis, with an optional fourth step of scale-up analysis. The TAPIR framework analyzes the demonstration project and its main technologies to assess the immediate viability and potential impact of demonstration projects, as well as their future implications as part of the development of the project's main technologies.

4.1. Framework Structure and Assessment Steps

The TAPIR assessment framework is shown in Figure 2. It is structured around two levels of analysis, the project level and the technology level, and three steps, plus an optional fourth step, through which a project proposal is evaluated and the results synthesized to inform a funding decision.

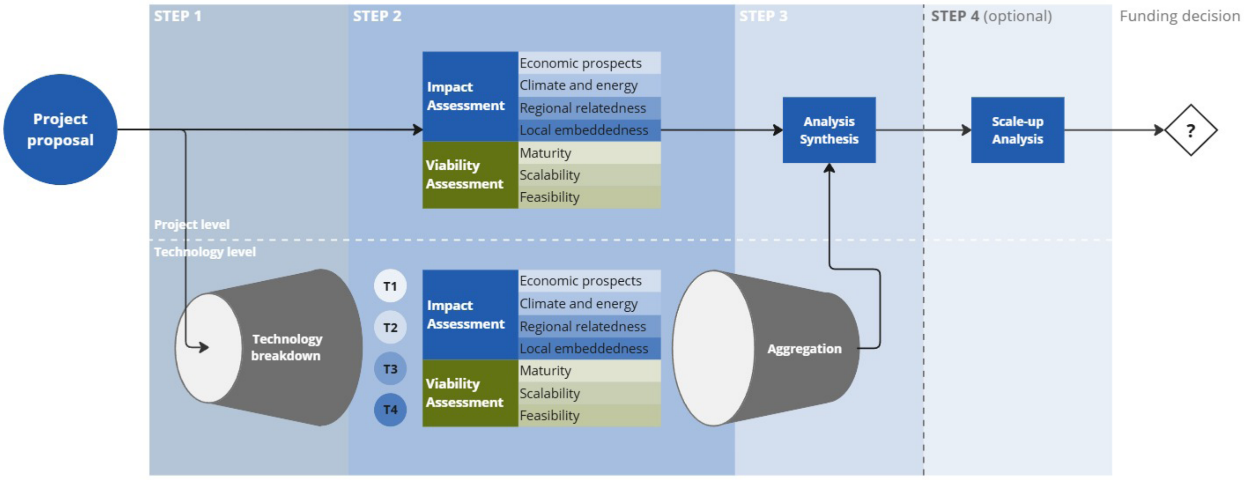

Figure 2. The extended TAPIR assessment framework's schematic representation.

Source: Authors' elaboration.

At the project level, the assessment focuses on the specific project proposal—for example, a particular process to produce synthetic fuels. At the technology level, the assessment focuses on the technologies that configure the device or process in the project proposal—for instance, the water electrolysis and chemical reactor technologies. To move from the project to the technology level, Step 1 involves a technology breakdown to identify the project's main technologies.

At the core of both levels, in Step 2, is an assessment framework, with two aspects: impact and viability. The impact assessment evaluates economic prospects, climate and energy impacts, regional relatedness, and local embeddedness. The viability assessment evaluates maturity, scalability, and feasibility. Projects and technologies can be assessed through complementary methods, such as expert opinion elicitation for projects and multicriteria assessment for technologies.

Finally, both levels are combined into an analysis synthesis in Step 3. If the projects appear promising, a more detailed analysis is conducted to assess their potential for scaling up in Step 4.

Therefore, project proposals are evaluated in the following steps:

- **Step 1:** core technologies in the project are identified by a technology breakdown.
- **Step 2:** the project's and its main technologies' impact and viability are assessed along several dimensions.
- **Step 3:** results are combined and summarized in an analysis synthesis.

An optional **Step 4** investigates the implications of scaling up the technologies in the project in a scenario analysis.

The following sections describe each of these steps.

4.2. Step 1: Technology Breakdown

The first step is the technology breakdown. For each demonstration project, a hierarchical approach to categorize and organize their technological components is used to identify key technologies. Identifying a project's different technologies involves recognizing the system's various components, which include diverse elements, each serving a distinct function within the device or process. For each project, process engineering schematics can help to isolate steps that rely on different technological principles (e.g., electrolysis, chemical synthesis, flow separations).

This step enables evaluating each technology individually, recognizing that they may vary in maturity levels and face different viability challenges.

4.3. Step 2: Impact and Viability Assessment

In the second step, projects and technologies are evaluated across two aspects: potential impact and future viability.

Impact Assessment

An impact assessment systematically evaluates the potential effects of a project or technology on the economy, environment, and society by identifying, foreseeing, and assessing the likely consequences of the project or technology and analyzing their significance and magnitude.

The TAPIR assessment framework focuses on four aspects: economic prospects, climate and energy impacts, regional relatedness, and local embeddedness.

Economic prospects

The assessment of economic prospects considers current and future costs and demand, as well as possible cost reductions, to assess the economic potential of the projects and technologies. Given the uncertainty about a technology's future, substitution and competition risks can also be important. The early stage of the technologies makes it difficult to find reliable data for all indicators. Therefore, the TAPIR assessment framework suggests prioritizing indicators of cost-competitiveness, market size and future demand, and cost structure, while complementing these indicators with others when necessary. Table 1 provides guiding questions and examples of metrics for those indicators, with a more complete list included in the Appendix.

Climate and energy impacts

The assessment of climate and energy impacts evaluates a technology's potential contribution to solving the climate and energy crises. The complexity of these crises poses a major challenge for investigating how much a new product or process could help address them. To make this complexity more manageable, the TAPIR assessment framework suggests multiple indicators that combine multiple sources of knowledge (a list is found in the Appendix).

The TAPIR assessment framework suggests concentrating on the indicators listed in Table 1. For instance, reasonable estimates for emissions reductions achieved by the technologies provide a measure of the scale of their potential contribution to the climate crisis. These estimates are typically quantified as a percentage of current emissions or as a comparison between a baseline scenario (without mitigation) and an intervention scenario (with mitigation). In addition, prominence in policy scenarios can reveal not only the expected contribution of the technology to the climate and energy crises but also political commitment to its deployment. Finally, the potential to produce clean energy and store it informs about the magnitude of the contribution to the energy crisis that can be expected from the technology.

Regional relatedness

Economic relatedness measures the "similarity" or "compatibility" between an economic region and an economic activity (13). Here, the term is adapted to the TAPIR assessment framework's scope to evaluate the alignment of proposed projects and their technologies with existing industrial activity in the project's region.

Multiple indicators can be considered, as shown in Table 1, which may differ depending on the goals of the program supporting the demonstration projects and the regional context. In the case of CGES, involvement by industry actors based in Switzerland and the export potential of the technologies were considered key objectives. Therefore, special efforts were made to assess indicators like the presence of Swiss firms in the value chain, ongoing projects, and export potential. A longer list of indicators is found in the Appendix.

Local embeddedness

Local embeddedness refers to the extent to which a demonstration project and its main technologies can be integrated into and impact their local community, economy, and environment. This includes considerations such as job creation, improved local air pollution levels, and enhanced resilience to climate-related risks.

Evaluating local embeddedness indicators is complex and requires careful consideration. To work around the complexity, economic integration and policy alignment can be prioritized (see Table 1), while many other indicators can be considered, as listed in the Appendix.

A combined effort of directed literature review, desk research, and targeted expert consultation can provide insights into the different indicators presented along the four impact factors. Given the resources, data, and time available to the analyst, different indicators may be prioritized and considered in greater detail.

Table 1 summarizes the four impact factors and provides examples of indicators and metrics.

Table 1.
Impact assessment factors and indicators.

Impact factor	Guiding question	Indicator examples	Metric examples
Economic prospects	*What is the technology's future economic viability?*	• Cost-competitiveness • Market size and demand forecast • Cost structure	• Levelized cost of electricity • Total energy demand • CAPEX and OPEX
Climate and energy impacts	*What is the technology's potential contribution to solving the climate and energy crises?*	• CO_2 emissions reduction • Prominence in policy scenarios • Clean energy production • Energy storage	• Avoided emissions • Share of future energy demand • Production potential • Storage potential
Regional relatedness	*What is the technology's alignment with regional industrial activity?*	• Swiss firms in the value chain • Commercialization by Swiss firms • Ongoing projects in the region • Export potential	• Market share of firms • Number of firms • Number of projects • Global market trend
Local embeddedness	*What is the technology's integration into the local community, economy, and environment?*	• Economic integration • Policy alignment	• Number of local jobs created • Compliance with local regulations and policies

Viability Assessment

Assessing the viability of a project or a technology involves evaluating its readiness for implementation and investigating risks and opportunities for their future deployment, which can be studied through three key factors: maturity, scalability, and feasibility.

Maturity

Maturity reflects a technology's reliability and performance. A mature technology is more likely to have undergone rigorous testing, validation, and refinement, reducing the risks associated with deployment and increasing confidence in its ability to deliver desired outcomes. A technology's maturity can be assessed through different indicators, ranging from its readiness level to the diversity of technology options.

A widely used indicator of technology maturity is the Technology Readiness Level (TRL) scale, which ranges from TRL 1 (basic principles observed) to TRL 11 (stability has been proved and growth is predictable). Each level represents a specific stage of development, testing, and validation, helping us understand how ready each technology is for commercialization. Data on the TRL of various technologies are accessible in open-access databases such as the IEA's ETP Clean Energy Technology Guide (5). Some prominent indicators are listed in Table 2, with a longer list in the Appendix.

Scalability

Scalability represents the capacity of technologies to transcend pilot or large-scale demonstration projects and transition to broader adoption. Assessing scalability is important for ensuring that the technologies can effectively address challenges at larger scales, ultimately facilitating their widespread deployment.

There are multiple ways for scaling up technologies, like through mass-produced devices or custom-made installations, involving different levels of complexity and dependence on local value chains and resources concentrated in specific geographies. All of this makes evaluating scalability difficult. Table 2 shows some prioritized indicators, within the context of the CGES initiative, such as market potential in Switzerland and abroad and largest project built around the world. The Appendix provides a longer list of indicators.

Feasibility

Feasibility mainly refers to the availability of required resources, infrastructure, and logistics needed for successful project development and future technology deployment. Different technologies will have different resource requirements, for example, based on the inputs they need to operate. In the CGES initiative, the initial focus on synthetic fuels makes resource and infrastructure availability two crucial indicators for the feasibility of the projects, as shown in Table 2. Other indicators are listed in the Appendix.

Similarly to the impact assessment, a combined effort of directed literature review, desk research, and targeted expert consultations can be used for investigating the different feasibility indicators.

Table 2 summarizes the three factors and selected indicators.

Viability factor	Guiding question	Indicator examples	Metric examples
Maturity	*What is the technology's readiness for market adoption?*	• Technology readiness level • Deployment stage • Technology variation	• TRL • Number of installations and type • Number of design variations
Scalability	*What is the technology's potential to be deployed at a larger scale?*	• Market potential • Largest project built	• Expected market size • Number and size of installations
Feasibility	*What is the technology's likelihood of successful implementation?*	• Resource availability • Infrastructure availability	• Input requirement per output unit • Capacity required

Table 2. Viability assessment factors and indicators.

Expert Opinions

In the TAPIR assessment framework, both projects and technologies are evaluated based on their impact and viability. However, the higher specificity of demonstration projects calls for additional insights to inform their analysis. Experts with direct knowledge of the devices and processes in the demonstration projects and of their regional context can offer valuable insights through their critical perspectives on the impact and viability of proposed projects and on potential barriers.

Expert opinions can be collected and analyzed in multiple ways. In the CGES initiative, forty-four experts were contacted, most of them with a technical background and working in industry, together with some scientists working in Swiss institutions. Expert opinions were collected through workshops, surveys, and interviews. Survey questions can be found in the Appendix.

4.4. Step 3: Synthesis of Analysis

In the third step, project and technology assessments are combined to deliver a full picture of each project proposal's impact and viability. It involves aggregating and summarizing the results to make them accessible to decision-makers. A useful approach includes organizing data into spreadsheets with separate sheets for each project proposal, containing the evaluations of different columns of technologies through rows of indicators. This way, analysts can identify which technologies pose challenges more easily.

To further synthesize results, tiers for each factor (e.g., economic prospects) can be developed to allow for qualitative comparisons across project proposals (see Figure 3). Tiers indicate a factor's contribution or ease of implementation in each dimension, from greater (Tier 1) to lower (Tier 3). Using color-coded visualizations, stakeholders can quickly identify enabling (e.g., green) and challenging (e.g., red) factors.

Figure 3. Example of a synthesis of project assessment results.

	Project 1	Project 2	Project 3	Project 4	Project 5	Project 6
Economic prospects	Missing data	🟩	🟩	Missing data	🟩	🟨
Climate and energy impacts	🟩	🟥	🟩	🟩	🟩	🟨
Regional relatedness	🟩	🟩	🟩	🟨	🟩	🟩
Local embeddedness	🟨	🟨	🟨	🟨	🟨	🟩
Maturity	🟨	🟨	🟨	🟨	🟥	🟨
Scalability	🟩	🟥	🟩	🟨	🟩	🟨
Feasibility	🟩	🟩	🟩	🟩	🟩	🟩

Tier 1 🟩 Tier 2 🟨 Tier 3 🟥

Tiers qualitatively indicate contribution or ease of implementation in each dimension, from greater (Tier 1) to lower (Tier 3). Qualitative summary based on **preliminary results**, subject to **significant uncertainties**.

4.5. Step 4: Scale-up Analysis

To complement the previous analysis, an optional fourth step is to evaluate the project's potential for scaling-up in a specific region. This analysis relies on techno-economic modeling and involves creating scenarios based on different hypotheses. It includes a quantitative analysis of the project's impact and viability, as well as a qualitative assessment of the implications of scaling up. For example, it is possible to create several scenarios with different resource availability hypotheses and compare the results to regional demand in 2030 or 2050 to understand the potential impact of scaling up the project. The analysis scope and set-up is highly dependent on the project and its main technologies, and analysts may have to adapt it accordingly.

5. ASSESSMENT OF A PROJECT PROPOSAL

This section illustrates how to use the TAPIR assessment framework by applying it to an anonymized demonstration project proposal submitted to the CGES initiative: Project M.

Project M's goal is to accelerate sustainable synthetic fuels technologies across Switzerland to strengthen energy system resilience without additional CO_2 emissions. To achieve this goal, Project M aims to demonstrate the technical, economic, environmental and social feasibility of producing synthetic fuels seasonally to deliver power, heating, and synthetic aviation fuel (SAF).

Project M's demonstration plant will produce hydrogen through water electrolysis powered by renewable electricity and combine it with carbon captured from a nearby industrial facility to produce methanol, methane, and SAF (see Figure 4). It will operate differently in summer and winter. In summer, with higher renewable electricity generation, energy will be partly stored as methanol (see Figure 4 A) and used in winter, when renewable electricity generation will be lower (see Figure 4 B). SAF production will operate flexibly throughout the year.

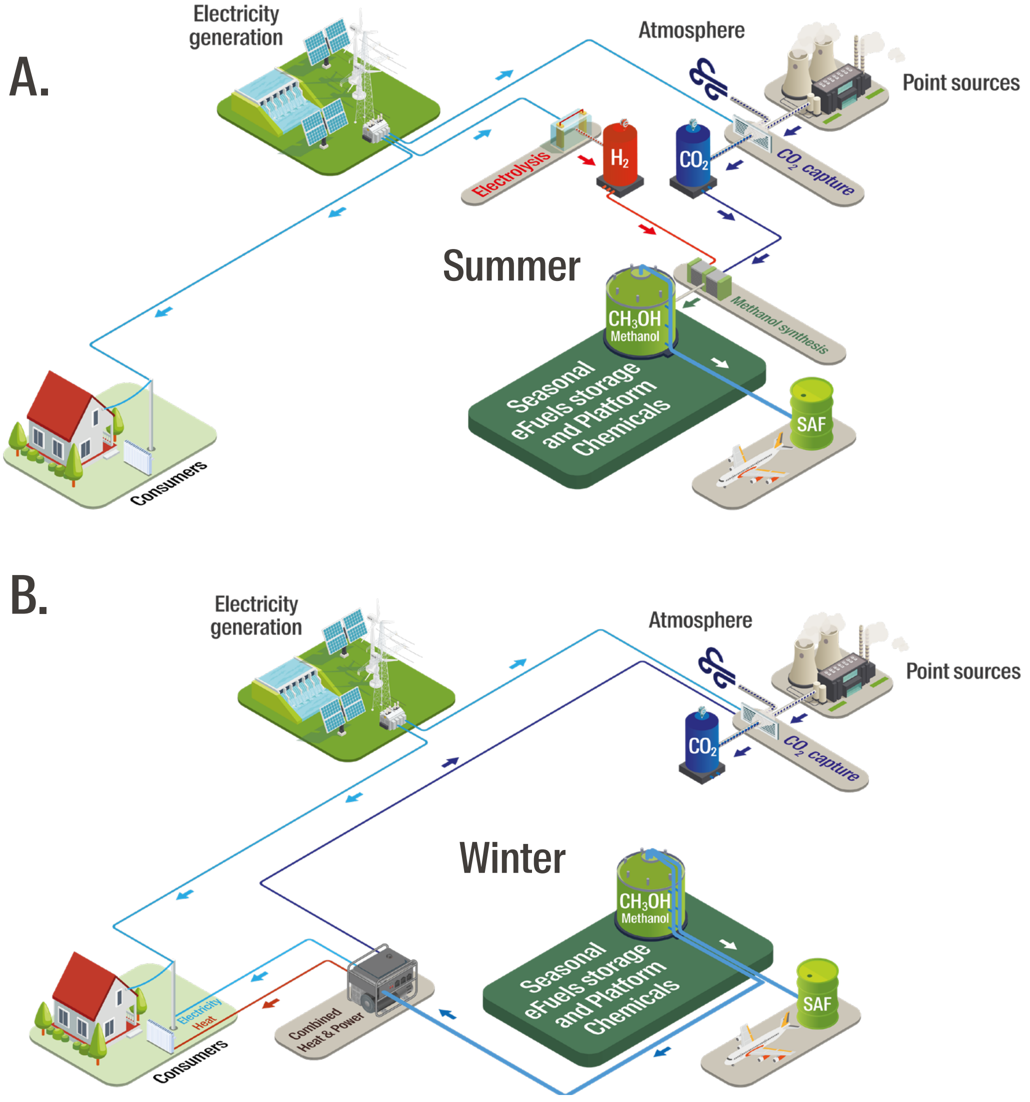

Figure 4. Demonstration plant proposal operation in summer (A) and winter (B).

The figure illustrates the operation of the demonstration plant to produce methanol. The illustration for methane production would be similar.

Project M's proposal identifies seven potential locations across Switzerland, with the primary one being in a small municipality with an industrial facility that emits several kilotons of CO_2 per year. Several partners, including companies, ranging from energy producers and distributors to industrial services, as well as local institutions and research groups, are part of the proposal, which plans to be operational by the end of 2025.

The assessment team received a slide deck with the proposal to develop Project M, including details about the processes and technologies involved, scale and location, budget and timeline, which served as the basis to apply the TAPIR assessment framework.

5.1. Technology Breakdown

In Step 1, technologies in Project M are disaggregated. Project M's technologies can be identified based on the processes inputs, such as captured carbon dioxide (CO_2) and hydrogen (H_2), and targeted outputs, methanol, methane, and SAF. Following this principle, five technology groups were identified:

- **Point-source CO_2 capture**: technologies for capturing the carbon in an industrial facility's exhaust, using methods like chemical absorption or pressure swing adsorption;

- **Water electrolysis**: technologies for producing hydrogen by splitting water with renewable electricity, for example, an alkaline electrolyzer;

- **Methane production**: technologies to combine captured carbon dioxide and hydrogen in a Sabatier reactor to produce synthetic methane;

- **Methanol production**: technologies to synthesize methanol from captured carbon dioxide and hydrogen using a catalytic process;

- **SAF production**: technologies to convert methanol into SAF through processes like methanol-to-olefins.

5.2. Impact and Viability Assessment

In Step 2, the demonstration plant's project and its main technologies are assessed. Technologies in Project M were assessed individually along seven impact and viability factors, and the project itself was assessed based on expert opinions.

Impact Assessment

The impact of Project M's technologies was assessed along four factors—economic prospects, contributions to addressing the climate and energy crises, regional relatedness, and local embeddedness—with one main indicator per factor. The main takeaways from all five technology groups are:

- **Economic Prospects**: Overall, all technologies are still costly, leading to synthetic fuels being pricier than fossil fuels. However, economic prospects vary across technologies. Renewable hydrogen and synthetic methane have better prospects of achieving cost-competitiveness and a positive economic impact than methanol and SAF production.
- **Climate and Energy impacts**: All technologies can have a significant in reducing global CO_2 emissions, from 1.9% to 8% of cumulative emissions by 2050, based on IEA estimates (14), and their contribution to seasonal storage can improve energy resilience.
- **Regional Relatedness:** The project technologies are aligned with regional industrial activity, with many Swiss firms active in their value chains, who may benefit from an acceleration in their development.
- **Local Embeddedness:** The project technologies are increasingly supported by national policies, and their use is foreseen in the national strategy to achieve net-zero by 2050, potentially benefiting local economies who host them by attracting economic activity and policy support.

Viability Assessment

The viability of the project technologies was evaluated based on three factors—maturity, scalability, and feasibility—with one main indicator for each:

- **Maturity**: The project technologies are relatively mature, with TRLs ranging from 6 (large prototype) to 9 (first-of-a-kind commercial application), with water electrolysis and point-source carbon capture as the closest to market-readiness.
- **Scalability**: All technologies show significant market potential that could drive deployment at scale. Global demand for hydrogen and carbon capture is expected to multiply under net-zero policies, and methane and methanol demands are on the rise.
- **Feasibility**: The technologies are technically feasible, but their high energy and resource requirements and potential need for new infrastructure, may pose implementation challenges.

The complete impact and viability assessments are found in Tables 13 and 14 in the Appendix.

Expert Opinion

To assess the demonstration project, forty-four industry and research experts gave their opinions on Project M's proposal after attending an online presentation. First, they were asked about the project's potential. Experts indicated how much they agreed with statements about the project's future impact—from strongly disagree to strongly agree—as shown in Figure 5.

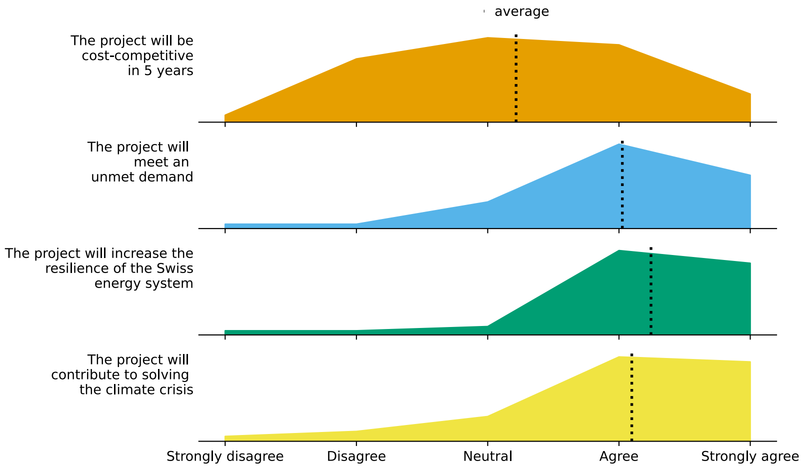

Figure 5. Expert opinions about Project M's impact potential.

Experts widely agree that the project has the potential to make a significant impact. They believe that the project will meet an unmet demand, help address the energy crisis by making the energy system more resilient and help solve the climate crisis. However, experts were on average neutral about the project's potential to become cost competitiveness within five years. Next, experts were asked about the project's viability. By classifying eight items into major and minor issues, experts expressed their opinions about what barriers they project may face and which items they were most uncertain about (i.e. no answer) (see Figure 6).

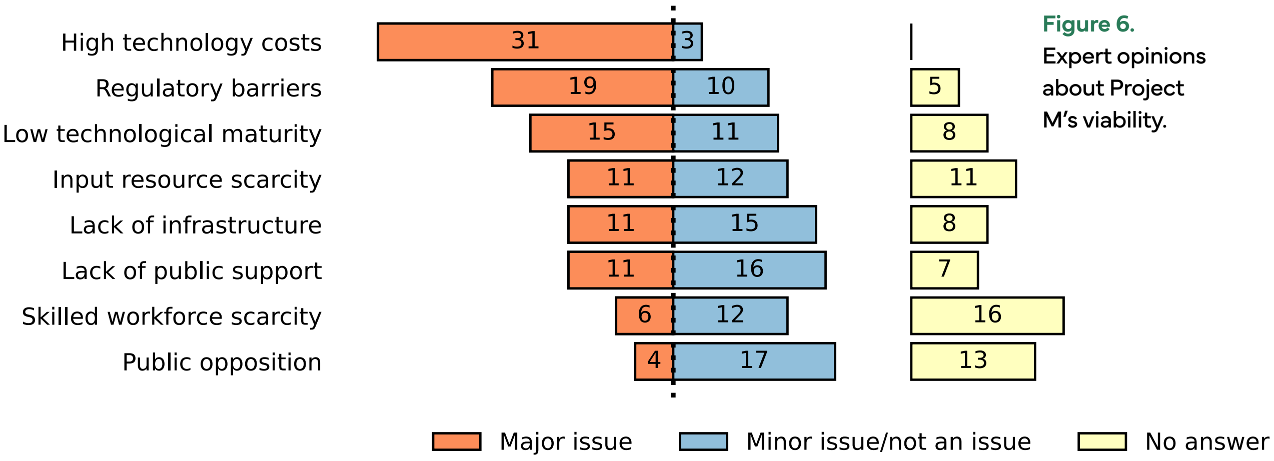

Figure 6. Expert opinions about Project M's viability.

Experts' concerns about high technology costs were unambiguously confirmed, with nearly all of them listing costs as the most significant obstacle for the project. Experts considered regulatory barriers as the second biggest challenge, followed by technological maturity, input scarcity, infrastructure, and public support availability, in which they were split. Finally, skilled workforce scarcity and public opposition were considered largely unproblematic, with at least twice as many experts thinking they will be a minor issue than a major obstacle. Notably, experts were most uncertain about questions regarding skilled workforce availability and public opposition.

Overall, expert opinions suggest that they consider the project relevant and technically viable, but they expect costs and regulation to be major issues.

5.3. Synthesis of Analysis

In Step 3, the assessment of the project and its main technologies was synthesized into Table 3.

Table 3. Synthesis of analysis for Project M's proposal.

Factor	Synthesis
Economic prospects	• Demand for synthetic fuels is expected to multiply by 2050 for decarbonizing industrial processes, aviation, shipping, and other applications (14). • However, synthetic fuel are x2 to x8 times costlier than fossil fuels. Costs are expected to fall rapidly, but there is high uncertainty (15) (16). • Cost competitiveness may be a major barrier, say local experts.
Climate and energy impacts	• Methanol accounts for 10% of global chemical industry emissions (16). • Synthetic fuels in aviation and shipping could cut global CO_2 emissions by 5% by 2050 (14). • Synthetic fuels can be stored in existing facilities with minimal modifications.
Regional relatedness	• Swiss firms are active in key segments of the value chain: engineering and technology providers (GE Vernova, Casale, Metafuels), energy utilities (Alpiq, Axpo, Romande Energie), large emitters (Holcim, Satom), and infrastructure firms (Gaznat).
Local embeddedness	• Numerous policies support the technologies involved in the project. • A 1 MW green hydrogen project could create 15 jobs for construction and 6 jobs for operation (17). • Regulatory barriers may pose challenges, say local experts.
Maturity	• Technologies are relatively mature, with TRLs ranging between 6 and 9. • Patenting activity in these technologies is rapidly growing worldwide (15).
Scalability	• Key technologies–water electrolysis, point-source carbon capture, methanol synthesis–are increasingly available at scale (15) (16). • Large-scale operating and planned plants for CO_2 capture and synthetic methanol demonstrate the potential for commercial-scale deployment (18).
Feasibility	• Substantial synthetic fuel production in Switzerland can be achieved with current CO_2 sources but requires a major scale-up of renewable hydrogen supply. • Compatibility with existing infrastructure minimizes integration challenges.

This analysis synthesis highlights Project M's positive impact and possible viability challenges. Impacts on climate and energy, along with regional relatedness and local embeddedness, are largely positive. In contrast, maturity, scalability, and feasibility are neutral. Economic prospects pose the greatest challenge due to high technology costs.

5.4. Scale-up Analysis

In an additional fourth step, three scenarios based on assumptions about the availability of captured carbon (scenarios 1 and 3) and renewable electricity (scenario 2) were used to assess Project M's potential for scaling up (see Table 4). In all scenarios, methane and methanol production were assumed to receive half of inputs each, as suggested in the project proposal.

Scenario	Captured carbon per year (kt CO_2)	Annual renewable electricity (TWh)	Description
1. Reference	766	-	This scenario assumes two locations identified in the proposal, with a total capturable CO_2 emissions potential of 766 kt CO_2 (2 locations).
2. All excess renewable energy	-	9.2	Based on the Swiss government's 2050 energy strategy, this scenario assumes all 9.2 TWh of expected surplus renewable electricity during the summer are available for synthetic fuel production (at least 3 locations).
3. All large-scale CO_2 emitters	6,863	-	Based on 2019 data about large-scale emitters (>100 kt CO_2/year) in Switzerland, this scenario assumes all 6,863 kt of capturable CO_2 emissions are used for synthetic fuel production (32 locations).

Table 4.
Scale-up scenarios.

Two additional references are used to assess these scenarios. First, the Swiss government's expected 2050 hydrogen demand of 15.5 TWh, which is expected to be met by domestic hydrogen production (4.4 TWh) and imports (11.1 TWh), in the form of synthetic fuels. And second, the expected 2050 demand for synthetic fuels in Switzerland of 11.1 TWh, which is expected to be fully met by imports (19).

Based on energy and mass balances, key metrics including renewable electricity required, captured CO_2, hydrogen production, methane and methanol production potentials were calculated. Data for conversion efficiencies and assumptions are found in Table 15 in the Appendix.

Table 5 summarizes the main results. In terms of energy inputs, Scenario 1 would use 76% of expected excess renewable energy in Switzerland and Scenario 2 would use 100% (based on the scenario design). In contrast, Scenario 3 would require over 6 times as much electricity, posing a major scaling-up challenge.

In terms of captured carbon inputs, Scenario 1 and Scenario 2 use only a small percentage of capturable emissions by large-scale emitters in Switzerland, 11.2% and 16.5% respectively. Far from the 100% assumed in Scenario 3. This indicates that CO_2 available for capture will not limit the project's scalability.

Table 5. Results of the scale-up analysis.

	1. Reference	2. All excess renewable energy	3. All large-scale CO_2 emitters
Renewable electricity (TWh)	7.0	9.2*	56.9
Captured carbon (kt CO_2)	766*	1,134	6,863*
Renewable hydrogen production (TWh)	4.1	5.9	36.4
Methane production (TWh)	1.9	2.5	17.3
Methanol production (TWh)	1.5	2.6	13.8
Coverage of 2050 synthetic fuels demand in Switzerland (%)	31.3%	45.5%	280%
Share of captured CO_2 emissions from large-scale emitters in Switzerland (%)	11.2%*	16.5%	100%*

*Scenario assumption

Figure 7 and Figure 8 analyze the scale-up scenarios based on their required renewable hydrogen production and expected methane and methanol outputs.

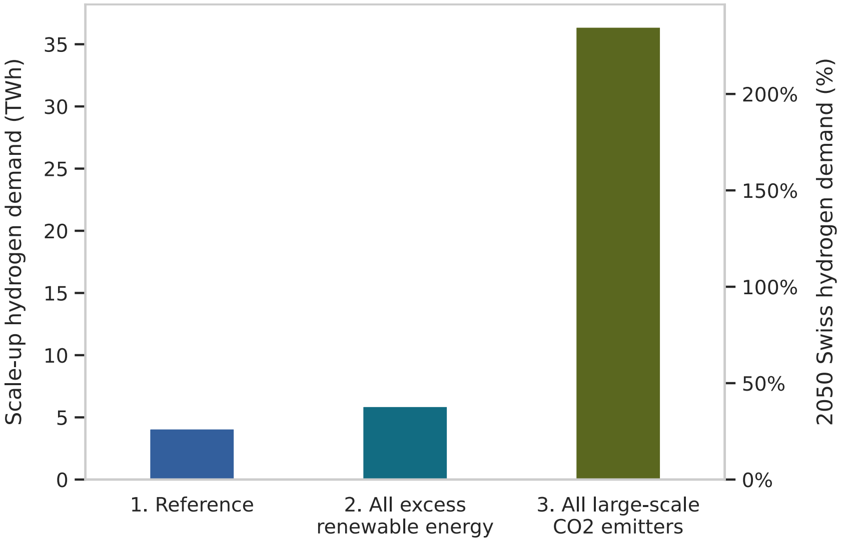

Figure 7. Total H_2 used to produce methane and methanol (TWh).

Figure 7 shows the amount of H_2 needed to produce methane and methanol in the three scenarios. In Scenarios 1 and 2, 91% and 134% of the 2050 foreseen hydrogen production would be used. Scenario 3 would require 235% of the foreseen hydrogen production and imports, which seems unfeasible. This indicates that the quantity of renewable electricity available, and thus of H_2, could be a limiting factor for scaling up the project to the scale of Scenario 3, as already identified in the viability assessment.

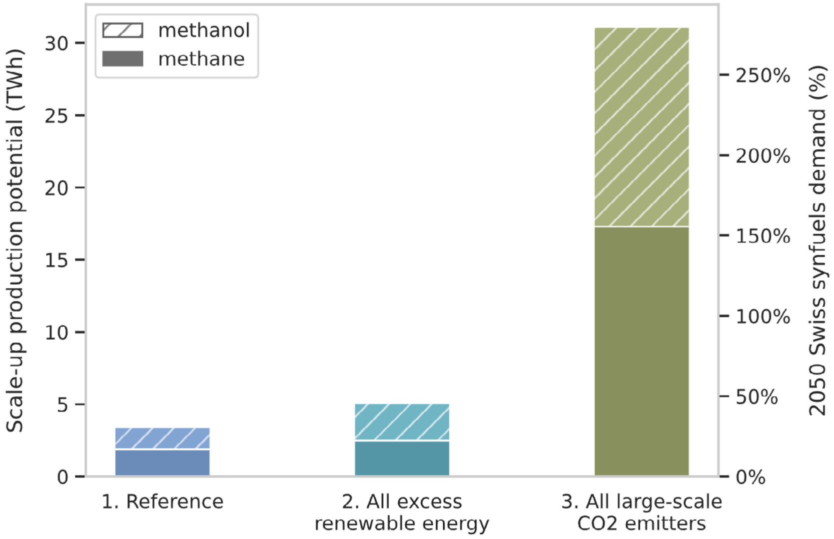

Figure 8.
Methane and methanol production potentials (TWh).

Figure 8 shows the production potentials of methane and methanol for the three scenarios. In Scenario 1, approximately one-third of the synthetic fuel demand in Switzerland would be met. Scenario 2 would raise this coverage to 46%, meaning that more than half of the demand would still need to be fulfilled by other projects or imports. In contrast, Scenario 3 would produce significantly more synthetic fuel than Switzerland is expected to require, with nearly three times the projected demand. This indicates that scaling up to such levels may be unnecessary unless considerable exports can be foreseen.

The scale-up analysis shows that the amount of CO_2 available for capture will not limit the scaling of the project. However, the availability of renewable electricity to produce hydrogen could pose a significant constraint.

Still, Scenarios 2 and 3 present significant challenges for implementation. Scenario 2 aims to utilize all surplus renewable electricity generated during the summer in Switzerland by the year 2050, and Scenario 3 seeks to capture and utilize all CO_2 emissions from large-scale emitters across the country. Therefore, Scenario 1, which focuses on two specific locations, appears to be the most feasible path to scale up.

6. ADVANTAGES AND LIMITATIONS

Compared to other tools for assessing demonstration projects for climate and energy technologies, the TAPIR assessment framework has two main advantages.

First, it integrates project and technology assessment levels into a single framework. This dual approach enables analysts to assess not only the impact and viability of individual technologies but also the technologies' role in the demonstration project. This characteristic of the TAPIR framework ensures that project assessments are constrained by the underlying technologies, avoiding cases of wishful thinking. It also explicitly takes into account the project's regional context. As a result, TAPIR provides information about the potential of the demonstration project for helping launch innovation ecosystems that eventually lead to technology commercialization.

Second, the TAPIR assessment framework's standardized and structured methodology facilitates comparison across project proposals and enables future evaluations that are consistent and fact-based. Together with the use of qualitative and quantitative data, a standardized methodology allows TAPIR to answer questions related to the project and technologies under deep uncertainty by applying the same assessment steps to different technology variations.

These two advantages make the TAPIR assessment framework a helpful tool to identify new solutions that can be quickly implemented to make immediate impacts, as well as those with the potential for significant contributions over time. A capability that is further reinforced when scale-up scenarios are included in the analysis.

The TAPIR assessment framework has some limitations. First, it partly relies on expert opinions, which may introduce biases and raises questions of sampling and truthful responses. Second, its current set of indicators, while comprehensive, may not fully capture broader societal factors like social acceptance. Third, it was developed for demonstration projects located in Switzerland, which influenced indicator selection. Fourth, it aggregates information for each proposal to inform project funding decisions. To mitigate these limitations, more robust methods to consider expert opinions could be considered, such as Delphi studies, and more indicators could be included, for example, related to social acceptance and specific geographical contexts. In addition, the analysis synthesis step could be refined to disaggregate challenges and opportunities at the project and technology levels.

7. CONCLUSIONS

Developing and commercializing new solutions for the climate and energy crises is more urgent than ever, but investors, philanthropists, companies, and governments need better tools for choosing which demonstration projects to support. This report presents the Technology And Project Impact and Readiness (TAPIR) assessment framework.

The TAPIR assessment framework provides guidelines to assess demonstration project proposals for climate and energy technologies. It helps answering questions about growth potential, including multiple criteria at the technology and project levels and considering the project's regional context, and it helps dealing with deep uncertainty by combining qualitative and quantitative data.

The TAPIR assessment framework has two main advantages. First, it has an integrated assessment of both project and technology levels based on multiple impact and viability factors that include the project's regional context. Second, its standardized and structured methodology facilitates comparison across project proposals and future evaluations that are consistent and fact-based.

Together, these advantages distinguish TAPIR from general technology assessment frameworks that ignore the growth potential of specific projects and narrow feasibility studies that neglect the technology's bigger picture.

The TAPIR assessment framework is a particularly helpful tool for philanthropy and government-led initiatives that receive multiple project proposals and aim to assess which ones have the potential to become solutions to the climate and energy crises.

8. APPENDIX

Table 6. Economic prospects indicators.

Indicator	Guiding question	Metric examples
Cost-competitiveness	*What is the technology's current cost?*	Levelized cost of electricity
Market size and future demand	*What is the technology's projected growth?*	Power demand, storage demand, fuel demand
Cost structure	*What are the technology's investment and operational costs?*	Capital expenditures (CAPEX) and operational expenditures (OPEX)
Learning rate	*How fast can technology costs be reduced through learning?*	% cost reduction per doubling of cumulative installations
Scaling factor	*How much can technology costs be reduced through scaling?*	% cost reduction per doubling of unit size
Substitution risk	*How likely is substitution by emerging alternatives?*	Number of substitutes, market size of substitutes
Competition risk	*How fierce is the competition by similar technologies?*	Number of competitors, market share of competitors
Potential for improvement	*How much (more) can the technology improve?*	Current efficiency compared to theoretical maximum efficiency

Table 7. Climate and energy impact indicators.

Indicator	Guiding question	Metric examples
CO_2 emissions reduction	*What are reasonable estimates for total CO_2 emissions reductions addressable by this technology?*	Avoided emissions, share of current emissions that can be avoided
Prominence in policy scenarios	*How prominently does this technology feature in policy scenarios?*	% of future energy demand, % of avoided emissions in scenarios
Clean energy production	*What are reasonable estimates for energy supply potential by this technology?*	Production potential, % of current/ future energy demand
Energy storage	*What are reasonable estimates of the storage potential for this technology?*	Storage potential, % of future energy storage needs
Flexibility provision	*How much load/supply flexibility can the technology provide?*	Ramping capacity, time to full capacity, time to shutdown
Lifecycle greenhouse gas emissions	*What are the lifecycle emissions of the technology?*	Emissions per energy unit

Indicator	Guiding question	Metric examples
Regional firms in the value chain	*How many and how big are regional companies in the value chain?*	Number of firms, market share of firms, annual revenues, number of employees
Commercialization by regional firms	*How many and which regional companies are selling products based on this technology?*	Number of firms, annual sales
Ongoing projects in the region	*How many and which regional companies are engaged in similar projects domestically and internationally?*	Number of projects, location of projects, size of projects, stage of projects
Export potential	*How easy and how much could be exported from the region?*	Global market trend, specific weight, infrastructure availability
Related economic capability in the region	*Are there related economic sectors whose capabilities are relevant to the technology?*	Specific sectors and capabilities, value chain overlaps/connections
Firm entries and exits	*How many firms are entering/ exiting this technology in the region?*	Number of entries and exits of firms
Actor-network in the region	*How large and connected is the network of regional actors around this technology?*	Number of nodes, links, evolution over time
Macro-economic context	*Is the broad regional economic context favorable?*	Access and cost of finance, skilled workforce availability, land/ resources, regulation
Education and research	*How many and which regional institutions have relevant education and R&D programs?*	Number of projects, funding size of projects, stage of projects

Table 8. Regional relatedness indicators.

Indicator	Guiding question	Metric examples
Economic integration	*What is the project's contribution to the local economy?*	Number of local jobs created, % of project materials and services sourced from local suppliers
Policy alignment	*What role does the technology play in local policy strategies?*	Policies to support the technologies, official endorsements from local government authorities
Institutional relationships	*How strong are the project's connections with local institutions?*	Number of formal agreements or collaborations with local organizations
Local knowledge utilization	*To what extent does the project incorporate local knowledge and expertise?*	Number of local experts involved in the project

Table 9. Local embeddedness indicators.

Table 10.
Maturity indicators.

Indicator	Guiding question	Metric examples
Technology readiness level (TRL)	*How ready is the technology for commercialization?*	TRL
Expectations	*What are the expectations about the future of this technology?*	Future market size
Deployment stage	*What stage and how many installations exist (e.g., lab, pilot, demo, commercial)?*	Number of installations and type
Technology variation	*How stable is the technology design?*	Number of design variations
Patenting activity	*How much, where, and about what are patents being filed?*	Number of patents
R&D expenditures	*How much, who, and on what is being spent for R&D on this technology?*	R&D expenses
Regulation and standards	*How stable are regulations and standards on this technology?*	Number of regulations, years of introduction, number of global/local standards

Table 11.
Scalability indicators.

Indicator	Guiding question	Metric examples
Market potential	*What is the domestic and international market potential for this technology?*	Expected market size
Largest project built	*What are the largest projects built around this technology?*	Number and size of installations
Technology complexity	*How many interfaces and components are there? How standardized are they?*	Number of interfaces and components, number of standards
Mass-production potential	*What is the need for customization for deployment units of this technology?*	Expert opinions, interviews, % of standardized components
Technology modularity	*To what extent can the technology be manufactured and produced modularly?*	Expert opinions, interviews, unit size of central component
Supply chain scalability	*To what extent can the supply chain be scaled up (input industry scalability) and automated?*	Expert opinions, interviews, unit size of central component
Geographical dependency	*To what extent does the technology depend on geographical elements (sun, minerals)?*	Expert opinions, interviews, input needs per output unit (e.g., kg critical materials / TW)

Indicator	Guiding question	Metric examples
Resource availability	*Are critical input/resources widely available? At what cost? Is there competition for them?*	Input requirement per output unit (e.g., kWh of electricity per kg H_2), available inputs
Infrastructure availability	*Is critical infrastructure and complementors available? Is it easy to access? Is there competition to access it?*	Capacity required, utilization/ congestion rates of current infrastructure
Investment trends	*How much is being invested in this technology? Is investment growing?*	Annual investment, number of projects
Skilled workforce	*Are skilled workers available? Is there competition for them?*	Employment rate, number of graduates in relevant fields per year
Integration requirements	*Does the integration of the technology in existing energy systems require new infrastructure?*	Capacity required, utilization/ congestion rates of current infrastructure
Public acceptability	*What is the public opinion about the technology? Is there or can be expected active opposition?*	Survey data, interviews, group tests
Policy support	*What is the level of public policy support?*	Number of policies, level of subsidies, policy targets for the technology
Environmental impact	*Are there environmental concerns with this technology?*	Lifecycle analysis, environmental impact analysis, local impacts
Failure rates	*Does the technology have a history of failures?*	Historical record of failures

Table 12.
Feasibility indicators.

Survey Questions

Impact

How much do you agree with the following statements?

	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
	0	1	2	3	4
Economic prospects: The Catapult technologies will achieve cost-competitiveness in 5 years.					
Economic prospects: The Catapult technologies will meet an unmet demand.					
Energy transition: The Catapult technologies will enhance the resilience of the Swiss energy system.					
Energy transition: The Catapult technologies will contribute to solving the climate crisis.					

Viability

- What are the major obstacles for scaling up the Catapult technologies?
- If you are unsure, leave items where they are.

Major obstacle	Minor or no obstacle
______ Low technological maturity (1)	______ Low technological maturity (1)
______ High technology costs (2)	______ High technology costs (2)
______ Input resource scarcity (3)	______ Input resource scarcity (3)
______ Skilled workforce scarcity (4)	______ Skilled workforce scarcity (4)
______ Lack of public support (5)	______ Lack of public support (5)
______ Regulatory barriers (6)	______ Regulatory barriers (6)
______ Lack of infrastructure (7)	______ Lack of infrastructure (7)
______ Public opposition (8)	______ Public opposition (8)

Table 13.

Impact assessment of the Project M proposal.

	Economic prospects	**Climate and energy crises**	**Regional relatedness**	**Local Embeddedness**
	Cost-competitiveness	**Global CO_2 emissions reduction**	**Swiss firms in value chain**	**Policies supporting the technology**
Water electrolysis	• Renewable hydrogen production costs: 2-12 USD/kg H_2 (15) • Hydrogen from fossil fuels production costs: 1-3 USD/kg H_2 (15)	• 4% cumulative CO_2 reduction by 2050 (14)	• Several Swiss firms are active in hydrogen production, delivery, and use in trucks.[a]	• 4.4 TWh of H_2 production by 2050 in Switzerland (19) • The Swiss Confederation published a national hydrogen strategy in December 2024.
CO_2 capture	• Captured CO_2 costs: 8-200 USD/t CO_2 (20) • EU ETS carbon pricing: 75 USD/t CO_2 (21) (22)	• 8% cumulative CO_2 reduction by 2050 (14)	• Numerous Swiss firms are active in carbon capture at different segments of the value chain.[b]	• Switzerland committed to net-zero by 2050 in 2019, and acknowledged the need for CCS and CDR technologies to mitigate or offset hard-to-abate emissions (23).
Methane synthesis	• Synthetic methane production cost: 0.05-0.4 USD/kWh (22) (24) • Natural gas prices for households in the EU in 2023: 0.12 USD/kWh (22) (25)	• In 2022, the global energy-related greenhouse gas emissions reached 41.3 $GtCO_2eq$ CO_2. • 7.1 $GtCO_2eq$ CO_2 (17%) emissions from natural gas • 3.6 $GtCO_2eq$ (9%) • methane emissions (26)	• Several Swiss companies and international companies with a presence in CH.[c]	• In 2024, the Swiss National Council and Parliament approved the use of synthetic fuels for new road vehicles as part of the revised CO_2 Act, supporting Switzerland's 2050 net-zero target and energy security (27).
Methanol synthesis	• Synthetic methanol production cost: 820-2380 USD/t (16) • Methanol from fossil fuels: 100-250 USD/t (16)	• 10.11 Mt CO_2 per year by 2030 under NZE scenarios, representing 23% of CO_2 capture needs for ammonia, methanol, and high-value chemicals (28).	• Several Swiss companies and international companies with a presence in CH.[d]	• In 2024, the Swiss National Council and Parliament approved the use of synthetic fuels for new road vehicles as part of the revised CO_2 Act, supporting Switzerland's 2050 net-zero target and energy security (27).
SAF from MeOH	• Synthetic kerosene from electrolytic hydrogen: 450-820 USD/bbl. (15) • Kerosene from fossil fuels: 45-100 USD/bbl (29,30)	• 1.9% cumulative CO_2 reduction by 2050 (14)	• Some Swiss companies and international companies with a presence in CH.[e]	• The CO_2 Act mandates aviation fuel suppliers to blend 2% sustainable fuels by 2025. SAF imports and sales have been allowed since July 2021, aligning with EU guidelines (23).

[a] H_2 Mobility Switzerland.

[b] Neustark, Climeworks, Ad Terra, and others (Swiss Carbon Removal Platform 2023).

[c] Air Liquide, MAN, Hitachi, Gaznat (CH), AlphaSynt (CH).

[d] Thyssenkrupp/Swiss Liquid Future, bse engineering/BASF, Johnson Matthey & Brandenberger AG (IRENA 2021) Metafuels, Casale (project partners).

[e] MAN (MAN 2023).

Table 14. Viability assessment of the SSFA project proposal.

	Maturity	Scalability	Feasibility
	Technology readiness level (TRL)	**Market potential**	**Resources needed and efficiency**
Water electrolysis	• TRL: 9 for PEM and alkaline electrolyzers, 8 for SOEC electrolyzers, 6 or less for others (5)	• Global 2022 demand of 95 Mt is expected to grow to 150 Mt by 2030 under NZE scenarios • Europe is 8% of global demand (15)	• Electrolyzer efficiency ranges 65-70% of lower heating value, between 48 to 51 kWh of electricity per kg of H_2 (15)
CO_2 capture	• TRL: 9 for the most mature (post-combustion) technologies based on chemical absorption or physical absorption. Most others 7-8 TRL, including for methanol synthesis (31)	• Global 2023 CO_2 capture in operation was 49 Mtpa CO_2, while planned projects reached 312 Mtpa CO_2 (32). A jump to 1024 Mtpa by 2030 and 6040 Mtpa by 2050 would be needed under NZE scenarios (14)	• Resource consumption varies by capture technology • For post-combustion technologies, energy consumption ranges between 1.1 to 1.35 MJe/kg CO_2 (306 to 375 kWh/t CO_2) (33)
Methane synthesis	• TRL: 5 for biomass gasification and methanation with CCUS (biomethane), 8 for anaerobic digestion and CO_2 separation with CCUS (biomethane) (5)	• Gas represents 12.8% of gross energy consumption in CH • CH gas demand summer 2022: 7 GWh • CH gas demand winter 2022/2023: 29.5 GWh (34)	• Assumption of the electrical energy consumption for a methanation system of a PtG plant in 2030: 25 kWh per operation hour and per installed MW (35) • The conversion rate (from CO_2 and H_2 to CH_4) can be 100% depending on the technology (36)
Methanol synthesis	• TRL: 7 (15) • Given the number of operational plants, some technologies may be at TRLs 8-9. Depending on the process, some parts may be TRLs 1-4 (37)	• Global 2022 demand of 15.9 Mt of H_2 for methanol production • Global 2030 demand of about 17.5 Mt of H_2, with 3.5 Mt of H_2 expected from low-carbon sources (15)	• To produce 1 t of methanol, about 1.38 t of CO_2 and 0.19 t of H_2 (~1.7 t of water) are needed. About 10-11 MWh of electricity is required to produce 1 t of e-methanol • With a 100 MW electrolyzer, about 225 t/d of e-methanol could be produced (16)
SAF from MeOH	• TRL: 6-7 for alcohol to jet fuel (kerosene) processes (38) • Other assessments suggest 6-9 range (39) • Ongoing projects lower the estimate to 5-6 for methane to kerosene processes (40)	• Aviation demand is expected to grow 275% by 2050, even under NZE scenarios, and synthetic hydrogen-based fuels to provide 37% of the final energy demand in aviation (14)	• Simulated studies point to a yield of ~25% for converting methanol to kerosene (41). • This suggests that resource requirements for methanol synthesis would multiply by four to about 5.5 t of CO_2 and 0.75 t of H_2 per ton of kerosene (Own estimation)

Variable	Value	Unit	Source
Electrolyzer efficiency	64.00%	% kWh H_2/kWh e	IEA FOH 2019
Methanation reactor efficiency	77.00%	% kWh CH_4/kWh H_2	IEA FOH 2019
Methanol reactor efficiency	78.50%	% kWh CH_3OH/kWh H_2	IEA FOH 2019
CO_2 capture rate	90.00%	% of emitted CO_2	Carbon Limits 2023
Lower heating value of hydrogen	33.33	kWh H_2/kg H_2	ET
Lower heating value of methane	13.90	kWh CH_4/kg CH_4	ET
Lower heating value of methanol	5.54	kWh CH_3OH /kg CH_3OH	ET
Methane to CO_2 mass ratio $CO_2 + 4*H_2 \rightarrow CH_4 + 2*H_2O$	2.750	kg CO_2/kg CH_4	Own estimation
Methanol to CO_2 mass ratio $CO_2 + 3*H_2 \rightarrow CH_3OH + H_2O$	1.375	kg CO_2/kg CH_3OH	Own estimation
Hydrogen to methane mass ratio $CO_2 + 4*H_2 \rightarrow CH_4 + 2*H_2O$	0.500	kg H_2/kg CH_4	Own estimation
Hydrogen to methanol mass ratio $CO_2 + 3*H_2 \rightarrow CH_3OH + H_2O$	0.188	kg H_2/kg CH_3OH	Own estimation

Table 15. Assumptions for scale-up analysis calculations.

9. GLOSSARY

CAPEX	Capital Expenditures
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CGES	Coalition for Green Energy and Storage
IEA	International Energy Agency
OPEX	Operational Expenditures
P2X	Power-to-X
PtG	Power-to-Gas
SAF	Sustainable Aviation Fuel
SSFA	Sustainable Synthetic Fuels Accelerator
TAPIR	Technology And Project Impact and Readiness
TRL	Technology Readiness Level

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