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POLIZERO

Swiss Policy towards Zero CO_2 Emissions compatible with European Decarbonisation Pathways

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Summary

The POLIZERO project explores how Switzerland can successfully transition its energy system to achieve net-zero greenhouse gas emissions by 2050, by identifying essential measures to reach this goal. The project focuses on three objectives: first, to identify a suite of suitable energy sector decarbonisation policies for Switzerland that appeal broadly to a wide range of stakeholders, such as policy and administration, economy and energy, consumers, manufacturing or businesses; second to assess the Swiss energy transition to net-zero GHG emissions by explicitly accounting for the interactions between Switzerland and the EU in the energy system transformation, the energy markets and energy and climate change mitigation policy; and third, to generate dynamic adaptive policy pathways to handle policy targets agilely by accounting for the uncertainties arising from different national and international contextual factors, e.g. societal, technical, economic, or demographic. The pathways consider the ideal timing for policy implementation, critical success factors, and monitoring of uncertainties affecting policy performance. POLIZERO thus offers clear, actionable guidance for meeting Switzerland's long-term energy and climate goals.

POLIZERO combined various methods, including an inventory of successful European policies, consultation with Swiss stakeholders, advanced European and Swiss energy modelling using the JRC-EU-TIMES model and explorative policy pathways using the Adaptive Policymaking Model (AIM). The insights gathered from the policy inventory, the stakeholder and energy systems modelling analyses, and from further exchanges with the Swiss Federal Administration led to four key policy packages with four underlying philosophies: subsidies, taxes, EU-wide harmonisation policies, and regulatory mandates. These packages were evaluated with the two modelling tools of POLIZERO for their effectiveness in delivering the required emissions reduction across three levels of ambition (intensity) and against 22 uncontrollable uncertain factors, such as economic and demographic developments, technology costs, resource potentials and fuel import prices and availability. By contrasting energy system transformations under these packages with net-zero requirements, critical uncertainties and success factors were identified, helping to guide policy monitoring and adjustment.

Related to **POLIZERO's first objective**, **the stakeholder analysis** performed in the project emphasises integrating transport and buildings into the EU-ETS2, adopting technology-neutral renewable incentives, carbon border tax adjustments, contracts of difference, and bilateral agreements with the EU for electricity, biofuels, and hydrogen. Stakeholders also recommend simplifying regulations, promoting clean fuels, and enhancing CO_2 transport and electric vehicle charging infrastructure. Challenges like retrofitting costs, skilled labour shortages, and social acceptance are also highlighted, some of which could be addressed through financial incentives, soft loans, carbon taxes, and mandatory energy audits.

Regarding **POLIZERO's second objective**, **the energy system analysis of three scenario pathways** of the Swiss energy system with the JRC-EU-TIMES model identifies 2025 to 2035 as a critical window for the Swiss energy transition. By 2030, much of the existing heating, transportation and industry infrastructure will need replacing. To minimise reliance on imported electricity when replacing these ageing infrastructures with more environmentally compatible ones, Switzerland must significantly expand renewable energy sources, particularly solar power, which needs to triple from today's level by 2035. Reducing the country's total final energy consumption by approximately 15% (from 2020 to 2035) through efficiency measures is also essential. Switzerland is gradually phasing out nuclear power, making the growth of domestic wind and bioenergy capacity necessary to maintain low electricity imports. By 2050, Switzerland needs to produce around 12 TWh of electricity annually from wind and bioenergy, with roughly half required during winter months.

Specific sectors require targeted actions. The energy system analysis in POLIZERO highlights the expansion of the district heating network, supported by large-scale heat pumps, which are expected to supply over 10% of district heating demand by 2035 and one-third by 2050. In transportation, adopting electric vehicles must regain momentum; by 2035, electric cars should represent 50% of the passenger car fleet to comply with anticipated EU vehicle emissions standards. In the industrial and aviation sectors, the integration of sustainable fuels and hydrogen into the Swiss energy mix is essential, driven by

the participation of these sectors in the European Emissions Trading Scheme (EU-ETS). By 2050, Switzerland's industry will require about 6 TWh of hydrogen as an energy carrier, predominantly for the chemicals sector. Meanwhile, aviation and industrial heating will depend on 90 PJ of synthetic fuels imports. Domestic electrolysis can produce two-thirds of the required hydrogen, but synthetic fuel imports from regions such as the Middle East, North Africa and Latin America will remain crucial. Capturing CO_2 emissions will be critical in addressing emissions from hard-to-abate sectors like agriculture and industrial processes. According to the scenario analysis with the JRC-EU-TIMES, Switzerland will need to capture from 6 to 10 Mt CO_2/yr by 2050, depending on whether the mitigation of these emissions occurs solely domestically or a part of these emissions are compensated abroad. Bioenergy and waste incineration with CCS for electricity and heat can contribute to up to 5.5 Mt of CO_2 capture, while industrial processes up to 3 Mt. The rest must be captured via Direct Air Capture or compensated abroad. Domestic storage of the captured emissions is limited, requiring connections to the European CO_2 transport backbone network by the 2040s, making international cooperation essential.

Concerning **POLIZERO's third objective**, **the exploration of policy pathways** with AIM emphasises aligning Swiss energy and climate policies with the EU regulations. Participation in the EU-ETS, integration within the new EU-ETS2 for buildings and transport, and transposition of the EU vehicle emissions standards into Swiss legislation provide clearer emissions reduction targets and greater reliability than carbon taxes. Under the uncertainties examined in POLIZERO, the EU-ETS and EU-ETS2, by focusing on quantity-based emissions reductions, performed more robustly than carbon taxes, which provide CO_2 price certainty but lack certainty in mitigation outcome. The analysis also shows that the transport sector is more responsive to the EU vehicle emissions standards or bans on sales of internal combustion engines than to strengthened taxation in the sector. Harmonisation with EU regulations could avoid excessively high domestic taxes, which is especially beneficial in the heating and transport sectors. If taxation is to be chosen instead of harmonising with the EU regulations, it would need to be accompanied by prohibitively high gasoline or diesel prices through additional taxes to ensure robustness across the assessed uncertainties, to ensure that the required emissions cuts will be achieved with high probabilities.

Policy implementation timing and sequencing are crucial parameters for designing effective decarbonisation policy packages. The policy exploration with AIM highlights the benefits for Switzerland in promptly aligning with EU regulations to avoid compromising its climate targets. Initially, Switzerland could transpose these regulations into the national legislation at moderate intensity until 2035, after which ambition must increase to match the European Commission's higher aspirations. During this initial phase, substantial financial incentives will be necessary to accelerate the decarbonisation. Alternatively, if Switzerland focuses mainly on domestic tax-based approaches or regulatory mandates, these policies must be introduced immediately at higher intensities than current levels. Financial incentives, particularly targeting the residential sector, can kick-start the transition but will become less effective after 2030.

POLIZERO also identifies that combining EU harmonisation policies or taxes with regulatory mandate measures is possible. Two promising pathways emerged: the first combines moderate ambition of these packages and high subsidies until 2035, after which subsidies are phase out and intensities of the EU harmonisation or taxes and regulatory mandates increases; the second starts immediately with high policy intensity of these two packages, using subsidies only as optional and complementary measures. Overall, the analysis suggests that the implementation ambition of decarbonisation policy packages substantially increases after 2035, while subsidies alone cannot deliver the required emissions cuts. In addition, we find that changing policies abruptly could risk achieving the net-zero target by 2050.

Ultimately, the analyses defines three robust policy pathways with a high probability (>75%) of achieving net-zero emissions by 2050: (1) starting with high-intensity subsidies and moderate EU harmonisation policies and obligations until 2035, followed by to high-intensity EU harmonisation and obligations while phasing out subsidies; (2) similar to the first pathway, but retaining low-level subsidies beyond 2035; and (3) starting with high subsidies combined with moderate-intensity levies and regulatory mandates until 2030, subsequently shifting to high-intensity levies and mandates, with subsidies reduced to low intensity by 2035 and completely phased out post-2040. Both in the case of EU harmonisation and levies, two additional pathways were also explored and found viable, in which the intensities of the policy packages are kept constant.

Robust monitoring of uncertainties—such as synthetic fuel import prices and availability, bioenergy potential, gasoline and natural gas prices, as well as renewable electricity production—is essential to achieving high probabilities of success in achieving net-zero emissions by 2050. For instance, if the country's bioenergy potential becomes limited or below 100 PJ, greater imports of sustainable synthetic fuels would be necessary to ensure an adequate low-carbon fuel supply. To this end, EU harmonisation policies and regulatory mandates are less dependent on factors like fuel prices or energy imports and thus offer greater resilience compared to tax-based measures. Policies based on taxes require stable or increasing fossil fuel prices to remain effective. For example, gasoline prices should not fall more than 9% from 2020 to attain a price-response effect on the sector. Maintaining consistently high ambition in policy implementation, particularly with the harmonisation with the EU regulation and the regulatory mandates, significantly enhances the probability of meeting net-zero targets, reaching up to a 95% success rate across various scenarios. However, implementing these high-intensity policies could represent abrupt policy changes compared to the status quo, and their broader social and economic impacts need careful consideration and further exploration.

Overall, POLIZERO reveals increasing EU policy spillovers in Switzerland's energy system through the participation in an increasingly more ambitious EU-ETS and a potential adoption of other EU-wide regulations, such as vehicle emissions and other energy performance standards, or the EU-ETS2. The project's findings clearly underline the necessity of robust cooperation with the EU. Switzerland's growing reliance on imported biofuels, synthetic fuels, and hydrogen necessitates solid bilateral agreements and coordinated infrastructure development. In the short term, maintaining existing nuclear power plant operations will help bridge the gap as Switzerland transitions, ensuring energy security and reducing reliance on energy imports.

POLIZERO was an innovative research initiative that resulted in two PhD theses, peer-reviewed publications, and further collaborations with Swiss and European projects. It established a solid foundation for future energy and policy transition studies, especially regarding interactions between Swiss and European energy systems. However, the project had several important limitations. Stakeholder representation was incomplete due to COVID-19 restrictions and time and budget constraints, limiting insights from some critical experts involved in energy policy implementation.

The JRC-EU-TIMES model focuses only on the energy system, excluding broader macro- and microeconomic impacts, such as energy service demand feedback on their own prices or how policies would be financed or their revenues redistributed in the economy. As a result, detailed policy cost estimations could not be included. The model did not cover certain sectors, such as non-CO_2 greenhouse gas emissions outside the energy sector. As JRC-EU-TIMES is a partial equilibrium model, mechanisms like carbon border tax adjustment or even contract of differences cannot be straightforwardly represented. Also, the JRC-EU-TIMES model needs more detail in the intra-annual resolution and an even higher detail in some of the demand sectors to represent a broader range of policies. Finally, the adoption of the policy is assumed ex-ante, without considering any social (in-)acceptance.

The AIM framework allowed the exploration of pathways forward in time and the simulation of pathways sequentially, but it did not enable backward optimisation from the 2050 net-zero targets. Furthermore, the phase-out and lead-in effects of policies in the policy exploration could not be captured, implying that a slower or quicker model response to the actual policy implementation can be observed in the results. The AIM tool can be further improved to capture the pathway-wide interactions during policy shifts, therefore minimising instances of infeasibilities, which are a product of mathematical implementation rather than actual limitations. The uncertainty analysis was also limited due to computational resource constraints, restricting the number of context scenarios that the JRC-EU-TIMES could explore, thus limiting deeper insights from the AIM tool.

POLIZERO clearly illustrates the importance of immediate and sustained policy action for Switzerland to achieve net-zero emissions by 2050. Ensuring timely policy implementation, strong alignment with EU frameworks, and careful monitoring of uncertainties will position Switzerland effectively to meet its climate and energy goals.

Zusammenfassung

Im POLIZERO-Projekt wird untersucht, wie die Schweiz ihr Energiesystem erfolgreich umstellen kann, um bis 2050 Netto-Null Treibhausgasemissionen zu erreichen, indem essenzielle Massnahmen zur Erreichung dieses Ziels identifiziert werden. Das Projekt verfolgt drei Ziele: erstens die Identifizierung einer Reihe geeigneter Massnahmen zur Dekarbonisierung des Energiesektors für die Schweiz, die eine breite Akzeptanz bei unterschiedlichen Interessengruppen wie Politik und Verwaltung, Wirtschaft und Energie, Konsumenten, Industrie oder Unternehmen finden können; zweitens, die schweizerische Energiewende zu Netto-Null Emissionen zu bewerten, wobei explizit die Wechselwirkungen zwischen der Schweiz und der EU hinsichtlich der Transformation des Energiesystems, der Energiemärkte sowie der Energie- und Klimaschutzpolitik berücksichtigt werden; und drittens, dynamische adaptive Politikanpassungspfade zu entwickeln, um politische Ziele flexibel zu verfolgen, unter Berücksichtigung der Unsicherheiten, die sich aus verschiedenen nationalen und internationalen Kontextfaktoren ergeben, z.B. gesellschaftlichen, technischen, wirtschaftlichen oder demografischen. Diese Pfade berücksichtigen den idealen Zeitpunkt der Politikimplementierung, kritische Erfolgsfaktoren sowie das Monitoring von Unsicherheiten, die die Politikwirksamkeit beeinflussen. POLIZERO bietet somit klare, umsetzbare Handlungsleitlinien zur Erreichung der langfristigen Energie- und Klimaziele der Schweiz.

POLIZERO kombiniert verschiedene Ansätze: Eine Bestandsaufnahme erfolgreicher europäischer Politiken, Konsultationen mit Schweizer Stakeholdern, fortschrittliche europäische und schweizerische Energiemodellierung mit dem JRC-EU-TIMES-Modell, sowie eine explorative politische Pfadanalyse mit dem Adaptive Policymaking Model (AIM). Die gewonnenen Erkenntnisse führten zu vier zentralen Politikpaketen mit den zugrunde liegenden Ansätzen von Subventionen, Steuern, EU-weiten Harmonisierungspolitiken und regulatorischen Vorschriften. Diese Pakete wurden hinsichtlich ihrer Effektivität bei der Erreichung der erforderlichen Emissionsreduktionen über drei Ambitionsstufen und gegenüber 22 unkontrollierbaren Unsicherheiten, wie zum Beispiel wirtschaftlichen und demografischen Entwicklungen, Technologiekosten, Ressourcenpotenzialen sowie Brennstoffimportpreisen und -verfügbarkeit, bewertet. Durch den Vergleich der Energiesystemtransformation durch diese Pakete mit Netto-Null-Anforderungen wurden kritische Unsicherheiten und Erfolgsfaktoren identifiziert, die das Monitoring und die Anpassung der Politik unterstützen.

Im Hinblick auf **das erste Ziel von POLIZERO** betont die Stakeholderanalyse in POLIZERO die Integration des Verkehrs- und Gebäudesektors in das EU-ETS2, technologieoffene Anreize für erneuerbare Energien, CO_2-Grenzausgleichsabgaben, sowie Differenzverträge und bilaterale Abkommen mit der EU für Elektrizität, Biokraftstoffe und Wasserstoff. Weiterhin wurden Vereinfachungen der Regulierung, die Förderung sauberer Kraftstoffe, der Ausbau der CO_2-Transportinfrastruktur, und der Ausbau der Ladeinfrastruktur für Elektrofahrzeuge empfohlen. Herausforderungen wie Renovationskosten, Fachkräftemangel und soziale Akzeptanz wurden ebenfalls hervorgehoben, die teilweise durch finanzielle Anreize, günstige Kredite, CO_2-Steuern und verpflichtende Energieaudits angegangen werden könnten.

Bezüglich **POLIZEROs zweitem Ziel** identifiziert die Energiesystemanalyse drei Szenariopfade mit dem JRC-EU-TIMES-Modell, wobei 2025 bis 2035 die kritische Phase für die Schweizer Energiewende darstellt. Bis 2030 müsste ein Grossteil der bestehenden Infrastruktur in den Bereichen Heizung, Verkehr und Industrie ersetzt werden. Um Abhängigkeiten von importiertem Strom zu minimieren, muss die Schweiz erneuerbare Energien erheblich ausbauen, insbesondere Solarenergie, die bis 2035 auf das Dreifache steigen müsste. Gleichzeitig ist eine Reduktion des gesamten Energieverbrauchs um etwa 15% erforderlich. Die Schweiz steigt schrittweise aus der Kernenergie aus, wodurch der Ausbau der inländischen Wind- und Bioenergiekapazität notwendig wird, um die Stromimporte niedrig zu halten. Bis 2050 sollte die Schweiz jährlich etwa 12 TWh Strom aus Wind- und Bioenergie erzeugen, wobei etwa die Hälfte davon in den Wintermonaten benötigt wird.

Bestimmte Energiesektoren erfordern gezielte Massnahmen. Die Energiesystemanalyse in POLIZERO hebt den Ausbau des Fernwärmenetzes hervor, das durch Grosswärmepumpen unterstützt wird, die bis 2035 voraussichtlich über 10% des Fernwärmebedarfs und bis 2050 ein Drittel des Bedarfs decken

werden. Im Verkehr sollten bis 2035 Elektroautos 50% der Pkw-Flotte ausmachen, um die voraussichtlichen EU-Normen für Fahrzeugemissionen zu erfüllen. In der Industrie und in der Luftfahrt ist die Integration nachhaltiger Kraftstoffe und von Wasserstoff in den Schweizer Energiemix von entscheidender Bedeutung, da diese Sektoren am Europäischen Emissionshandelssystem (EU-ETS) teilnehmen. Bis 2050 wird die Schweizer Industrie etwa 6 TWh Wasserstoff als Energieträger benötigen, vor allem im Chemiesektor. In der Zwischenzeit werden die Luftfahrt und die industriellen Heizungen von Importen synthetischer Brennstoffe (90 PJ) abhängig sein. Die inländische Elektrolyse kann zwei Drittel des benötigten Wasserstoffs produzieren, aber die Importe synthetischer Brennstoffe aus Regionen wie dem Nahen Osten, Nordafrika und Lateinamerika werden weiterhin von entscheidender Bedeutung sein. Die Abscheidung von CO_2-Emissionen wird entscheidend sein für Emissionen aus schwer zu reduzierenden Sektoren wie der Landwirtschaft und industriellen Prozessen. Gemäss der Szenarioanalyse mit dem JRC-EU-TIMES muss die Schweiz bis 2050 zwischen 6 und 10 Mio. tCO_2/Jahr abscheiden, je nachdem, ob die Reduzierung dieser Emissionen ausschliesslich im Inland erfolgt oder ein Teil im Ausland kompensiert wird. Bioenergie- und Kehrichtverwertungsanlagen mit CCS für Strom und Wärme können mit bis zu 5,5 $MtCO_2$-Abscheidung beitragen, während industrielle Prozesse bis zu 3 Mt beitragen können. Der Rest muss durch direkte Luftabscheidung oder im Ausland kompensiert werden. Die inländische Speicherung der abgeschiedenen Emissionen ist begrenzt, sodass bis 2040 Anschlüsse an das europäische CO_2-Transport-Backbone-Netz erforderlich sind, was eine internationale Zusammenarbeit unerlässlich macht.

Was das **dritte Ziel von POLIZERO** betrifft, so betont **die Erforschung politischer Wege** in der Analyse mit AIM die Angleichung der Schweizer Energie- und Klimapolitik an die EU-Vorschriften. Die Teilnahme am EU-ETS, die Integration in das neue EU-ETS2 für Gebäude und für Verkehr und die Umsetzung der EU-Fahrzeugemissionsnormen in die Schweizer Gesetzgebung bieten klarere Emissionsminderungsziele und eine grössere Zuverlässigkeit als CO_2-Steuern. Unter den in POLIZERO untersuchten Unsicherheiten schnitten das EU-ETS und das EU-ETS2 durch mengenbasierte Emissionsreduktionen besser ab als CO_2-Steuern, die zwar eine Preissicherheit für CO_2 bieten, aber keine Gewissheit über die Ergebnisse der Emissionsminderung. Die Analyse zeigt auch, dass der Verkehrssektor stärker auf die EU-Fahrzeugemissionsnormen oder Verkaufsverbote für Verbrennungsmotoren reagiert als auf eine verstärkte Besteuerung in diesem Sektor. Durch eine Harmonisierung mit den EU-Vorschriften könnten übermässig hohe inländische Steuern vermieden werden, was insbesondere im Heizungs- und Verkehrssektor von Vorteil ist. Wenn statt einer Harmonisierung mit den EU-Vorschriften eine Besteuerung gewählt wird, müsste diese durch zusätzliche Steuern mit sehr hohen Benzin- oder Dieselpreisen einhergehen, um die Robustheit gegenüber den bewerteten Unsicherheiten zu gewährleisten und sicherzustellen, dass die erforderlichen Emissionssenkungen mit hoher Wahrscheinlichkeit erreicht werden.

Der Zeitpunkt und die Abfolge der Umsetzung von Richtlinien sind entscheidende Parameter für die Gestaltung wirksamer Massnahmenpakete zur Dekarbonisierung. Die Untersuchung der Politikoptionen mit AIM zeigt die Vorteile für die Schweiz auf, wenn sie sich an EU-Vorschriften anpasst, um ihre Klimaziele zu erreichen. Zunächst könnte die Schweiz diese Vorschriften bis 2035 mit mässiger Intensität in die nationale Gesetzgebung umsetzen. Danach muss das Engagement erhöht werden, um den höheren Ansprüchen der Europäischen Kommission gerecht zu werden. In dieser Anfangsphase werden erhebliche finanzielle Anreize erforderlich sein, um die Dekarbonisierung zu beschleunigen. Wenn sich die Schweiz hingegen hauptsächlich auf steuerbasierte Ansätze oder Regulierungsaufträge im Inland konzentriert, müssen diese Maßnahmen sofort mit einer höheren Intensität als derzeit eingeführt werden. Finanzielle Anreize, die insbesondere auf den Wohnsektor abzielen, können den Übergang ankurbeln, werden aber nach 2030 an Wirksamkeit verlieren.

POLIZERO stellt auch fest, dass eine Kombination von EU-Harmonisierungsmassnahmen und von Steuern mit Massnahmen im Rahmen von Regulierungsaufträgen möglich ist. Es haben sich zwei vielversprechende Wege herauskristallisiert: Der erste kombiniert die moderaten Ziele dieser Pakete mit hohen Subventionen bis 2035, danach werden die Subventionen auslaufen und die Intensität der EU-Harmonisierung oder der Steuern und Regulierungsmandate wird zunehmen; der zweite beginnt sofort mit einer hohen politischen Intensität dieser beiden Pakete, wobei Subventionen nur als optionale und ergänzende Massnahmen eingesetzt werden. Insgesamt deutet die Analyse darauf hin, dass die Umsetzungsambitionen der Dekarbonisierungspolitikpakete nach 2035 erheblich zunehmen, während Subventionen allein nicht die erforderlichen Emissionssenkungen bewirken können. Darüber hinaus stellen wir fest, dass ein abrupter Politikwechsel das Risiko birgt, das Netto-Null-Ziel bis 2050 nicht zu erreichen.

Schlussendlich definiert die Analyse drei robuste politische Wege, die mit hoher Wahrscheinlichkeit (>75%) Netto-Null-Emissionen bis 2050 erreichen: (1) Beginnend mit intensiven Subventionen und moderaten EU-Harmonisierungsmaßnahmen und -verpflichtungen bis 2035, gefolgt von intensiven EU-Harmonisierungsmaßnahmen und -verpflichtungen bei gleichzeitiger Abschaffung der Subventionen; (2) ähnlich wie beim ersten Weg, aber unter Beibehaltung niedriger Subventionen über das Jahr 2035 hinaus; und (3) beginnend mit hohen Subventionen in Kombination mit Abgaben und Regulierungsauflagen mittlerer Intensität bis 2030, anschliessend Übergang zu Abgaben und Auflagen hoher Intensität, wobei die Subventionen bis 2035 auf eine niedrige Intensität reduziert und nach 2040 vollständig eingestellt werden. Sowohl im Falle der EU-Harmonisierung als auch der Abgaben wurden zwei zusätzliche Wege untersucht und für tragfähig befunden, bei denen die Intensität der Massnahmenpakete konstant gehalten wird.

Eine konstante Nachverfolgung von Unsicherheiten – wie z. B. Importpreise und Verfügbarkeit synthetischer Kraftstoffe, Bioenergiepotenzial, Benzin- und Erdgaspreise sowie die Stromerzeugung aus erneuerbaren Energien – ist unerlässlich, um eine hohe Erfolgswahrscheinlichkeit bei der Erreichung von Netto-Null-Emissionen bis 2050 zu erreichen. Wenn beispielsweise das Bioenergiepotenzial des Landes begrenzt wird oder unter 100 PJ fällt, wären grössere Importe nachhaltiger synthetischer Kraftstoffe erforderlich, um eine angemessene Versorgung mit kohlenstoffarmen Kraftstoffen sicherzustellen. Die Harmonisierungsmassnahmen und Regulierungsmandate der EU sind hingegen weniger von Faktoren wie Kraftstoffpreise oder Energieimporte abhängig und bieten daher eine grössere Widerstandsfähigkeit im Vergleich zu steuerlichen Massnahmen. Steuerbasierte Massnahmen erfordern stabile oder steigende Preise für fossile Brennstoffe, um wirksam zu bleiben. Beispielsweise sollten die Benzinpreise ab 2020 nicht mehr als 9% fallen, um einen Preisreaktionseffekt im Sektor zu erzielen. Die Beibehaltung einer konstant hohen Rate bei der Umsetzung der Politik, insbesondere bei der Harmonisierung mit der EU-Verordnung und den Regulierungsmandaten, erhöht die Wahrscheinlichkeit, die Netto-Null-Ziele zu erreichen erheblich und erreicht in verschiedenen Szenarien eine Erfolgsquote von bis zu 95%. Die Umsetzung dieser (hoch-)intensiven Richtlinien könnte jedoch im Vergleich zum Status quo abrupte politische Veränderungen darstellen, und ihre breiteren sozialen und wirtschaftlichen Auswirkungen müssen sorgfältig abgewogen und weiter untersucht werden.

Insgesamt zeigt POLIZERO zunehmende Auswirkungen der EU-Politik auf das Energiesystem der Schweiz durch die Teilnahme an einem zunehmend umfassenderen EU-ETS und die mögliche Übernahme anderer EU-weiter Vorschriften, wie z. B. Fahrzeugemissionen und andere Energieeffizienzstandards oder das EU-ETS2. Die Ergebnisse des Projekts unterstreichen deutlich die Notwendigkeit einer soliden Zusammenarbeit mit der EU. Die zunehmende Abhängigkeit der Schweiz von importierten Biokraftstoffen, synthetischen Kraftstoffen und Wasserstoff erfordert solide bilaterale Abkommen und eine koordinierte Infrastrukturentwicklung. Kurzfristig wird die Aufrechterhaltung des Betriebs bestehender Kernkraftwerke dazu beitragen, eine Stromlücke während der Energiewende der Schweiz zu verhindern, die Energiesicherheit zu gewährleisten und die Abhängigkeit von Energieimporten zu verringern.

POLIZERO war eine innovative Forschungsprojekt, die zu zwei Doktorarbeiten, Peer-Review-Publikationen und weiteren Kooperationen mit schweizerischen und europäischen Projekten führte. Es schuf eine solide Grundlage für zukünftige Studien zum Energie- und Politikwandel, insbesondere im Hinblick auf die Wechselwirkungen zwischen den schweizerischen und europäischen Energiesystem. Das Projekt hatte jedoch mehrere wichtige Einschränkungen. Die Vertretung der Interessengruppen war aufgrund von COVID-19-Beschränkungen sowie Zeit- und Budgetbeschränkungen unvollständig, was die Erkenntnisse einiger kritischer Experten, die an der Umsetzung der Energiepolitik beteiligt waren, einschränkte.

Das JRC-EU-TIMES-Modell konzentriert sich nur auf das Energiesystem und schliesst umfassendere makro- und mikroökonomische Auswirkungen aus, wie z. B. der Rückkopplung der Nachfrage nach Energiedienstleistungen auf ihre eigenen Preise oder die Frage, wie politische Maßnahmen finanziert oder ihre Einnahmen in der Wirtschaft umverteilt würden. Daher konnten detaillierte Kostenschätzungen für politische Massnahmen nicht einbezogen werden. Das Modell deckte bestimmte Sektoren nicht ab, wie z.B. die Emissionen von Nicht-CO_2-Treibhausgasen ausserhalb des Energiesektors. Da es sich bei JRC-EU-TIMES um ein partielles Gleichgewichtsmodell handelt, können Mechanismen wie der CO_2-Grenzausgleich oder Differenzverträge nicht direkt dargestellt werden. Ausserdem benötigt das JRC-EU-TIMES-Modell mehr Details in der unterjährigen Auflösung und noch detailliertere Informationen in einigen Nachfragesektoren, um ein breiteres Spektrum an politischen Massnahmen abzubilden. Schliesslich wird die Annahme der Politik ex ante angenommen, ohne die gesellschaftliche (Nicht-)Akzeptanz zu berücksichtigen.

Der AIM-Rahmen ermöglichte die Analyse Zukunftswegen und die Simulation verschiedener Wegen nacheinander, aber er ermöglichte keine Rückwärtsoptimierung von den Netto-Null-Zielen vom Jahr 2050 aus. Darüber hinaus konnten die Auslauf- und Einführungseffekte von Massnahmen in der Massnahmenuntersuchung nicht erfasst werden, was bedeutet, dass in den Ergebnissen eine langsamere oder schnellere Modellreaktion auf die tatsächliche Umsetzung der Massnahmen zu beobachten ist. Das AIM-Tool kann weiter verbessert werden, um die pfadweiten Interaktionen während des Politikwechsels zu erfassen und so Fälle von Undurchführbarkeit zu minimieren, die eher ein Produkt der mathematischen Umsetzung als tatsächlicher Einschränkungen sind. Die Unsicherheitsanalyse war auch aufgrund von Einschränkungen der Rechenressourcen begrenzt, wodurch die Anzahl der Kontextszenarien, die JRC-EU-TIMES untersuchen konnte, begrenzt wurde, was wiederum tiefere Analyse im AIM-Tool einschränkte.

POLIZERO veranschaulicht deutlich, wie wichtig sofortige und nachhaltige politische Maßnahmen für die Schweiz sind, um bis 2050 Netto-Null-Emissionen zu erreichen. Durch die rechtzeitige Umsetzung politischer Maßnahmen, eine starke Ausrichtung an den EU-Rahmenbedingungen und eine sorgfältige Überwachung von Unsicherheiten wird die Schweiz in die Lage versetzt, ihre Klima- und Energieziele zu erreichen.

Résumé

Le projet POLIZERO explore comment la Suisse peut réussir la transition de son système énergétique afin d’atteindre la neutralité carbone d’ici 2050, en identifiant les mesures essentielles pour parvenir à cet objectif. Le projet s’articule autour de trois objectifs : Premièrement, identifier un ensemble de politiques de décarbonisation du secteur énergétique adaptées à la Suisse, susceptibles de rallier un large éventail de parties prenantes, tels que les décideurs politiques et administratifs, les secteurs de l’économie et de l'énergie, les consommateurs, l‘industrie ou les entreprises ; deuxièmement, évaluer la transition énergétique suisse vers la neutralité en gaz à effet de serre (GES) en tenant compte explicitement des interactions entre la Suisse et l'UE dans la transformation du système énergétique, les marchés de l'énergie ainsi que les politiques énergétiques et climatiques; et troisièmement, générer des trajectoires politiques adaptatives dynamiques pour atteindre les objectifs politiques avec agilité en tenant compte des incertitudes liées à de différents facteurs contextuels nationaux et internationaux,(ex. sociétaux, techniques, économiques ou démographiques). Ces trajectoires tiennent compte du moment idéal pour la mise en œuvre de la politique, des facteurs clés de réussite et le suivi des incertitudes affectant la performance de la politique. POLIZERO offre ainsi des orientations claires et concrètes pour atteindre les objectifs énergétiques et climatiques à long terme de la Suisse.

POLIZERO a combiné plusieurs méthodes, notamment un inventaire des politiques européennes ayant fait leurs preuves, consultation des parties prenantes suisses, une modélisation énergétique européenne et suisse avancée à l'aide du modèle JRC-EU-TIMES, ainsi que l’exploration de trajectoires politiques à l'aide du modèle de planification adaptative des politiques (AIM). Les conclusions tirées de l'inventaire des politiques, des analyses des parties prenantes et de la modélisation des systèmes énergétiques, ainsi que des échanges supplémentaires avec l'administration fédérale suisse, ont permis de définir quatre ensembles de politiques clés fondées sur quatre philosophies distinctes : subventions, taxes, l'harmonisation des politiques à l'échelle de l'UE et les mandats réglementaires. Ces ensembles

ont été évalués à l'aide des deux outils de modélisation de POLIZERO afin de mesurer leur efficacité à réduire les émissions selon trois niveaux d'ambition (intensité) et en tenant compte de 22 facteurs d'incertitude incontrôlables, tels que les développements économiques et démographiques, les coûts technologiques, le potentiel des ressources et les prix et la disponibilité des importations de combustibles. En comparant les transformations des systèmes énergétiques dans le cadre de ces différents ensembles de politiques aux exigences de la neutralité carbone, les incertitudes critiques et les facteurs clés de réussite ont été identifiés, contribuant ainsi à orienter le suivi et l'ajustement des politiques.

En rapport avec le **premier objectif de POLIZERO**, **l'analyse des parties prenantes** réalisée dans le cadre de POLIZERO a mis l'accent sur l'intégration des transports et des bâtiments dans l'EU-ETS2, l'adoption de mesures d'incitation en faveur des énergies renouvelables neutres sur le plan technologique , de mettre en place des ajustements de la taxe carbone aux frontières, des contrats de différence ainsi que des accords bilatéraux avec l'UE concernant l'électricité, les biocarburants et l'hydrogène. Ils ont également recommandé de simplifier les réglementations, de promouvoir les carburants propres, et renforcer les infrastructures de recharge des véhicules électriques et de transport de CO_2. Des défis tels que les coûts de rénovation, la pénurie de main-d'œuvre qualifiée et l'acceptation sociale des mesures ont également été soulignés, dont certains pourraient être surmontés grâce à des incitations financières, des prêts à taux préférentiels, des taxes carbones et des audits énergétiques obligatoires.

En ce qui concerne le **deuxième objectif de POLIZERO**, **l'analyse de trois scénarios** du système énergétique suisse à l'aide du modèle JRC-EU-TIMES, a identifié la période 2025-2035 comme une fenêtre critique pour la transition énergétique suisse. D'ici 2030, une grande partie de l'infrastructure existante pour le chauffage, le transport et l'industrie devra être remplacée. Afin de réduire la dépendance vis-à-vis des importations d'électricité lors du remplacement de ces infrastructures vieillissantes par des alternatives plus respectueuses de l'environnement, il sera impératif pour la Suisse de développer significativement les énergies renouvelables, en particulier l'énergie solaire, dont a production devra être tripler d'ici 2035 par rapport à son niveau actuel. Il est également essentiel de réduire la consommation totale d'énergie du pays d'environ 15 % grâce à des mesures d'efficacité énergétique. Le désengagement progressif du nucléaire en Suisse accentue la nécessité d'augmenter les capacités éoliennes et bioénergétiques nationales, afin de maintenir les importations d'électricité à un niveau faible. D'ici 2050, la Suisse devra produire environ 12 TWh d'électricité par an à partir de l'énergie éolienne et de la bioénergie, dont environ la moitié pendant les mois d'hiver.

Certains secteurs nécessitent des actions ciblées. L'analyse du système énergétique menée dans le cadre de POLIZERO met en évidence l'expansion du réseau de chauffage à distance, soutenue par des pompes à chaleur à grande échelle, qui devraient couvrir plus de 10 % de la demande de chauffage à distance, d'ici à 2035 et à un tiers d'ici à 2050. Dans le secteur des transports, l'adoption de véhicules électriques doit reprendre son élan ; d'ici 2035, les voitures électriques devraient représenter 50 % du parc automobile de tourisme pour se conformer aux normes d'émissions prévues par l'UE. Dans les secteurs de l'industrie et de l'aviation, l'intégration des carburants durables et de l'hydrogène dans le bouquet énergétique suisse est essentielle, motivée par la participation de ces secteurs au système européen d'échange de quotas d'émission (EU-ETS). À l'horizon 2050, l'industrie suisse aura besoin d'environ 6 TWh d'hydrogène comme vecteur énergétique, principalement pour le secteur chimique. Par ailleurs, l'aviation et le chauffage industriel dépendront de 90 PJ d'importations de carburants synthétiques. La production domestique par électrolyse pourra couvrir deux tiers des besoins en hydrogène, mais les importations de combustibles synthétiques en provenance de régions telles que le Moyen-Orient, l'Afrique du Nord et l'Amérique latine resteront cruciales. La captation du CO2 sera essentielle pour lutter contre les émissions provenant de secteurs difficiles à décarboner, tels que l'agriculture et certains processus industriels. Selon l'analyse de scénarios réalisée avec le JRC-EU-TIMES, la Suisse devra capter entre 6 à 10 millions de tonnes de CO_2 par an d'ici à 2050, selon que l'atténuation de ces émissions se fasse exclusivement au niveau national ou qu'une partie de ces émissions soit compensée à l'étranger. La bioénergie et l'incinération des déchets avec CCS pour la production d'électricité et de chaleur pourraient permettre de jusqu'à 5,5 Mt de CO_2, tandis que les processus industriels pourraient en capter jusqu'à 3 Mt. Le reste devra être capté par des technologies de captage direct dans l'air ou compensé à l'étranger. La capacité de stockage domestique des émissions capturées est limitée, il sera nécessaire, dès les années 2040, de raccorder la Suisse au réseau dorsal européen de transport du CO2, rendant ainsi la coopération internationale indispensable.

En ce qui concerne le **troisième objectif de POLIZERO**, **l'exploration des trajectoires politiques** avec l'AIM met en avant l'importance d'un alignement des politiques énergétiques et climatiques suisses avec les réglementations de l'UE. La participation à l'EU-ETS, l'intégration au nouveau systèmeEU-ETS2 pour les secteurs du bâtiment et des transports, et la transposition des normes européennes d'émissions des véhicules dans la législation suisse fournissent des objectifs de réduction des émissions plus clairs et offrent une plus grande fiabilité que la simple mise en place de taxes carbone. Dans le cadre des incertitudes examinées dans POLIZERO, les systèmes EU-ETS et EU-ETS2, en misant sur des réductions quantitatives des émissions, se sont révélés plus robustes que les taxes carbones, qui garantissent un prix du CO2 mais ne fournissent pas la même certitude sur les résultats de réduction des émissions. L'analyse montre également que le secteur des transports réagit davantage aux normes européennes d'émissions des véhicules ou aux interdictions de vente de moteurs à combustion interne qu'au renforcement de la fiscalité dans ce secteur. L'harmonisation avec les réglementations de l'UE pourrait permettre d'éviter des niveaux excessifs de taxation domestique, ce qui est particulièrement bénéfique dans les secteurs du chauffage et des transports. Dans le cas où la taxation serait préférée à l'harmonisation avec les réglementations de l'UE, il faudrait que les prix de l'essence ou du diesel soient prohibitifs en raison de taxes supplémentaires afin de garantir une robustesse face aux incertitudes évaluées et d'assurer que les réductions d'émissions requises soient atteintes avec une probabilité élevée.

Le calendrier et l'enchaînement de la mise en œuvre des politiques sont des paramètres cruciaux pour la conception de paquets de politiques de décarbonisation efficaces. L'exploration des politiques avec le modèle AIM met en évidence les avantages pour la Suisse de s'aligner rapidement sur les réglementations de l'UE afin d'éviter de compromettre ses objectifs climatiques. Dans un premier temps, la Suisse pourrait transposer ces réglementations dans la législation nationale avec une intensité modérée jusqu'en 2035, puis augmenter son niveau d'ambition afin de correspondre aux aspirations plus élevées fixés par la Commission européenne. Au cours de cette phase initiale, des incitations financières substantielles seront nécessaires pour accélérer la décarbonisation. Par ailleurs, si la Suisse se concentre principalement sur des approches fiscales nationales ou des mandats réglementaires, ces politiques devront être introduites immédiatement avec des intensités supérieures aux niveaux actuels. Les incitations financières, ciblant en particulier le secteur résidentiel, peuvent servir de levier initial pour amorcer la transition, mais elles perdront de leur efficacité après 2030.

POLIZERO souligne également qu'il est possible de combiner les politiques d'harmonisation ou les taxes de l'UE avec des mesures de mandat réglementaire. Deux voies prometteuses se dégagent : la première combine l'ambition modérée de ces paquets et des subventions élevées jusqu'en 2035, après cette date, les subventions sont progressivement supprimées et l'intensité de l'harmonisation de l'UE ou des taxes et des mandats réglementaires est renforcée.; la seconde trajectoire commence immédiatement avec une forte intensité politique de ces deux types e mesures, en utilisant les subventions uniquement en tant que outils optionnels et complémentaires. Dans l'ensemble, l'analyse suggère que l'ambition de la mise en œuvre des politiques de décarbonisation augmente considérablement après 2035, tandis que les subventions à elles seules ne suffisent pas à atteindre les réductions d'émissions nécessaires. En outre, nous constatons que des changements brusques des politiques pourrait compromettre la réalisation de l'objectif de neutralité carbone à l'horizon 2050.

En définitive, les analyses définissent trois trajectoires politiques robustes avec une forte probabilité (>75%) d'atteindre la neutralité carbone d'ici 2050 : (1) commencer par des subventions de forte intensité, combinées à des politiques et obligations d'harmonisation européenne modérées jusqu'en 2035, puis passer à une forte intensité d'harmonisation et des obligations européennes, tout en supprimant progressivement les subventions ; (2) Suivre une trajectoire similaire à la première, mais en conservant des subventions de faible niveau au-delà de 2035 ; et (3) commencer par des subventions élevées combinées à des prélèvements et des mandats réglementaires d'intensité modérée jusqu'en 2030, puis passer à des prélèvements et des mandats d'intensité élevée, les subventions étant ramenées à une faible intensité d'ici 2035 et entièrement supprimées après 2040. Dans le cas de l'harmonisation de l'UE et des prélèvements, deux trajectoires supplémentaires ont également été explorées et jugées viables, dans lesquelles les intensités des ensembles de mesures restent constantes.

Un suivi rigoureux des incertitudes - telles que les prix des importations de carburants synthétiques et leur disponibilité, le potentiel bioénergétique, les prix de l'essence et du gaz naturel, ainsi que la production d'électricité renouvelable - est essentiel pour garantir une forte probabilité de réussite dans l'atteinte de la neutralité carbone d'ici à 2050. Par exemple, si le potentiel bioénergétique du pays s'avère limité ou inférieur à 100 PJ, des importations supplémentaires de carburants synthétiques durables seront nécessaires pour garantir un approvisionnement adéquat en carburants à faible teneur en carbone. À cette fin, les politiques d'harmonisation avec l'UE et les mandats réglementaires sont moins dépendants de facteurs tels que les prix des carburants ou les importations d'énergie et offrent donc une plus grande résilience comparée aux mesures fiscales. Les politiques fiscales, nécessitent des prix stables ou croissants des combustibles fossiles afin de rester efficaces. Par exemple, les prix de l'essence ne devraient pas baisser de plus de 9 % à partir de 2020 pour avoir un effet de réponse aux prix sur le secteur. Le maintien d'une ambition élevée dans la mise en œuvre des politiques, en particulier via l'harmonisation avec la réglementation de l'UE et les mandats réglementaires, augmente considérablement la probabilité d'atteindre les objectifs de zéro net, atteignant jusqu'à 95 % de taux de réussite dans différents scénarios. Toutefois, la mise en œuvre de ces politiques à forte intensité pourrait représenter des changements politiques brusque par rapport au statu quo, et leurs impacts sociaux et économiques plus larges doivent être examinés attentivement et étudiés plus en détail.

Dans l'ensemble, POLIZERO met en évidence une augmentation des retombées des politiques de l'UE sur le système énergétique suisse, à travers la participation à un système d'échange de quotas d'émission (EU-ETS) de plus en plus ambitieux, ainsi que l'adoption potentielle d'autres réglementations à l'échelle de l'UE, telles que les normes d'émissions des véhicules et d'autres normes de performance énergétique, ou encore l'EU-ETS2. Les conclusions du projet soulignent clairement la nécessité d'une coopération étroite avec l'UE. La dépendance croissante de la Suisse à l'égard des importations de biocarburants, de carburants synthétiques et d'hydrogène nécessite la mise en place des accords bilatéraux solides et un développement coordonné des infrastructures. À court terme, le maintien des activités des centrales nucléaires existantes contribuera à assurer la sécurité énergétique pendant la transition de la Suisse, et à réduire sa dépendance aux importations d'énergie.

POLIZERO a été une initiative de recherche innovante qui a donné lieu à deux thèses de doctorat, à plusieurs publications évaluées par des pairs ainsi qu'à de nouvelles collaborations avec des projets suisses et européens. Le projet a permis de poser des bases solides pour de futures études sur la transition énergétique et politique, notamment en ce qui concerne les interactions entre les systèmes énergétiques suisse et européen. Toutefois, le projet présentait plusieurs limites importantes. La représentation des parties prenantes était incomplète en raison des restrictions liées à la pandémie de COVID-19 et des contraintes de temps et de budget, ce qui a limité les perspectives de certains experts critiques impliqués dans la mise en œuvre de la politique énergétique.

Le modèle JRC-EU-TIMES se concentre uniquement sur le système énergétique, excluant les impacts macro et microéconomiques plus larges, tels que la rétroaction de la demande de services énergétiques sur leurs propres prix, ou encore les modalités de financement des politiques ou la redistribution des revenus qu'elles génèrent au sein de l'économie. Par conséquent, des estimations détaillées des coûts des politiques n'ont pas pu être intégrées. Le modèle ne couvrait pas certains secteurs, notamment les émissions de gaz à effet de serre autres que le CO2 en dehors du secteur énergétique. Étant un modèle d'équilibre partiel, JRC-EU-TIMES ne permet pas de représenter de manière directe certains mécanismes tels que l'ajustement de la taxe carbone à la frontière ou les contrats de différence. En outre, le modèle JRC-EU-TIMES doit être plus détaillé dans la résolution intra-annuelle et encore plus détaillé dans certains secteurs de la demande pour représenter un éventail plus large de politiques. Enfin, l'adoption de la politique est supposée ex ante, sans tenir compte de l'(in)acceptation sociale.

Le cadre AIM a permis d'explorer des trajectoires à l'avance dans le temps et de simuler dès leur déroulement de manière séquentielle, mais il ne permet pas une optimisation rétroactive à partir des objectifs de neutralité carbone à l'horizon 2050. En outre, les effets de montée en puissance (lead-in) et de suppression progressive (phase-out) des politiques n'ont pas pu être saisis, ce qui implique qu'une réponse plus lente ou plus rapide du modèle à la mise en œuvre réelle de la politique peut être observée dans les résultats. L'outil AIM peut encore être amélioré pour mieux représenter les interactions entre les politiques sur l'ensemble de la trajectoire, notamment lors des changements d'orientation stratégique, ce qui permettrait de réduire les cas d'infaisabilité, qui sont le produit de la mise en œuvre mathématique plutôt que des limitations réelles. L'analyse d'incertitude a également été limitée en raison de contraintes des ressources de calcul disponibles, restreignant le nombre de scénarios contextuels que le JRC-EU-TIMES a pu explorer, ce qui a limité l'approfondissement de l'outil AIM.

POLIZERO illustre clairement l'importance d'une action politique immédiate et soutenue pour permettre à la Suisse d'atteindre la neutralité carbone d'ici 2050. Une mise en œuvre rapide des politiques, un alignement solide sur les cadres de l'UE, ainsi qu'un suivi rigoureux des incertitudes sont des éléments clés pour positionner efficacement la Suisse face à ses objectifs climatiques et énergétiques.

Main findings («Take-Home Messages»)

- POLIZERO aimed to a) identify a suite of suitable decarbonisation policies for Switzerland with broad acceptance from stakeholders; b) assess the Swiss energy transition to net-zero GHG emissions by explicitly accounting with the interactions between Switzerland and the EU in energy markets, infrastructure and policies; c) to use the information from the previous two objectives in order to generate dynamic and adaptive policy pathways to agilely handle policy targets in an uncertain implementation environment.
- With respect to the first objective POLIZERO found that **stakeholders advocate for greater integration with the EU,** including the adoption of EU-ETS2 and agreements for the electricity, biofuel, and hydrogen markets. They recommend the simplification of regulations for new energy investments and technology-neutral incentives by avoiding technology bans. Main challenges to be tackled are the upfront investment costs for clean technologies in households, skilled labour shortages, environmental concerns, security of energy supply, and social acceptance of new technologies and energy carriers.
- With respect to the second objective, the analysis of the **net-zero transition of the Swiss energy system** by considering its interaction with the European energy markets, regulations and infrastructure, revealed three main areas of critical action:
    - **From 2025 to 2035, Switzerland faces a critical energy transition period** requiring expanded renewable capacity and energy efficiency. Solar capacity must triple, and overall energy consumption needs to decrease by 15%. By 2050, 12 TWh of wind and bioenergy electricity production will also be needed to maintain independence from imports, particularly in winter.
    - **Direct end-uses electrification**, but also indirect via **the electrification of district heating** are essential for decarbonising heating and mobility. By 2035, over 10% of district heating must be supplied by large-scale heat pumps, increasing to one-third by 2050. The transport sector must integrate 50% electric vehicles by 2035, aided by EU emissions standards.
    - **Hydrogen and synthetic fuels are essential for industry and aviation decarbonisation**, with the need for about 6 TWh of hydrogen and 90 PJ of synthetic fuels by 2050. Domestic electrolysis can fulfill two-thirds of the hydrogen demand, but synthetic fuels will largely rely on imports. Limited CO_2 storage options necessitate connections to the European CO_2 transport network by the 2040s, making international cooperation vital.
- With respect to POLIZERO's third objective, the exploration of policy pathways that consider the aforementioned stakeholder concerns and the findings of energy system analysis of the future interactions between the EU and Swiss energy system, concluded that:

- **Four policy approaches—subsidies, levies, harmonisation with the EU regulations, and mandates—were evaluated, with EU harmonisation offering "quantity certainty" for emissions reductions.** While effective under stable fuel prices, tax-based instruments face challenges in switching to net-zero emissions in the transport sector. Subsidies can front-load the decarbonisation, but their effectiveness over time diminishes, and the implementation of EU harmonisation policies or regulatory mandates will be necessary. When no mandates, obligations or bans are implemented, the net-zero target cannot be achieved, even if other instruments, such as high subsidies or taxes, are in place.
- Uncertainty analysis highlighted **bioenergy potential, synfuel imports and prices, and gasoline and gas prices** as significantly affecting the effectiveness of policy pathways. High-intensity harmonisation with EU regulations diminishes dependence on these variables, ensuring stronger outcomes than tax-based approaches.
- **Policy shifts:** Choosing tax-based policies instead of EU harmonisation could jeopardise the net-zero target because taxes, such as CO_2 levies, provide less certainty in achieving emissions reductions compared to the "quantity certainty" offered by the EU ETS and ETS2 frameworks. Monitoring renewable energy potential and, in parallel, the potential for imported electricity, biofuels, and e-fuels can help manage the uncertainty in the effectiveness of the decarbonisation policy packages assessed in the project.

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AIM	Adaptive Policymaking Model
ATR	Autothermal Reforming technology for hydrogen production
BECCS	Bioenergy with CO_2 capture and storage
BtL	Bioenergy to Liquids
CBAM	Carbon Border tax Adjustment Mechanism
CC(U)S	CO_2 capture, utilisation and storage
CCfD	Contracts for Difference
CCS	CO_2 capture and storage
CCU	Carbon Capture and Utilisation
CHP	Combined Heat and Power
COP	Coefficient Of Performance
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
COVID-19	Severe Acute Respiratory Syndrome due to the Coronavirus disease in 2019
CROSS	CooRdination Of Scenarios for SWEET
DACCS	Direct air CO_2 capture and storage
DAPP	Dynamic Adaptive Policy Pathways
EED	Energy Efficiency Directive 2018/2002
EMA	Exploratory Modelling and Analysis
EP2050+	Energy Perspectives 2050+ study of the Swiss Federal Office of Energy
EPBD	Energy Performance of Buildings Directive 2018/844/EU
ETS	Emissions Trading Scheme
ETSAP	Energy Technology Systems Analysis Program
EU	European Union
EV	Electric vehicle
GEAK	building energy certificate of the cantons
GHG	Greenhouse gas
GWR	Federal Register of Buildings and Dwellings
ICAO	International Civil Aviation Organisation
ICEV	Internal Combustion Engine Vehicle
ICT	Information and Communication Technologies
IEA	International Energy Agency
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
ITMO	Internationally Transferred Mitigation Option

JRC	Joint Research Centre of the European Commission
LULUCF	Land-use, Land-Use Change and Forestry
LULUCF	Land use, Land Use Change and Forestry
NDC	Nationally Determined Contributions
NETs	Negative Emissions Technologies
NGO	Non-Governmental Organisation
OECD	Organisation for Economic Co-operation and Development
PRIM	Patient Rule Induction Method
PSI	Paul Scherrer Institute
PtX	Power-to-X
PV	Photovoltaics
R&D	Research and Development
RES	Renewable Energy Sources
SFOE	Swiss Federal Office of Energy
SMR	Steam Methane Reforming technology for hydrogen production
STEM	Swiss TIMES Energy system Model
StL	Sun to Liquids
SWEET	SWiss Energy research for the Energy Transition funding programme
TEESlab	Techno-Economics of Energy Systems laboratory
TIMES	The Integrated MARKAL-EFOM System
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
UNIPI	University of Piraeus
UPRC	University of Piraeus Research Centre
WP	Work package

1 Introduction

1.1 Context and motivation

The energy transition challenge towards a zero-carbon Swiss energy system by 2050 requires coordinated decarbonisation policies across all sectors. An effective policy design should consider domestic uncertainties, such as resource potentials and demographic and economic developments. At the same time, the ambitious EU climate change mitigation targets also affect Switzerland due to its deep integration with the EU energy infrastructure. Uncertainties arising from the interdependency of the Swiss and European energy grids, markets, and policies should also be accounted for in a cost-effective climate-neutral energy transition and for the alleviation of concerns about security of supply and energy imports.

So far, the Swiss energy transition analyses have only partly considered these multi-level interactions arising from the shared Swiss and European energy infrastructures, market participation and climate policy ambition. For example, they only account for the cross-border electricity trade and markets (Abrell et al., 2019; Heim, S. et al., 2017; Patturpara, 2016) neglecting other energy carriers needed for the transition. Or, they analyse policies in specific sectors (Alberini et al., 2015; Díaz et al., 2017; Hettich, P. et al., 2020; Schmidt & Sewerin, 2019; Sperscha, A. et al., 2016), which either deal with governance rather than impact quantification or do not explicitly consider their systemic interdependencies. Or, else, they consider these interdependencies as exogenous assumptions (Kirchner et al., 2021; Panos et al., 2019, 2023). Almost all studies neglect the adaptation of specific policy measures determined by what is known and what might be experienced and learned in the future.

The above indicates two important gaps in state-of-the-art research on deep decarbonisation policies in Switzerland. First, the current assessments do not include an extensive, quantified analysis of the impact of European policies on Swiss policies and the energy system. Second, when decision-makers face the complex interactions of energy systems that span beyond the national scope, they need adaptive policy plans that hedge against uncertainties affecting policy implementation and outcomes.

1.2 Project objectives

The project "Swiss Policy towards Zero CO_2 Emissions compatible with European Decarbonisation Pathways"—short POLIZERO—explores the Swiss energy transition to 2050 by explicitly accounting for its interaction with the EU's energy system transformation envisioned in the Green Deal (EC, 2024) and the REPowerEU plan (EC, 2022). Using the insights from this analysis, POLIZERO also supports decision-makers in designing adaptive policy pathways that ensure robustness and cost-effective achievement of the Swiss climate change mitigation targets. In this regard, POLIZERO has three objectives:

1) To identify a suite of suitable energy sector decarbonisation policies for Switzerland that are relevant to stakeholders
2) To assess the Swiss energy transition to net-zero GHG emissions by explicitly accounting for the interactions between Switzerland and the EU in the energy system transformation, the energy markets and energy and climate change mitigation policy.
3) To generate dynamic adaptive policy pathways to handle policy targets agilely by accounting for the uncertainties arising from different national and international contextual factors, e.g. societal, technical, economic, or demographic.

Some of the research questions for which POLIZERO provides insights are:

- Which policies can help deliver the net-zero GHG emissions in Switzerland by 2050?
- What are the spillovers of the EU policies for the Swiss policy and energy transition?
- What contextual factors should be monitored to ensure effective policy implementation?

Section 2.1 describes the methodology followed. Its main limitations are discussed in section **Error! Reference source not found.**. The results from the stakeholder analysis are presented in the section 3.1, from the energy system analysis in the section 3.2 and from the policy exploration in the section 3.3. The conclusions and outlook are discussed in the section 4, while sections 5 and 6 discuss the collaboration and dissemination activities pursued in the project, respectively. The report is accompanied by ten Appendices (8.1 - 8.10).

2 Approach and method

POLIZERO is an innovative project that applies stakeholder consultation, prospective quantitative analysis with the JRC-EU-TIMES full-scale European energy systems model (Simoes et al., 2013a, 2013b), and dynamic adaptive policy pathways analysis with the AIM model (Michas et al., 2020).

Stakeholders' input is used to identify key Swiss policies and contextual factors influencing their efficiency and effectiveness in delivering the Swiss long-term emissions reduction targets. A stocktake of current and under-discussed Swiss and EU policies served as input to stakeholders to identify those policies that can provide substantial emissions cuts and are socially and financially acceptable. Examining various stakeholders and their respective policy priorities is fundamental to facilitating a smooth policy-making process, as the stakeholders offer broader legitimacy and provide knowledge and expertise to the proposed policies. The identified policies were grouped into policy packages spanning all sectors of the energy system. In forming these packages, additional care was given to the fact that they are relevant to the academic research, and they can be implemented and analysed with the modelling frameworks employed in the project. Additional consultation rounds with the Swiss Federal Office for Energy and other Federal Administration Offices were performed to refine these policy packages further.

The quantitative modelling assessed the performance of the formulated policy packages across several indicators related to the main targets of the Swiss energy (BFE, 2017) and climate strategy (SFOEN, 2021), as these strategies have been updated with the new post-2021 developments. The assessment was performed by accounting for interactions with the European energy policies and considering key uncertainties, such as resource potentials, demographic and economic growth, technology costs, international fuel prices, and availability of imported energy carriers to Switzerland. The output from this analysis provided input to the dynamic adaptive pathways analysis to identify robust policy pathways and their time implementation sequence to achieve the Swiss net-zero transition.

The JRC-EU-TIMES model was used for an additional scenario analysis, complementing the dynamic policy pathway analysis. Three key "what-if" scenarios were examined to assess where the current policies can lead us and where we will need to be by 2050 when all main energy and climate targets of the Swiss Energy and Climate Strategies are met. These three scenarios served also as a benchmark to the dynamic adaptive policy pathways analysis: a) BAU (business-as-usual); b) CLI (aims at net-zero GHG emissions in the EU and CH to be achieved with domestic measures; c) CLI90 (as CLI but up to 10% of the Swiss GHG emissions in 2050 can be compensated abroad via negative emissions technologies). This scenario analysis helps answer the research question on the impacts of the EU policy on the Swiss energy system and identify possible energy system configurations of Switzerland towards 2050 to inform decision-making. It also serves as a benchmark for the effectiveness of emission reductions and energy system costs in the identified policy pathways by AIM.

2.1 Methods

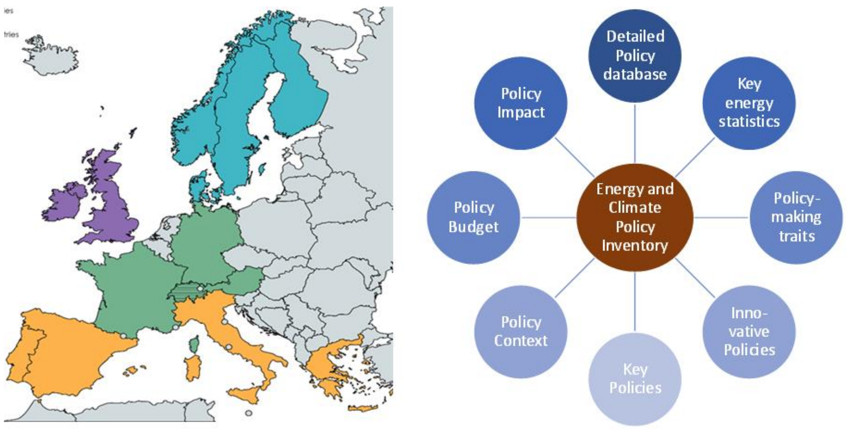
The following provides an overview of the methods and tools applied to the POLIZERO project. The Appendices of this report give more details about the POLIZERO methodology. Relevant scientific publications and tool documentation are also cited and can be used to obtain more insights.

2.1.1.Stocktake and Inventory of current and being discussed Swiss and EU Policies

A comprehensive inventory of policies that have been or are planned to be implemented in the near term in Switzerland and major European countries was created in POLIZERO to serve as input to the stakeholders' preferences elicitation. The main sources of the inventory were open policy databases, such as the IEA Policy Database[1], the Climate Policy Database[2], IEA country policy brief reports[3], the RES Legal database[4], energy and climate strategies, laws and acts, transposition of the EU directives to national legislation, relevant research projects and literature, and media releases. Figure 1 presents an overview of the countries whose policies were considered for the inventory, the main data categories, and an extract of its contents.

Substantial effort was made to consolidate the policies collected from the different sources, remove duplicates or incomplete policies, and eliminate ambiguities. In addition, an effort was made to decompose large policy packages into individual key policies. The resulting inventory is a comprehensive and open-source database describing policies, implementation periods and status, sectors and technologies to which the policy is relevant and, whenever possible, policies' budgets and impacts. It also provides a timeline of the different policies, including start and end dates, as well as which policies substitute others and by when. Hence, the inventory also gives an overview of the policy history development. A subset of policies identified by the authors as key ones, based on budgets, impacts, timeframes, or policy type, is included for each country, summarising the main instruments used in different geographies and economic and social contexts.

The inventory is available for download: https://polizero.ch/energy-and-climate-policy-inventory.



(a) (b)

ID	Policy	Policy type	Description	Start	End (	Status	Part of	Replaces	Sector	Technologies	Jurisdic	Budget	Impact	Source
FR37	Decree of 24 of April 2016 on	Targets	Decree of 24 April 201	2016	2023	In force	FR44	FR60	Energy sector	Renewable technol	National		15 GW (2018);	https://www.legifran
FR38	EV Infrastructure Charging Pro	Economic instr	In 2016, the ADVENIR	2016		In force			Transport	Charging infrastruc	National	100 MEUR (202	58700 charging	http://advenir.mobi/
FR39	Low Emissions Zone (Crit'Air)	Regulation	In France, the scheme	2016		In force	FR44		Transport	Vehicles	National			https://www.iea.org/
FR40	Support scheme for electricity	Economic instr	The Energy Transition	2016		In force	FR44	FR86	Energy sector	Renewable technol	National			https://www.iea.org/
FR41	Building code - EV charging	Regulation	Residential: New Buildi	2015		In force			Industry, Servic	Charging infrastruc	National			https://www.iea.org/
FR42	Demonstration Fund "Vehicle	Capacity Buildir	The main objectives pu	2015	2017	Ended		FR46	Transport		National	1.2 BEUR		https://appelsaprojet

(c)

[1] https://www.iea.org/policies
[2] https://climatepolicydatabase.org
[3] https://www.iea.org/countries
[4] http://www.res-legal.eu

Figure 1: (a) Countries included in the POLIZERO energy and climate policy inventory, (b) the policy inventory database dimensions, (c) example of its contents for France

2.1.2.Stakeholder Analysis with Workshops and Natural Language Processing Tools

Natural Language Processing (NLP) tools and stakeholder workshops are used to consult on selecting the policy instruments from the inventory described in section 2.1.1. However, the formulation of the policy packages and selection of policy instruments in the packages were determined based on broader criteria, such as sectoral coverage, model capabilities and novelty of the instrument, or even academic research interest, and not solely on the stakeholders' opinions. The rationale is that neither the workshop nor the assessment of the position papers of stakeholders with Natural Language Processing Tools guarantees coverage of all stakeholders of Switzerland.

Two stakeholder workshops and additional extensive analysis of stakeholders' position documents from the consultation rounds of the Energy Act (EnG) 2020 Revision[5] and CO_2 Act (CO_2 Gesetzt) 2021 Revision[6] were used as a starting point to elicit stakeholder preferences about the social and financial feasibility of policies delivering substantial emissions cuts.

The first Stakeholder Workshop was held on 26th November 2021 and, because of COVID-19 restrictions, was performed only with members from the Common Advisory Board of POLIZERO together with the research teams from EPFL, ETHZ, University of Geneva, and HESO that led projects from the same EWG Research Call sharing the same advisory board with POLIZERO. The stakeholder meeting was structured around thematic tables: buildings, transport, industry and energy supply. Stakeholders' support towards the policy instruments is indicated, their opinion on decarbonisation efficacy is voiced, and finally, their view on the timeline and order of the instruments is inquired. The policy instruments presented to the stakeholders were short-listed based on their novelty as instruments for Switzerland and sectoral experts from the modelling team. All received inputs were inquired about with justification.

Before hosting the second workshop, topic modelling based on the Latent Dirichlet Allocation algorithm (Blei et al., 2003) was utilised to gain an overview of the stakeholders and their policy priorities. Topic Modelling is a form of Machine Learning for Natural Language Processing. The Topic Modelling approach implemented in POLIZERO is graphically shown in Figure 2. It is suitable for processing a large corpus of data to uncover topics that can characterise this dataset. A topic is a set of words with the highest probability of co-occurring. In this set-up, each stakeholder's position document of the corpus is defined by the topic that occurred most in the document. The words used to identify the topic are interpreted as stakeholders' interests. Analysing these interests, supported by qualitative approaches, helps determine the policies acceptable to the different stakeholders and the rationale for their acceptability. In the second step, we relayed the topics to specific stakeholders and performed clustering around the stakeholders' attributes and diversity of positions. The reader is directed to (Zhang et al., 2024) for more details on the implementation and insights from the Topic Modelling in POLIZERO. The topic modelling results assist in scoping the stakeholders invited for the second workshop, as some stakeholders shared quite similar positions towards the climate and energy policies. The stakeholders that were analysed with Topic Modelling are listed in the Appendix "8.2 Stakeholders Included in Topic Modelling ".

With the insights gained through desk research on the published stakeholders' positions, the second Workshop was held on June 1st, 2022. This workshop extends to stakeholders from several administrative Federal Offices and academics, as well as industry and utility associations, consumer associations, NGOs, and experts from the energy domain in Switzerland. It followed the same organisation as the first workshop, with a World Café with the same thematic tables. The 21 stakeholders who participated in the workshop are listed in Appendix "8.1 Stakeholders Participated in the POLIZERO Workshop".

The input from the stakeholders was used to inspire policy packages for the dynamic adaptive policy pathways exploration analysis (please see Section "3.1 Stakeholder analysis to identify policy packages for delivering a carbon-free Swiss energy system by 2050"). Thus, the stakeholder analysis was not

[5] https://fedlex.data.admin.ch/filestore/fedlex.data.admin.ch/eli/dl/proj/6020/14/cons_1/doc_1/de/pdf-a/fedlex-data-admin-ch-eli-dl-proj-6020-14-cons_1-doc_1-de-pdf-a.pdf

[6] https://fedlex.data.admin.ch/eli/dl/proj/2021/123/cons_1

directly used to select the policy instruments to be implemented into the model, but to highlight the policy priorities and philosophies. The identification of policy packages was a two-step approach. Each policy package is characterised by a “philosophy” such as financial instruments, bans, and mandates. Then, the policies included in a package are those that can serve the package’s philosophy.

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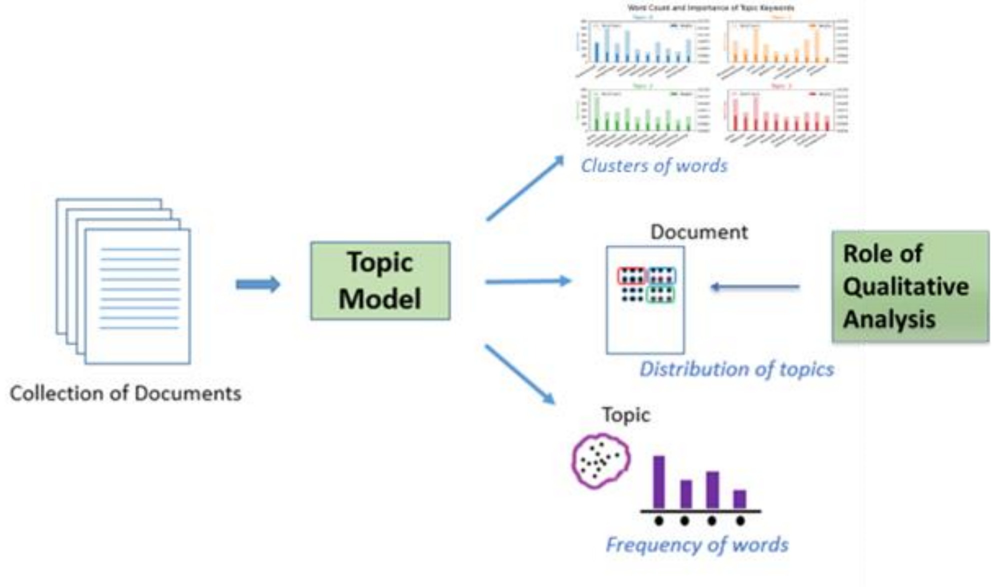

Figure 2: Conceptual graph of the topic modelling mechanism

In addition, the stakeholder feedback was used not only to sense the concerns and interests of the stakeholders but also to design meaningful and plausible scenarios for the policy exploration. The level of harmonisation of the Swiss regulation to the EU regulation, or the technologies and solutions that can be considered relevant for decarbonising the Swiss energy system, are essential inputs for designing the POLIZERO scenarios and were informed by the stakeholder analysis.

2.1.3.The JRC-EU-TIMES model

The JRC-EU-TIMES model is an open-source energy systems model developed and maintained by the Joint Research Centres of the European Commission. (Simoes et al., 2013a). It is based on the TIMES energy systems model framework developed by the IEA-ETSAP (Loulou et al., 2016). It is a partial equilibrium framework representing the entire energy system of 36 European countries, including Switzerland, from an engineering techno-economic perspective. It has a full range of energy processes, including exploitation, conversion, transmission, distribution, storage, and energy end-use (Figure 3). The model consists of the following sectors of the energy system (see also Appendix “8.4 Sectoral representation of the JRC-EU-TIMES model“):

- Upstream sector, including the production and extraction of resources, energy imports and exports
- Conversion sector that includes electricity and heat production, hydrogen production, production of biofuels and e-fuels
- Final energy consumption sectors, including industry, services, residential, and transport
- CO_2 capture, sequestration and utilisation sectors

JRC-EU-TIMES aims to supply energy services at a minimum energy system cost by simultaneously making energy technology investments and operating decisions to reach a demand-supply equilibrium state. The optimisation considers several constraints related to policy, technology deployment, resource potential or other constraints surrounding the configuration of the future energy system. The demand-supply equilibrium found by the optimisation has the property of maximising the total surplus. The model has a long-term horizon. This analysis focuses on the developments until 2050, with reporting years 2020, 2025, 2030, 2035, 2040, 2045 and 2050. We apply a 5% social discount rate and technology-specific interest rates of up to 12%, depending on the sector and technologies (Simoes et al., 2013a). An important feature of the model is that it explicitly accounts for the construction times, decommissioning, lifetime extensions and retrofitting of the energy infrastructure assets. At the same time, it tracks their vintages (please see Appendix "8.8 Investment, construction times and decommissioning in JRC-EU-TIMES" for more details). Key outputs of the model are the annual stock and activity of supply, demand, and trade technologies, as well as the associated material and energy flow for each region and period. The model also provides operation and maintenance costs, investment costs, and prices for energy emissions and materials commodities.

Among its unique characteristics are the endogenous trade of energy carriers such as electricity, gas, and hydrogen, the endogenous trade of carbon permits and green certificates, and a DC power flow approximation of the electricity transmission grid in Europe. It also has a detailed representation of other backbone European energy infrastructures, such as storage, pipelines, and terminals. In addition, the model tracks the vintages of energy technologies, including the option for early retirement of existing capacities. A detailed description for the interested reader is provided in (Simoes et al., 2013a).

The main role of JRC-EU-TIMES in the policy cycle is anticipation, with a focus on technology policy. Technology policy analyses with JRC-EU-TIMES can complement the European Commission's reference analyses in the areas of energy, transport and climate action. The baseline scenario of JRC-EU-TIMES is aligned with the latest EU reference scenario. A typical question that JRC-EU-TIMES can address is which technological improvements are needed to make technologies competitive under various low-carbon energy scenarios. JRC-EU-TIMES can support studies which require (1) modelling at the level of an energy system, (2) a high level of detail of technologies, and (3) inter-temporal results on the evolution of the energy system. Within POLIZERO, several model components underwent significant redesign and refinement, either to reflect current policy and technology developments or to represent the policy packages identified by the stakeholders in detail. This led to an improved model version with consolidated statistics from different data sources (please see Appendix 8.3 Databases used for the calibration of the JRC-EU-TIMES model") and a representation of the energy system of Switzerland with the same sectoral and technology detail as in the well-established Swiss TIMES energy system model – STEM (Panos et al., 2023). In addition, the JRC-EU-TIMES includes features not yet present in STEM, such as aviation technology granularity and material flows for the industrial sectors. However, the hourly resolution of STEM is not included in the JRC-EU-TIMES for computational complexity reasons. JRC-EU-TIMES operates at a more aggregated timeslice level, which could underestimate the need for dispatchable generation and storage, overestimate the uptake of renewable energy and overestimate the electricity supply (and trade from) weather-dependent renewable energy sources. The reason for this was the computational complexity of developing an hourly energy systems model with endogenous capacity expansion for the entire Europe. We reserve this development for the future. These enhancements were structural enhancements, such as the explicit representation of green hydrogen and sustainable synthetic fuels production pathways that were missing from the original version of the JRC-EU-TIMES or extensive data refinements[7]. Some of these improvements are listed below:

- Improvements in the industry sector: material flows for industrial processes, updated metal scrap costs, import and export of Fe-pellets inside and outside Europe, increased technology granularity, hydrogen use options for process heat, improvement of primary and secondary aluminium production pathways, updates on cost and potential of CO_2 capture technologies. In total, the enhanced version of the model includes more than 400 technologies for the industrial sectors.

[7] The enhanced JRC-EU-TIMES code developed in POLIZERO, the model's data used in the project, and the results obtained are available at https://gitea.psi.ch/POLIZERO/JRC-EU-TIMES ; with the exception of the results which are in EXCEL files, all other files are plain text files that ensure open access

- Improvements in the buildings sector: increased granularity of electrical appliances technologies, development of an endogenous building stock evolution submodule, differentiation of COPs of heat pumps depending on the longitude and latitude of the countries, several corrections in the model structure regarding technology characterisation inconsistencies
- Improvements in the transport sector: increased granularity of aviation technologies (different options depending on the travel distance), separate demands for national, intra-EU and extra-EU aviation
- Improvements in the supply sector: increased granularity of PtX technologies to also include BtL and StL options, updated costs and new technologies for electrolysis, endogenous trade of hydrogen and synthetic fuels, updated costs and potentials for hydrogen and synthetic fuels imports to Europe from the rest of the world.
- Several structural changes were needed to represent bans, mandates, standards, targets, and financial support schemes envisaged in the regulations, directives, and laws in the EU and Switzerland, as well as the implementation of ETS2 for buildings and transport sectors.

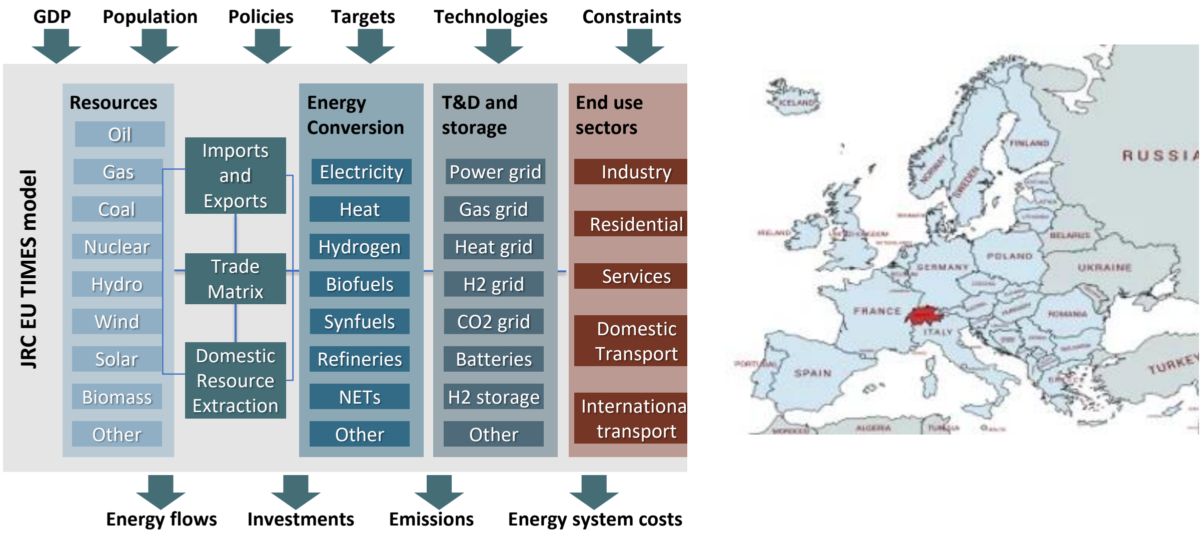

Figure 3: Overview of the JRC-EU-TIMES structure, including main inputs and outputs (left) and the countries represented (right)

2.1.4. The AIM model

The Adaptive Policymaking Model (AIM), developed by TEESlab at the University of Piraeus, facilitates the explorative design of policy sequences (pathways) and identifies contextual values which could hinder or enable the achievement of policy targets. It builds on Exploratory Modelling and Analysis (Kwakkel & Pruyt, 2013) and implements part of the Dynamic Adaptive Policy Pathways (DAPP) methodology (Haasnoot et al., 2013).

AIM consists of three modules. The first module evaluates the candidate policies across the simulated period and identifies the successful ones using a heuristic algorithm called the Patient Rule Induction Method (Papadelis & Flamos, 2019). Successful policies achieve the set targets above a user-defined threshold percentage of the uncertainty scenarios. In the second module, the exploratory design of policy pathways is implemented, meaning the selection and stepwise implementation of policies/policy packages. Finally, the third module identifies under which contextual conditions the designed pathway achieves its targets, enabling the exploration of alternative ones.

Within the scope of POLIZERO, AIM and JRC-EU-TIMES are linked together (Figure 4). To this end, several advancements have been implemented. Firstly, an automated interface was developed that respects the output and input formats of the two models, thus facilitating their soft linking. In addition, AIM has been expanded to allow for inter-sectoral or cross-sectoral analyses. This expansion enables multiple policy outcomes to be comparatively assessed simultaneously. The policy outcomes to be evaluated can be changed without additional hard coding simply by parameterising the AIM input files based on the JRC-EU-TIMES outputs.

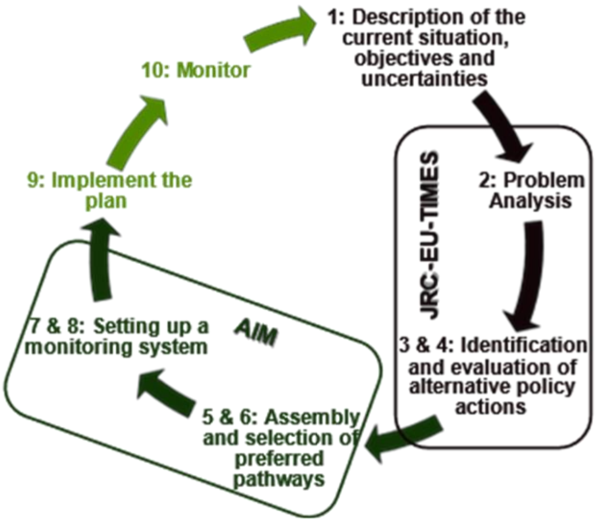

Figure 4: The steps of the Dynamic Adaptive Policy Pathways methodology in POLIZERO

The clustering functionality of AIM has also been expanded to account for multiple policy targets. The improved algorithm identifies contextual factors' value ranges, under which the assessed policy packages simultaneously satisfy all the targets under assessment. This functionality provides insight into the sensitivity of policies to context evolution. For example, suppose the space between the upper and the lower limits of a cluster of contextual evolutions that satisfy a certain target is small. In that case, this cluster does not contain many 'enabling' contextual evolutions, and the policy is thus sensitive to external forces.

In POLIZERO, AIM has also been updated to support multiple policy package implementations. After implementing a policy package for a specific period, users can implement another one, starting concurrently or later than the previously implemented package and extending until any timeframe within the assessment period. For more insights into the AIM model, the reader is directed to (Michas et al., 2020).

Additional insights on the AIM methodology and its application in the context of the POLIZERO project by interacting with the JRC-EU-TIMES for the policy exploration are provided in Appendix "8.10 Methodology for policy pathways generation with AIM".

2.1.5.POLIZERO scenarios

In POLIZERO, three core long-term scenarios were developed to assess the Swiss energy transition within the EU energy transition and the potential spillovers from the EU policy and energy system developments. These scenarios complement the policy exploration, identifying where the current policies can lead us and what is also needed to transform the Swiss energy system to net-zero GHG emissions.

- **BAU** (Business-As-Usual): This scenario implements policies in the EU and Switzerland that are in the legislation up to 1.1.2023 or have been decided to be implemented in the near term. It assumes a continuation of the current energy supply and consumption trends and is used as a benchmark for the other two scenarios.

- **CLI** (Climate change mitigation scenario): this scenario aims to achieve net-zero GHG emissions in the EU and Switzerland by 2050. The scope of the GHG emissions reduction target includes Energy (UNFCCC classification 1A-1B), Industrial Processes (2A-2H), Agriculture (3A-3J), LULUCF (4A-4H), Waste (5A-5E) and 50% of the emissions from international aviation and maritime. The transition to net zero is to be achieved in this scenario solely with domestic mitigation measures in the EU and Switzerland. The scenario also implements the Swiss targets of electricity production of 35 TWh in 2035 and 45 TWh in 2050 from renewable energy sources other than hydropower; and the hydropower electricity production targets of 37.9 TWh and 39.2 TWh for 2035 and 2050 respectively. It also implements the energy efficiency targets of a reduction in the electricity consumption per capita by 13% in 2035 and 5% in 2050 compared to 2000 levels, and a decrease of 43% in 2035 and 53% in 2050 of the final energy consumption per capita compared to 2000 levels.
- **CLI90** (only for Switzerland): it is a variant of CLI in which Switzerland achieves its net-zero GHG emissions target for 2050 also by compensating emissions abroad[8]. Up to 5.4 Mt CO_2-eq can be compensated abroad at costs ranging from 50 to 800 CHF/tCO_2-eq.

The main assumptions for the three scenarios are summarised in the Appendix "8.5 Main assumptions of the POLIZERO long-term energy transformation scenarios". Figure 5 lists the main policies implemented in the three scenarios in the JRC-EU-TIMES model.

Scenario	EU-27	Switzerland
Baseline (policies in the legislation until 1.1.2024)	• EED energy efficiency (EU2023/1791) • EPBD buildings performance standards (EU2018/844) • ETS (all revisions up to EU2023/959) • EU RED III renewable targets (up to EU2023/2413) • GHG effort sharing (up to EU2023/857) • Vehicle emissions standards (EU2019/631, EU2023/851) • Heavy vehicle emissions standards (EU2019/1242) • Coal phase out 2030 in DE, DK,FI,GR,HU,IE,IT,NL,PT,SI,SK,ES • Intra-EEA aviation in EU-ETS • NTC electricity capacities as in ENTSO-E TYNDP 2022 plan • Reduction of nuclear share in France • New nuclear plants those under construction/advanced planning	• Lifetime of existing reactors 60yrs; no new reactors • Swiss ETS coupled with the EU-ETS • Intra-EEA flights covered by the EU-ETS • SR 730.00 Energy Act (EnG) as of 1.1.2024 • SR 730.03 EnFV renewable subsidies as in 1.1.2024 • Buildings programme HFM 2015 • SR 641.71 CO2 Gesetz • SR 641.61 MinöStG fossil fuel taxes • SR 641.81 on PSVA and LSVA for heavy vehicles • MuKen 2014 buildings performance standards • Electricity grid expansion plans of Swissgrid 2025 network
CLI (net-zero target scenario)	• GHG emissions from 1990: -55% in 2030, -90% in 2040 • Net-Zero GHG emissions in 2050 at the EU-level • Individual net-zero GHG emissions targets of the member states • GHG emissions reduction scope as in the EU Climate Law - includes LULUCF and 50% of the international transport • Refuel aviation SAF mandates • EU-ETS-2 from 2030 (although incl. in 2023 revision of EU-ETS) • + 8GW new nuclear power (BG, CZ, RO, SI, SK, FI, FR)	• GHG reductions from 1990: -35% in 2030 (domestic) • Net-Zero GHG emissions in 2050 • KiG sectoral emissions reduction targets • GHG emissions reduction scope includes LULUCF • Carbon neutral international aviation • Mantelerlass targets for renewables & security of supply • Solarexpress and Windexpress • Energy savings targets (per capita consumption)
CLI-90 (variant of CLI for Switzerland)	EU-27 as in CLI	As in CLI and: • Up to 5.4 Mt CO2-eq can be compensated abroad via NETs with a cost from 50 to 800 CHF/tCO2-eq

Figure 5: Main policies implemented in the three core scenarios for the EU and Switzerland

2.1.6.POLIZERO Policy Packages and Policy Exploration

To explore robust policy pathways that can deliver the Swiss energy transition to net-zero emissions by 2050, by accounting for energy system configuration and policy spillovers from the EU Green Deal, the EU implements its CLI scenario while Switzerland is at the BAU. The input collected by the stakeholders (either physically through the workshops or via the processing of their position documents in the consultation rounds of the Energy Law in 2020 and the CO_2 Law in 2021) was used to inspire the formation of policy packages spanning all sectors of the energy system, The selection of the policy packages was further refined within consultation rounds with SFOE and other Federal Administrative Offices, while an important criterion in their selection was also their relevance for academic research and their implementation feasibility with the modelling frameworks of POLIZERO. Each policy package has a specific philosophy, and the policy instruments included in it serve this philosophy: for example, bans or obligations,

[8] In POLIZERO we do not explicitly identify whether the compensation abroad is achieved with NETs or mitigation measures. Instead, we use a single CO2 price for deploying the mitigation abroad.

subsidies, EU measures relevant to Switzerland, and taxes (please see Section " 3.1 Stakeholder analysis to identify policy packages for delivering a carbon-free Swiss energy system by 2050". These policy packages are assumed to be implemented from 2025 to 2050 at three constant intensities: low, medium and high. Each policy package is applied on top of the BAU scenario. In this setup, BAU represents the "policy status quo", and the policies included in the policy package are either new policies (e.g., ETS2 for buildings and transport) or policies overwriting the intensity of ones already represented in BAU (e.g., CO_2 levy). The performance of each policy package is assessed across key indicators of the Swiss energy and climate policy. These indicators are listed in Table 1.

All policies included in a policy package follow the overarching intensity of the package. For example, if a policy package is set at its high intensity, then all policies included in the package are set to their high intensity as well. The intensities of the different policies are based on literature review, on input from the POLIZERO Advisory Board, and on the quantification outcomes from the BAU, CLI and CLI90 scenario of the JRC-EU-TIMES model (e.g., the high intensity of the CO_2 levy was set to the marginal CO_2 cost obtained in the CLI scenario for Switzerland to ensure that the policy exploration could achieve net-zero with one at least intensity of this policy). Generally, the three intensities of the policy packages are higher than the intensity of the same existing policy instruments in BAU. However, for subsidies, there is an exception to this rule as the new revisions of the Energy Act (EnG) already foresee high levels of subsidies for various renewable energy installations. Hence, for such high subsidies, for example, those aimed at financing up to 60% of the CAPEX, we presume the subsidy level has peaked and would, in the future, be lowered. For new subsidies for which no evidence of current intensity exists, we set an arbitrary level of 10%-30%-50% of the CAPEX of the targeted technology.

Table 1: Indicators for assessing the performance of policy packages

Indicator	**2030**	**2035**	**2040**	**2050**
Total CO_2 emissions (Mt CO_2)	28.2			0
CO_2 emissions in industry (Mt CO_2)			5.0	1.0
CO_2 emissions in buildings (Mt CO_2)			3.1	0
CO_2 emissions in domestic transport (Mt CO_2)			6.2	0
CO_2 emissions in international aviation (Mt CO_2)				0
Maximum electricity net imports in winter (TWh)				5.0
Minimum electricity from non-hydro renewables (TWh)		35.0		45.0
Minimum electricity from hydropower (TWh)		37.9		39.2
Reduction in electricity consumption per capita from 2000 levels (%)		-13%		-5%
Reduction in final energy consumption per capita from 2000 levels (%)		-43%		-53%

Notes: The CO^2 emissions scope refers to Energy (1A-1B) and Industrial Processes (2A-2H). The domestic transport excludes intra- and extra-EU aviation. The electricity consumption and final energy consumption targets refer to domestic end-uses, excluding intra-EU and extra-EU aviation. All sectoral emissions targets are based on the KtG law[9].

The policy exploration analysis also accounts for key uncertainties surrounding the development of the Swiss energy system until 2050. These uncertainties, or contexts, are evolving from 2020 to 2050 and are represented as 22 random time-series variables grouped as follows:

- Economic and demographic: Population, GDP per capita
- Climate: Heating Degree Days, Cooling Degree Days
- Resource potentials: Solar PV, Wind electricity, Bioenergy, CO_2 storage in Switzerland, CO_2 storage in the EU

[9] https://www.fedlex.admin.ch/eli/fga/2022/2403/de

- Imports availability: Electricity, Biofuel, E-fuels
- Technology costs: Solar PV, Wind turbine, PEM electrolysis, Heat pumps, Electric vehicles
- International fuel prices: Gasoline and Diesel, Natural gas, Hydrogen, E-fuels.

For each random variable, a probability distribution is assumed together with a correlation matrix (please see the Appendix "8.6 Probability distributions and correlation matrix of the random variables representing key uncertainties surrounding the evolution of the Swiss energy system). Using Latin Hypercube Sampling, the joint distributions of the random variables are sampled to obtain 20 context scenarios. A context scenario combines random values for each of the 22 variables. In each sample, the value of all context variables is updated.

The combination of policy packages, intensities, and contexts resulted in 600 scenarios to be quantified by the JRC-EU-TIMES. The quantification needed 26'400 computational node hours, generated about 2 TB of data, and produced 306 policy impact files (the impact of each policy if it is consistently implemented until 2050) to be explored by AIM. For the quantification, the PSI's high-performance computing cluster MERLIN 6 was used.

In the following sections, the main outcomes and insights of POLIZERO are presented. The section is organised into three subsections: a) results from the stakeholder analysis that identified the policy packages to be quantified; b) results from the three core scenarios quantified by the JRC-EU-TIMES; c) results from the dynamic adaptive policy pathways exploration with AIM and JRC-EU-TIMES models.

3 Results and discussion

This section starts by presenting the results from the stakeholder analysis (Section 3.1), which are related to the first objective of POLIZERO, which is to identify relevant decarbonisation policies for Switzerland. It continues with the long-term energy scenario analysis that deals with the transition of the Swiss energy system to net-zero GHG emissions within the context of the EU Green Deal (Section 3.2), which directly relates to the second objective of POLIZERO, which is to examine the interactions between the EU and Swiss energy systems and policies. It concludes with the Dynamic Adaptive Policy Exploration (Section 3.3), which identifies robust policy pathways to net-zero emissions by 2050, and it is in line with the third objective of POLIZERO.

3.1 Stakeholder analysis to identify policy packages for delivering a carbon-free Swiss energy system by 2050

The policy package philosophies are identified based on the stakeholders who participated in the consultation rounds of the EnG 2020 and CO_2 Act 2021 revisions. Stakeholders are classified as shown in Figure 6. In total, more than 450 position papers were assessed for the two laws, corresponding to 214 stakeholders for EnG 2020 and 250 stakeholders for the CO_2 Act 2021 revision (there were overlaps in the stakeholders between the two laws). For a detailed list of the stakeholders assessed in the two revisions, the reader is directed to the Supplementary Material of (Zhang et al., 2024). Appendix "8.2 Stakeholders Included in Topic Modelling " lists the stakeholders who participated in the consultation rounds of the EnG 2020 and CO_2 Act 2021 revisions, classified into the categories shown in Figure 6.

The stakeholder groups are based on the end-use sector they relate to, the nature of the organisation, the energy technology they support, and the themes they align to, if they cannot be categorised in any of the other groups shown in the figure. This grouping helps identify policies targeting sectors or technology options relevant to the stakeholders who participated in the consultation rounds of the two Laws. Energy utilities and suppliers dominate the EnG stakeholders, but are drastically less in the CO_2 Act. The stakeholders under the energy/climate/landscape theme also have a consistent, substantial weight in both legislations. The CO_2 Act has a wider variety of stakeholders, with a more significant representation of stakeholders from mobility and other end-use consumer sectors.

Energy Source	ENG	CO2Act	Total
Wind	3.3%	0.0%	1.5%
Solar	2.8%	1.2%	1.9%
Sewage and Waste	5.6%	0.0%	2.6%
Nuclear	0.9%	1.2%	1.1%
Hydropower	1.4%	0.0%	0.6%
Heating	1.9%	0.8%	1.3%
Gas	1.9%	2.4%	2.2%
Carbon Removal/Offset	0.0%	0.8%	0.4%
Biomass	3.7%	2.8%	3.2%
Sectors			
Mobility	2.8%	9.6%	6.5%
Industry	3.7%	6.0%	5.0%
Commerce	4.2%	8.8%	6.7%
Building	4.7%	7.6%	6.3%
Aviation	0.0%	4.8%	2.6%
Agricluture	2.3%	4.0%	3.2%

Nature of Organization	ENG	CO2Act	Total
Union	0.5%	0.4%	0.4%
Political Party	5.1%	4.8%	5.0%
Lobby	0.0%	0.4%	0.2%
Federal Entity	1.4%	0.8%	1.1%
Canton/Municipality/Commune	16.8%	13.2%	14.9%
Academia	1.4%	1.2%	1.3%
Themes			
Energy Supply	18.2%	5.6%	11.4%
General Political Consulting	0.9%	0.8%	0.9%
International Development	0.0%	2.8%	1.5%
Heritage Building Protection	0.0%	5.2%	2.8%
Mountainous Region	0.9%	1.2%	1.1%
Energy/Climate/ Landscape	15.4%	13.6%	14.4%

Total stakeholders in ENG, n=214; CO2 Act, n=250

Figure 6: Classification of the stakeholders for Natural Language Processing based on their primary interest[10]

The application of Topic Modelling on the position documents from the stakeholders who participated in the consultation rounds of the EnG revealed three main topics, which can be interpreted as policy concerns for these stakeholders: focus on subsidies, market mechanisms and the environment. The application of Topic Modelling to the position documents of the stakeholders who participated in the consultation round of the CO_2 Act 2021 Revision revealed heterogeneous policy priorities clustered into five additional topics: emphasising strong climate mitigation, international and European alignment, heritage building preservation in energy transition, promotion of clean fuels, and the role of agriculture in GHG emissions mitigation. Unlike the stakeholders who participated in the consultation of the EnG 2020 Revision, those in the CO_2 Act 2021 Revision are more scattered among the topical groups (Figure 7). Appendix “8.2 Stakeholders Included in Topic Modelling “ lists the individual stakeholders who participated in the EnG 2020 and CO_2 Act 2021 revisions, mapped to the categories and topics shown in Figure 7. These topical clusters inspired the policy package philosophies. Additional discussion and insights from the stakeholder analysis from Topic Modelling are provided in Appendix “8.9 Additional insights from the Topic Modelling and the assessment of the positions papers of stakeholders “.

On the other hand, the POLIZERO workshops assisted in the identification of policies to be included in each package. The main findings are summarised below and are also available on POLIZERO’s website[11]:

- The stakeholders emphasise expanding Switzerland’s Emissions Trading Scheme (ETS) to include transport and building sectors, currently limited to major industrial emitters. As a transition instrument to fully implement the extended ETS, a CO_2 levy covering transport fuels is also suggested. The stakeholders acknowledged challenges related to the tax’s potential burden on households

[10] The difference between “mobility” and “aviation” is that the prior only includes stakeholders related to road transport. The difference between “heritage building protection” and “building” is that the former focuses on the preservation of landmarks and historical buildings. “Mountainous regions” include any association representing the political interests of the population from mountainous and rural regions, such as the “Schweizerische Ar-beitsgemeinschaft fuer die Berggebiete”.

and non-ETS industries. Solutions proposed include mechanisms like Carbon Contracts for Difference to manage financial risks and voluntary emissions agreements. According to stakeholders who participated in the workshops, the introduction of CBAM for imported goods, aligned with the EU standards, can protect the competitiveness of the Swiss industry.

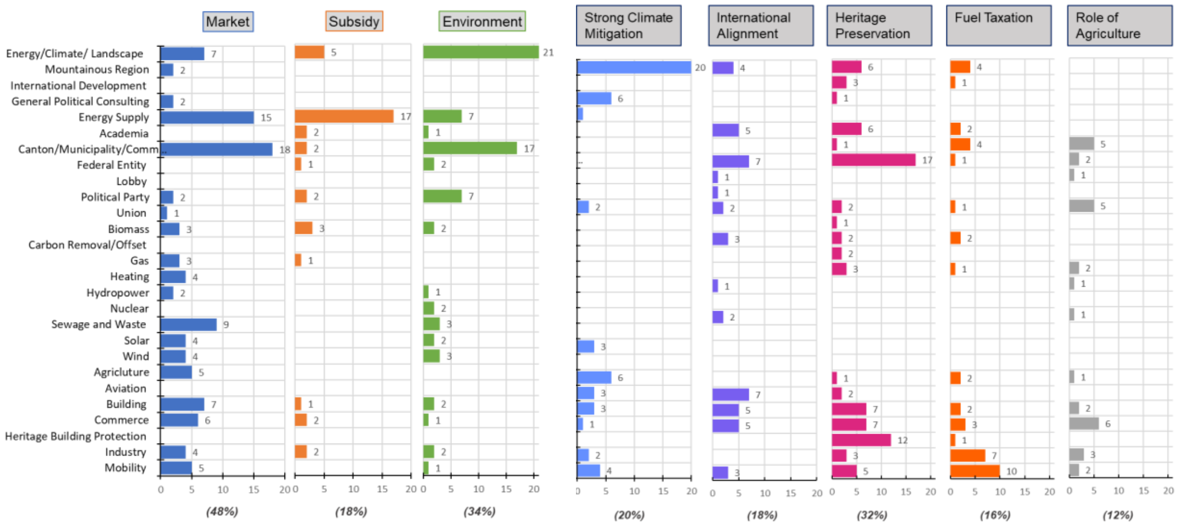

Figure 7: Number of stakeholders from each category (rows) belonging to the topical clusters (columns) of the EnG 2020 Revision (left) and the CO_2 Act 2021 Revision (right); the total percentage of the stakeholders belonging to each topical cluster is shown at the bottom of each topic

- Stakeholders advocate for simplifying regulatory processes and providing technology-neutral incentives for renewable projects. One-time capital subsidies and competitive tenders for larger projects are suggested. To bolster energy security, policy recommendations included support for energy storage and demand-response initiatives. Promoting renewables with good winter availability, such as alpine solar PV and wind energy, is also noted. By ensuring a diversified energy mix, including contributions from nuclear power (without subsidies), these measures aim to address seasonal supply fluctuations effectively.
- According to stakeholders, to enhance energy imports availability, Switzerland should pursue bilateral agreements with the EU for electricity, biofuels, hydrogen, and CO_2 transport, thus reducing import dependency on fossil fuels. Key priorities should be domestic infrastructure improvements, particularly for alternative fuels, EV charging stations, and CO_2 transport. Recommendations included implementing technology-neutral auctions, subsidies, and streamlined permitting to accelerate project timelines. Upgrading the transmission and distribution grid, as well as district heating, can enable a resilient infrastructure.
- The stakeholders also propose market-based instruments, like CO_2 taxes and ETS, as alternatives to outright bans on internal combustion engine vehicles. Carbon budgets, reduced fuel tax exemptions, and demand management initiatives such as car-sharing and e-bike infrastructure are emphasised as cost-effective solutions for transport decarbonisation. Besides ETS, carbon border tax adjustments can be a foundational tool for the industry. Stakeholders also suggest adding technology standards and financial support to encourage the adoption of low-carbon equipment. Bioenergy, e-fuels, and CO_2 transport infrastructure is essential to meet sectoral decarbonisation goals and are recommended for priority development. Decarbonising residential buildings presents challenges, including the high cost of retrofitting, incentive misalignment between landlords and tenants, and skilled labour shortages. Additional tax deductions for renovations, CO_2 taxes on heating fuels, and subsidies for CO_2-neutral heating systems are proposed for the short term.

- For 2030-2040, the stakeholders suggest soft loans for renovations, mandatory energy audits, and minimum energy performance standards. Long-term strategies (post-2040) include scaling up renovation financing, phasing out fossil fuel heating, and expanding the ETS to buildings, ensuring comprehensive sectoral integration into Switzerland's decarbonisation efforts. Technology switches should be supported in the short term, while behavioural changes should be targeted in the long run.

The stakeholder analysis and the input from the workshops help conclude four core policy package philosophies: "Subsidies", "Levies", "Obligations", and "EU harmonisation". These are shown as PP1, PP2, PP3 and PP4 policy packages in Table 2. Additionally, we mix these core policy packages into four combinations after exchanges with the POLIZERO Advisory Board, also summarised in Table 2. All the meaningful combinations with the "EU harmonisation" policy package were chosen to assess the possible advantages of Swiss policy harmonisation with the EU policy. The policies included in each of the four core policy packages PP1 – PP4 are shown in Table 3 to Table 6, together with their intensities, corresponding to the stringency of the policy. In these tables, "Subsidies" are expressed as a percentage of the capital expenditure. The combined policy packages include all the policy instruments of the core policy packages. The intensity of a combined policy package dictates the intensity of the core packages' policy instruments. An exception is for PP1, which can be at a different intensity than PP2, PP3 and PP4 when combined with them; for example, PP1 can be set to a low intensity, but PP2 at a high intensity when PP1 is combined with PP2. However, invalid combinations are excluded.

Table 2: Policy packages and their combinations identified from stakeholder analysis in POLIZERO

Policy package code	Policy Package Philosophy
PP1	Direct Subsidies (or "Rewarding the new")
PP2	CO_2 Levies (or "Penalising the old")
PP3	EU Harmonisation (or "Let the market play")
PP4	Obligations, bans, mandates (or "Forcing the change")
PP1 + PP3	Direct Subsidies + EU Harmonisation
PP3 + PP4	EU Harmonisation + Obligations
PP1 + PP2 + PP4	Direct Subsidies + CO_2 Levies + Obligations
PP1 + PP3 + PP4	Direct Subsidies + Obligations + EU Harmonisation

The intensities for the policy instruments are divided into three levels: low, high, and medium (Table 3 to Table 6). For reference, the tables also show the intensity of the BAU scenario if the policy exists in this scenario. For the interpretation of AIMs modelling results, all policy instrument intensities remain the same from the start year until the end of the modelling time horizon, 2050.

In the "Subsidies" package and for existing subsidy policy instruments, the BAU intensity level aligns with the subsidy levels from (Swiss Parliament, 2024b). The percentage of the subsidy is calculated based on the technology costs from (Bloch & Sauter, 2023) for solar installations and (Kirchner et al., 2021) for wind, biogas, and wood installations. Considering the current support schemes for solar PV, we assume that the policy intensity of the capital subsidies has peaked for these installations. For the CO_2 Levy, the low intensity refers to the levels proposed by the rejected CO_2 Law in 2021 (FOEN, 2020). In this regard, the level of a carbon tax of 210 CHF/t CO_2 for heating fuels is the lower policy intensity level for a new carbon policy in the post-2030 period, assuming that the CO_2 levy cannot be less than today's value of 120 CHF per ton CO_2 in the future. Other innovative subsidies that have yet to exist follow the same arbitrary levels of subsidies for each intensity, as described in the methodology section.

In the "EU-harmonisation" package, the instruments are mostly existing policy instruments in the EU that have yet to be completely transposed to Switzerland. The intensity is mainly chosen by shifting the ambition of the timelines. For the policy instruments in the "Obligations" policy package, the intensity variation follows the same logic as in the EU-harmonisation package, which is by advancing the timeline of the targets. The CO_2 emission reduction requirement is formulated as an aggregate constraint for sector mobility and buildings, of which the intensities follow the emissions reduction targets proposed in KiG (Swiss Parliament, 2024). The mandate for energy performance follows the average values of the Miniergie standards (Sidler & Humm, 2019) for various building types. The mandate for the minimum charging station is calculated by assuming a station's charging capacity of 10 kW and estimating the density of inhabitants per building, based on previous work performed at PSI (Luh et al., 2023).

Table 3: Policy instruments in the policy package PP and their intensity 1

PP1: Direct CAPEX subsidies or "rewarding the new" philosophy provided as a % of the CAPEX					
Sector	**Policy Instrument**	**BAU Level**	**Low Level**	**Medium Level**	**High Level**
Buildings	Subsidies to district heating networks	-	10%	30%	50%
Buildings	Subsidies for CO_2-neutral heating and building renovation	20%	30%	50%	70%
Energy sector	Subsidies for biogas and wood plants	20%	20%	40%	60%
Energy sector	Subsidies for wind turbines	50%	30%	60%	80%
Energy sector	Subsidies for solar PV (no self-consumption) >100kw	40%	15%	20%	25%
Energy sector	Subsidies for solar PV (no self-consumption) >30-100kw	60%	12%	17%	22%
Energy sector	Subsidies for solar PV (no self-consumption) < 30kw	30%	10%	15%	20%
Energy sector	Subsidies to hydropower (1-10MW &>10MW)	30%	10%	30%	50%
Energy sector	Subsidies to geothermal energy for electricity production	50%	10%	30%	50%
Energy sector	Subsidies for green hydrogen production	-	10%	30%	50%
Industry	Subsidies for clean technologies for process heating	-	10%	30%	50%
Industry	Subsidies for more efficient equipment	-	10%	30%	50%
Transport	Investment subsidies for charging infrastructure	-	10%	30%	50%
Transport	Investment subsidies for H_2 fuel charging infrastructure	-	10%	30%	50%

Table 4: Policy instruments included in the policy package PP2 and their intensity

PP2: Levies or "penalising the old" philosophy					
Sector	**Policy Instrument**	**BAU Level**	**Low Level**	**Medium Level**	**High Level**
Buildings, Industry, Energy sector	Strengthening the CO_2 levy, except for ETS participants and transport (CHF/tCO_2)	120	210	500	800
Transport	CO_2 tax for motor and aviation fuels (CHF/tCO_2)	-	180	500	800
Transport	CO_2-based vehicle registration and circulation taxes - % increase of the vehicle tax for fossil-based vehicles	-	30%	50%	100%

Table 5: Policy instruments included in the policy package PP3 and their intensity

PP3: EU Harmonisation or "let the market play" philosophy					
Sector	**Policy Instrument**	**BAU Level**	**Low Level**	**Medium Level**	**High Level**
Buildings, Transport	Expansion of the Emissions Trading Scheme in buildings and transport				
	emissions reduction target in 2030 from 2005	-	21%	42%	62%
	emissions reduction target in 2050 from 2005	-	42%	62%	95%
Industry, Energy Sector	Strengthening the Emissions Trading Scheme				
	emissions reduction target in 2030 from 2005	42%	62%	62%	82%
	emissions reduction target in 2050 from 2005	-	90%	95%	95%
Energy Sector	Subsidies for alternative fuel backbone pipelines	-	10%	30%	50%
Industry, Energy Sector	Subsidies for the CO_2 pipeline from CC(U)S	-	10%	30%	50%
Transport	Ban internal comb. engine cars sales (unless e-fuels) (year)	-	2040	2035	2030
Transport	Stricter emissions standards in 2035 (for new vehicles)				
	Cars (gCO_2 per km)	49.5	49.5	24.8	0.0
	LCVs (gCO_2 per km)	90.6	90.6	45.3	0.0
	HDT (gCO_2 per km relative to 2025 - target is for 2050)	-	45%	65%	90%

Table 6: Policy instruments included in the policy package PP4 and their intensity

PP4: Obligations or "forcing the change" philosophy					
Sector	**Policy Instrument**	**BAU Level**	**Low Level**	**Medium Level**	**High Level**
Buildings	CO_2 emissions requirements in buildings (reduction in 2040 from 1990 levels)	-	65%	82%	100%
Buildings	Minimum energy performance requirements in buildings in kWh per sqm (in 2040)	-	70	60	35
Buildings	Banning installation of new fossil heating systems (year)	-	2035	2030	2025
Buildings	Minimum solar PV and battery systems in new buildings in W per sqm	-	20	60	100
Transport	Carbon budgets for certain mobility modes in 2040 (e.g., cars and trucks) target in 2050	-	30%	57%	100%
Transport	Mandate for minimum number of charging stations per building (kW per building)	-	40	50	60
Industry	CO_2 emissions requirements in industry (reduction in 2050 from 1990 levels)	-	90%	95%	99%
	target in 2040	-	50%	70%	85%

3.2 Long-term Scenario Analysis for the EU and Switzerland

This section describes the BAU, CLI, and CLI90 core scenario analysis results with the JRC-EU-TIMES model and serves as the basis for the subsequent policy exploration. The EU and Switzerland developments are discussed, focusing on primary energy supply, final energy consumption, energy conversion, imports and emissions. The discussion starts by contrasting BAU and CLI and concludes by comparing CLI and CLI90 across key differences in the achieved emissions reductions and energy system configuration for Switzerland.

3.2.1. Total Primary Energy Supply in BAU and CLI Scenarios

In the EU-27, the decoupling of energy demand from economic growth has been the trend since 2006, while in Switzerland, since the 1980s, the primary energy consumption ratio to GDP has declined. In both regions, energy efficiency and renewable energy policies implemented in the current decade maintain the decoupling of energy consumption and economic growth until 2030, while afterwards, it is also driven by technological development. In the CLI scenario, this decoupling is a key enabler for meeting the GHG emissions reduction targets (Figure 8).

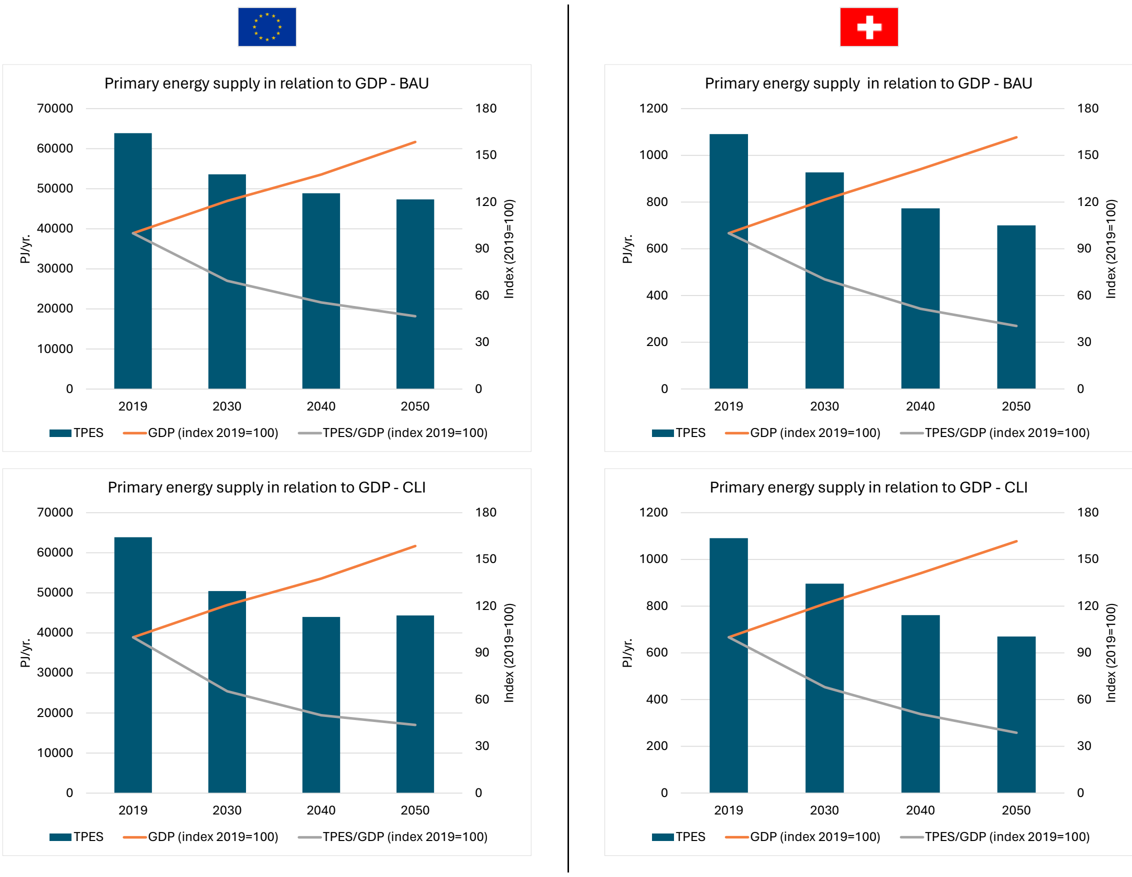

Figure 8: Total primary energy supply[12] in relation to GDP in the BAU and CLI scenarios

In the EU, the per capita primary supply reduces from 39’640 kWh/capita in 2020 to 29’800 kWh in BAU and 27’920 kWh in CLI by 2050. In Switzerland, the per capita primary energy supply reduces from 34’840 kWh in 2020 to 18’680 kWh in BAU and 17’900 kWh in CLI by 2050. The latter value resembles a “2000 Watt” society (Gutzwiller, 2006).

[12] It includes consumption for international aviation and maritime

3.2.2. Final Energy Consumption in BAU and CLI Scenarios

Figure 9 shows the final energy consumption by fuel in the EU and Switzerland for the BAU and CLI scenarios by fuel, and Figure 11 shows the total final energy consumption by sector.

In BAU, the decreasing trend of total primary energy consumption is associated with the developments in final energy demand and the shift to renewable energy sources in power generation. Several existing measures promote energy efficiency in the EU and Switzerland[13], and the period 2021 – 2030 sets the groundwork for a less energy-intensive economy in both regions. Due to efficiency gains, ETS, and increased electrification of mobility and heating, oil products and solid fuel consumption decrease over time, while natural gas remains relatively stable. Electrification of the end-uses is a persistent trend in BAU. Still, the absolute growth in electricity demand by 2050 is mainly driven by transport and, to a lesser extent, by the stationary energy sectors. In Switzerland, the share of the building sector in total final energy consumption remains relatively stable, which is attributable to the high population growth that Switzerland is assumed to experience, particularly in the post-2030 period.

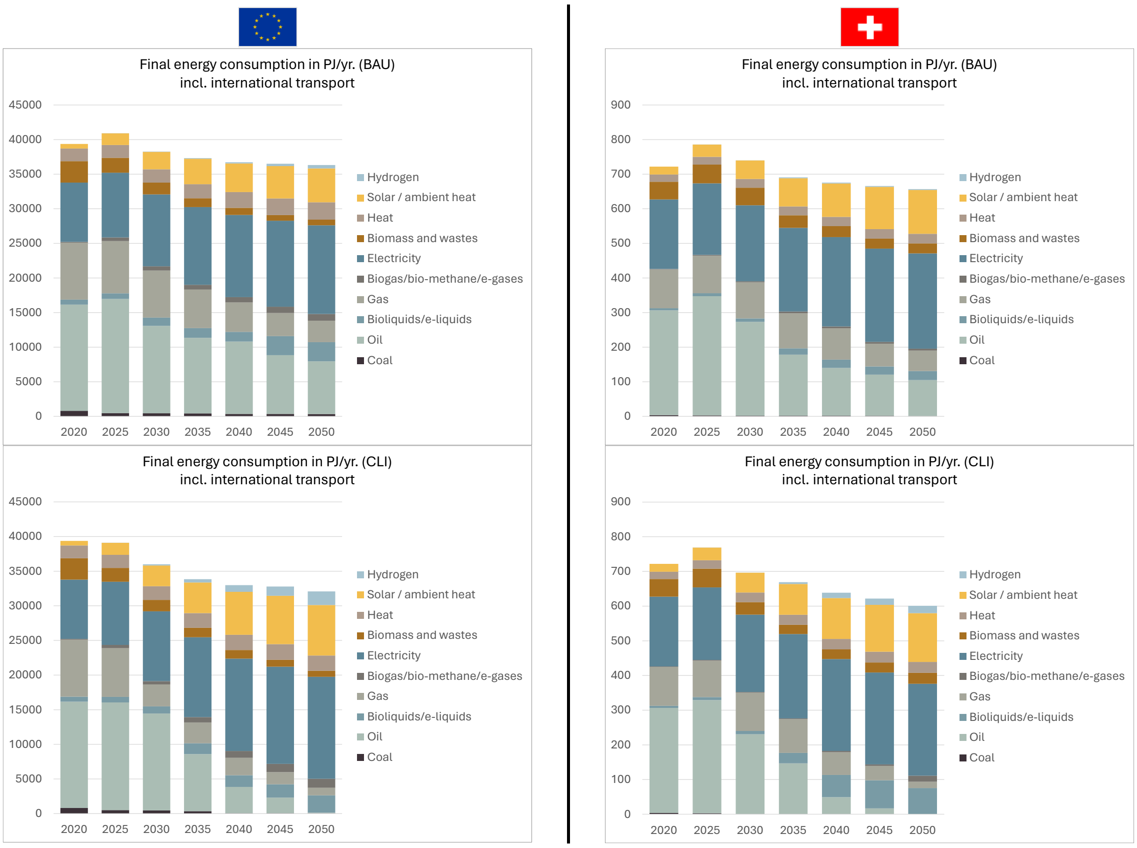

Figure 9: Final energy consumption by fuel in the BAU and CLI scenarios

In CLI, achieving the emissions reduction targets requires significantly lower energy demand than in BAU in both regions. In the EU, fossil fuels remain contributors to the final energy demand until 2030/2035, but their consumption reduces to a fraction of the 2020 level by 2050. Synthetic bio- or e-fuels meet the needs for zero-carbon molecules in this case. In contrast, the contribution of electricity to final energy demand is accelerated, driven mostly by electric mobility and heating, as the electricity consumption in appliances reduces over time due to energy efficiency improvements. Hydrogen

[13] Measures implemented in the model towards energy efficiency are the Energy Efficiency Directive, the Energy Performance of Buildings Directive, and the Eco-Design Directive in the EU. In Switzerland is the Buildings Program, the Buildings Standards and Eco-Design and Labelling. In both regions, the vehicle emissions performance standards also contribute to efficiency gains in the transport sector.

emerges in the final energy consumption, either directly or indirectly via synfuels, in industry and the transport sector (trucks, aviation, maritime), mainly after the 2030s. The CLI scenario for Switzerland displays similar developments as in the EU, with efficiency gains and electrification at the forefront of the net-zero transition. Hydrogen also emerges in Switzerland, driven by European developments in the aviation sector and the demand for synthetic fuels in the industry sector. ~~road freight transport sector.~~

The per capita final energy consumption reduction targets for 2035 and 2050 that are foreseen in the Swiss Energy Strategy are met. The share of electricity in final energy consumption reaches 44% by 2050, accounting also for the fuel consumption in international aviation and for environmental (ambient) heat used in heat pumps, signalling its role in decarbonising energy demand. The transport sector shows the largest reduction in energy demand, attributable to the acceleration of alternative and more efficient drivetrains. Next to transport, the residential and services sectors also achieve high energy savings. Additional insights on the sectoral developments in BAU and CLI scenarios, with respect to the fuel mixes in buildings, industry and transport sectors, are provided in the Appendix “8.7 Additional results from the POLIZERO scenarios BAU and CLI: developments in buildings, industry, electricity and transport sectors”.

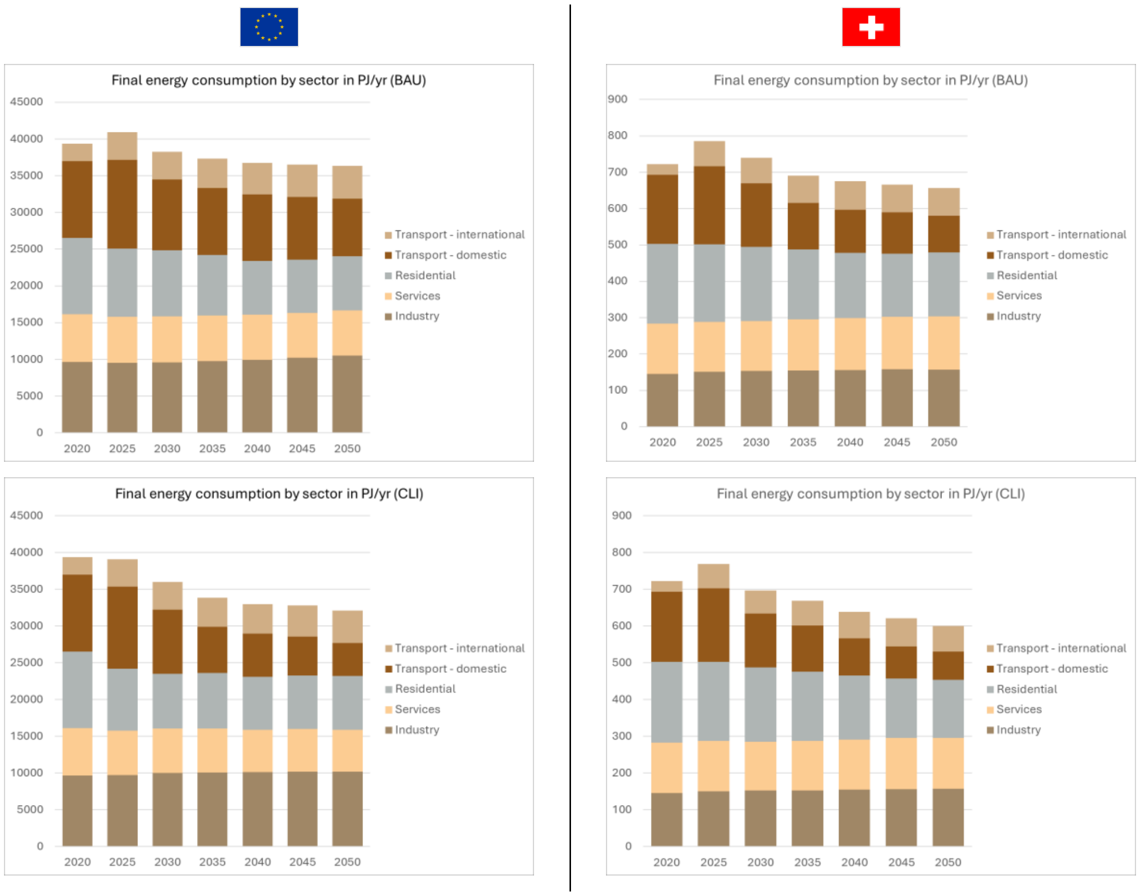

Figure 10: Final energy consumption by sector in the BAU and CLI scenarios

3.2.3. Electricity Supply in BAU and CLI Scenarios

Figure 11 presents the electricity supply mix in the EU-27 and Switzerland for BAU and CLI scenarios.

In BAU, the electricity supply sector in the EU-27 experiences a significant penetration of renewable energy technologies, with wind power significantly contributing to the European electricity mix – this is driven in BAU by current national commitments. Solar electricity in the EU-27 quadruples between 2019 and 2050, attributable to the support schemes in the near-term and the decreasing costs of solar panels in the long-term. Other non-hydro renewable energy sources only slightly increase in 2050 from 2019, while any expansion of hydropower in the EU-27 beyond the planned hydro-reservoir projects is mainly in small run-of-river plants. The share of coal-based generation significantly declines in the post-2030 period because of the coal phase-out policies (despite the fact that these policies were postponed in 2022, reflecting energy import dependence concerns due to the energy supply crisis this year) and the increased competitiveness of wind and solar energy. Natural gas contributes to load balancing and integrating renewable energy in power generation. Finally, the electricity generation from nuclear is driven downwards throughout the projection period due to phase-outs (e.g., in Germany), extended downtime of several units (France, Sweden) and delays in commissioning new nuclear power plants (Finland, Poland). Nuclear investments mainly occur in existing sites or are lifetime extensions. There are very few investments in nuclear capacities on new sites. In Switzerland, the total electricity supply increases moderately after the nuclear phase-out, as the electrification of transport is not accelerating, and the stationary sectors switch to efficient electric equipment. As the last nuclear reactor is decommissioned in the mid-2040s, non-hydro renewable electricity, particularly solar PV, sees its share in electricity generation increase substantially in 2050. Wind turbines increase their penetration in the BAU scenario, albeit at much lower rates than the ones observed in the EU-27, while bioenergy and wastes remain relatively stable until 2050. Electricity imports fill the supply gap after the nuclear phase-out.

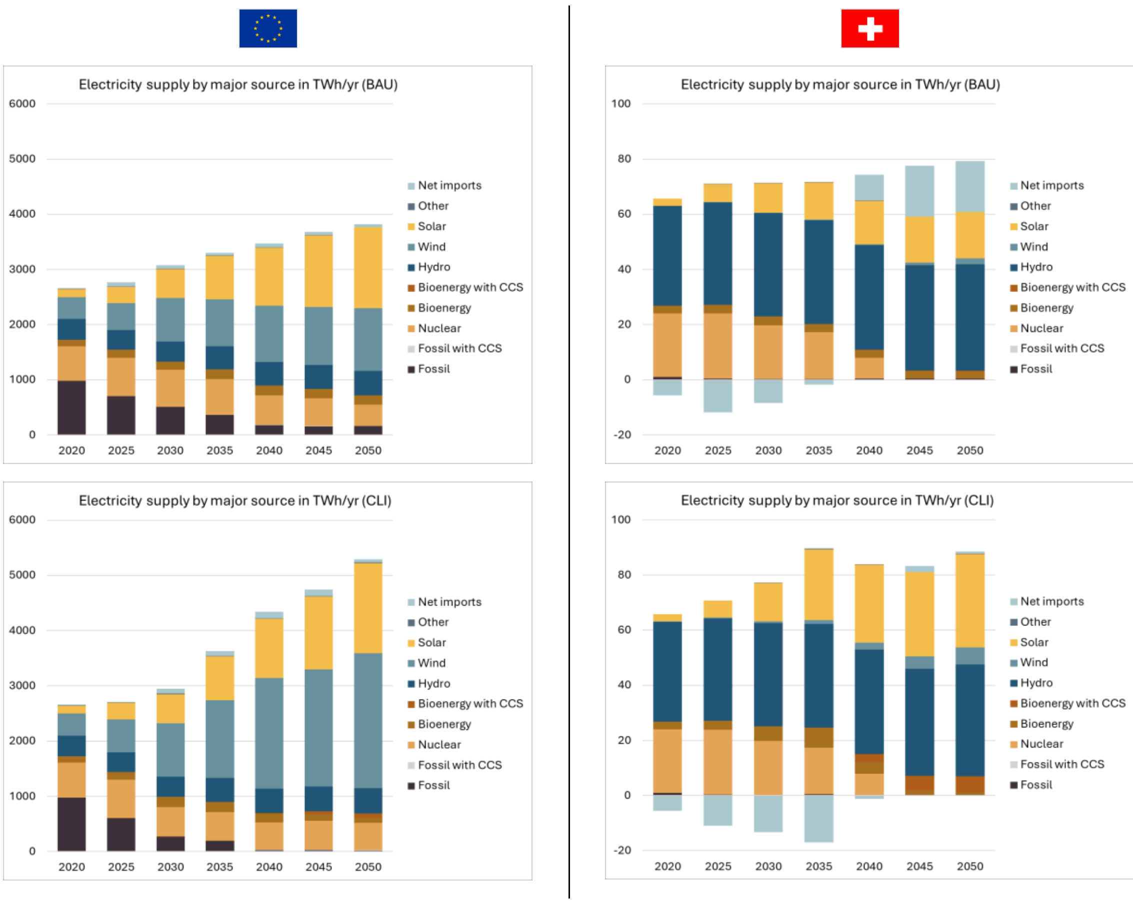

Figure 11: Electricity supply by major source in BAU and CLI scenarios

In CLI, the new electricity demand in the EU-27, mainly from the heating, transport and hydrogen production sectors, is satisfied through wind and solar. As a result of the new electricity uses, the electricity supply in the EU-27 doubles in 2050 from the 2020 levels. There is a significant increase after 2035 in the electricity supply in Europe. Major drivers for this increase are the strict vehicle emissions standards in transport (from 2035 only zero-carbon vehicles are allowed in the EU), the implementation of the

RefuelEU aviation directive that requires increased renewable hydrogen production in Europe for domestic sustainable aviation fuels synthesis, the reduction in the ETS allowances that shift industry to use more hydrogen in the process heat generation, and the implementation of the buildings codes and emissions performance standards that enable electrification of space heating. Nuclear power slightly expands to strengthen energy import independence in some European countries, such as Bulgaria, Czechia, Finland, France, Hungary, Poland, Romania, Slovenia and Slovakia, the UK, but also Sweden and Lithuania, as imported uranium can be stockpiled for 2-3 years in advance. Bioenergy does not significantly expand compared to BAU, but it should be acknowledged that the model does not capture all possible issues related to land availability and forest management strategies. With a strong shift towards carbon-neutral energy sources, fossil fuels become marginal contributors to the electricity supply. Meanwhile, hydrogen and synfuels are not substantially used in the power generation sector.

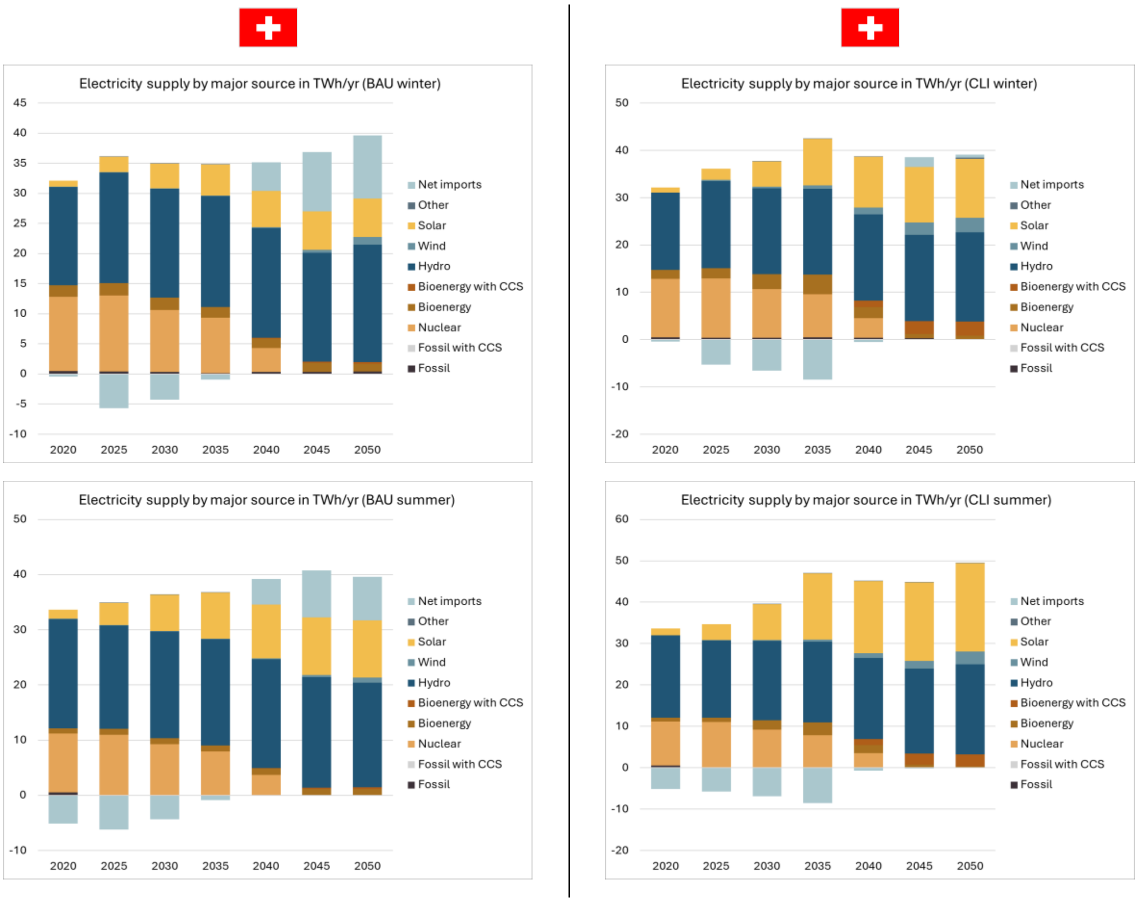

Figure 12: Seasonal Electricity supply by major source and season in BAU and CLI scenarios for Switzerland

Switzerland becomes a net exporter of electricity until 2035, as long as nuclear power is still available and the target of 35 TWh of non-hydro renewable energy is met. The net exports are driven by the fact that renewable energy in the EU does not ramp up by that time to the level required to fill in the gap in natural gas-based generation that is hindered due to the implementation of the REPowerEU plan, which aims at a reduce shared of gas in the energy by 2030. However, in the long term, Switzerland can balance its annual imports to zero. The electricity supply in Switzerland is dominated by renewable energy sources (hydro and non-hydro). Hydropower supplies around 38 TWh in 2035 (without accounting for the output from pump storage) and 40 TWh in 2050. Non-hydro renewables increase their contribution to electricity supply to 35 TWh in 2035 and 47 TWh in 2050. The electricity supply in Switzerland peaks around 2035, as increased exports occur this year, driven by European developments and the need for electricity. This outcome speaks to closing a bilateral agreement with the EU regarding Switzerland's participation in the internal electricity market to reap the benefits from cross-border trade.

Figure 12 shows the seasonal electricity supply for Switzerland for the winter and summer half years. In **BAU**, there are significant electricity imports after the nuclear phase-out in both seasons. In contrast, in **CLI** Switzerland can be claimed to be import independent, if the following two conditions are fulfilled: a) the non-hydro renewable electricity supply achieves the policy targets of 35 TWh in 2035 and 45 TWh by 2050; and b) the electricity consumption per capita is reduced in 2035 and 2050 compared to 2000 at least at the levels foreseen in the Swiss Energy Strategy (see Table 1). However, the JRC-EU-TIMES's intra-annual resolution is not sufficient to capture the full variability of renewable sources, which could lead to an overestimation of the wind and solar potential to supply winter electricity. This short-coming will be tackled in future model development.

3.2.4. District Heating Supply in Switzerland in BAU and CLI Scenarios

District heating supply (and consumption) increases in both scenarios compared to the current levels (Figure 13). In **BAU**, district heating is supplied almost solely from bioenergy after 2035, with wood-based district heating filling the gap in the demand as the supply of the around 30 waste incinerators in Switzerland cannot be scaled further up. Some contributions from nuclear remain until 2035, while fossil-based district heating continues declining and is phased out by the 2030s. Contributions of biogas to district heating remain very limited in the BAU scenario.

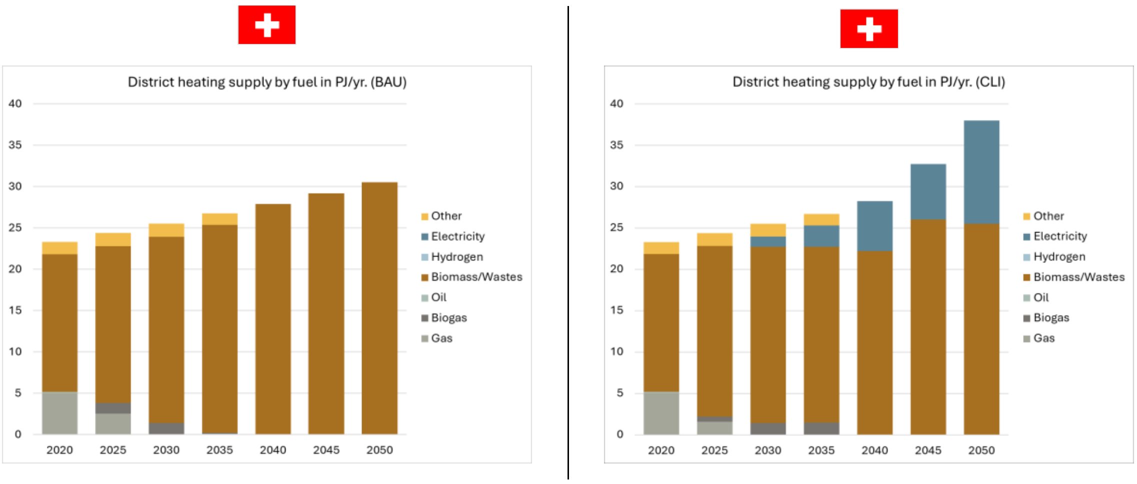

Figure 13: District heating supply in Switzerland in BAU and CLI scenarios by major source

In **CLI**, the increase in district heating supply and demand is substantial compared to BAU, reaching around 11 TWh in 2050 compared to 6.5 TWh in 2020, i.e., almost a doubling in the next 25 years. Next to its use in the building sector, new uses of district heating emerge in this scenario in industry (chemicals, paper and pulp and other low energy intensive industries such as food sector), as well as for Direct Air Capture that scales up in the CLI scenario (since this scenario aims at 100% domestic mitigation of the Swiss GHG emissions, see Figure 16). Large-scale heat pumps mainly provide an additional supply of district heating. In contrast to BAU, in CLI, there is no significant increase in biomass use for district heating, as wood is mainly used in larger facilities aiming to supply electricity with CCS to achieve net negative emissions.

3.2.5. Hydrogen Supply and E-fuels Production in the CLI Scenario

Figure 14 presents the hydrogen supply and the production of biogenic or electricity-based synthetic fuels (e-fuels) in the CLI scenario for the EU and Switzerland. In the CLI scenario, we take a conservative approach to the domestic hydrogen production targets of 10 Mt in the REPowerEU plan for 2030. Such a rapid scaling of hydrogen supply would imply electrolysis deployment rates exceeding the ones currently observed for solar PV and wind turbines[14]. Instead, we abstain from imposing domestic hydrogen production targets for the EU and let the JRC-EU-TIMES model identify the cost-optimal levels of domestic hydrogen production and use, by accounting for near-term hydrogen developments. Still, as domestic renewable electrolysis does not ramp up to the scale needed to supply all the demand for hydrogen in the EU, imports must contribute to the supply during the next two decades.

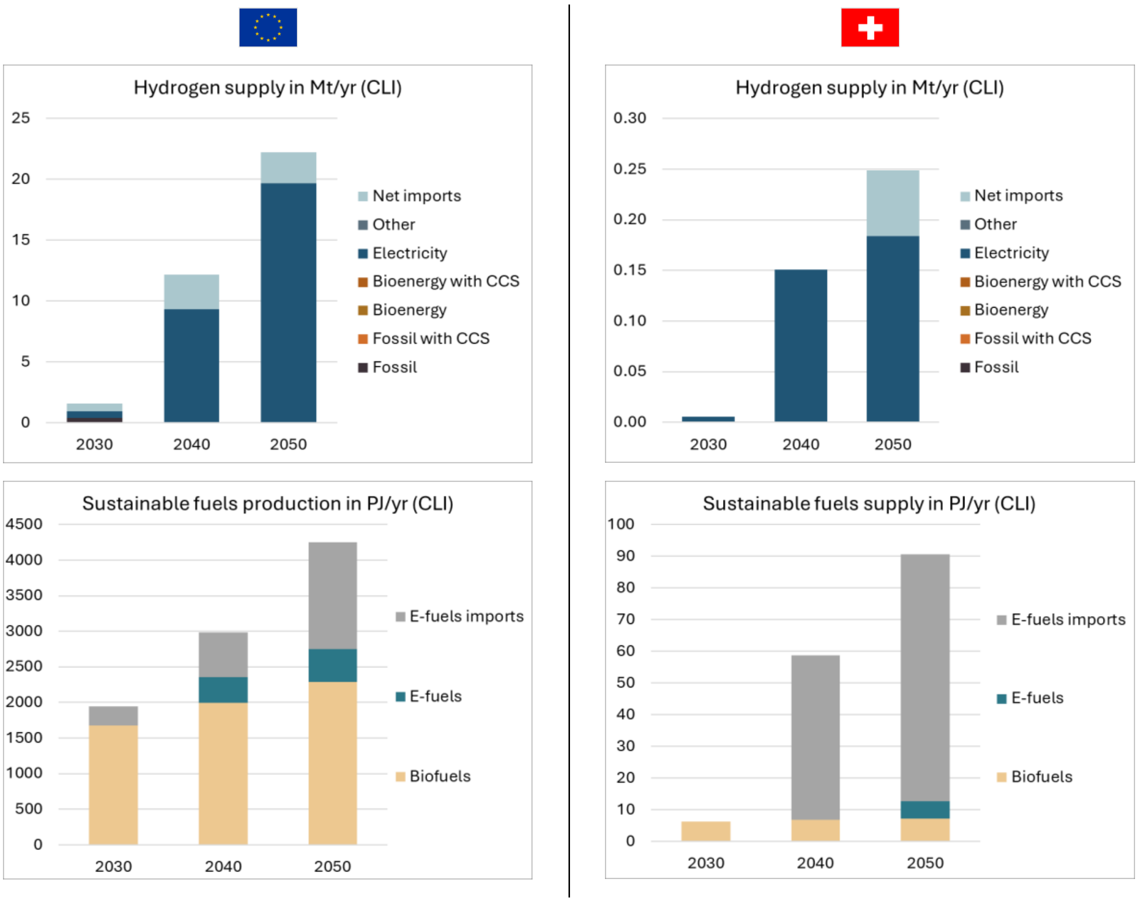

Figure 14: Hydrogen supply mix (top) and production of synthetic biofuels and e-fuels in the CLI scenario

In Switzerland, hydrogen also emerges around 2030, following European developments. Industry is the first mover for large-scale hydrogen applications. Domestic hydrogen production in Switzerland is mainly based on electrolysis. When carbon prices or hydrogen demand are high, wood gasification with CCS can also be potentially used for producing hydrogen, provided it becomes commercial before the 2050s and does not compete with other energetic and non-energetic uses of biomass; however, this option does not emerge in the results obtained for the CLI scenario.

The use of hydrogen for the domestic production of e-fuels in Switzerland is limited. The demand for e-fuels mainly comes from the international aviation sector, following the EU developments and the Refuel Aviation Directive. As Switzerland aims to achieve zero emissions by 2050 for international aviation, the

[14] The REPowerEU plan requires 10 Mt of domestic hydrogen production, which if it is all to be supplied by electrolysis would need to scale electrolysis at least to 100 GWe in 2030 from around 385MWe in 2024. Regarding the REPowerEU plan implementation in the model, we account for the reduction in the gas consumption, but we let the model to decide whether the gap will be covered with hydrogen, synthetic fuels, bioenergy or electricity.

consumption of e-fuels for refuelling aircraft in the Swiss airports is 65 PJ/yr. in 2050, roughly three-quarters of the total domestic e-fuels consumption in all sectors. The origin of hydrogen imports to Switzerland in 2050 is from Europe (less than 10% of the total) and North Africa (more than 90%). Imports of e-fuels start around 2035 at a quantity of 25 PJ/yr, and originate mainly from Europe (80%) and Latin America (20%), The contribution of Europe in imported e-fuels to Switzerland follows a declining trend beyond 2035 as other world regions gradually scale up their export infrastructure, ending up in less than 1% of the total e-fuels imports by 2050. At that time, major regions exporting e-fuels to Switzerland are the Middle East and North Africa (45% of the total) and Latin America (54%).

3.2.6. Comparison of BAU and CLI with the WWB and ZERO Basis Scenarios of EP2050+

A comparison between the BAU and CLI scenarios for Switzerland in POLIZERO and the corresponding WWB and ZERO Basis scenarios in EP2050+ is shown in Figure 15. The uptake of non-hydro renewable energy in BAU and CLI scenarios is higher than in WWB and ZERO Basis because of the new renewable support measures that came into force after the energy crisis in 2022. Moreover, by design, the CLI scenario passes through the “Mantelerlass” renewable energy targets in 2035 and slightly exceeds them in 2050.

In the final energy consumption, the BAU and CLI scenarios show slightly higher energy savings than WWB and ZERO Basis, reflecting the recent trends after the COVID-19 pandemic, which are persistent today, e.g., home-office, and the energy crisis of 2022. New policy developments that are considered in the BAU scenarios compared to the ones in EP2050+ are the updated EU-ETS directive targets for 2030, the updated buildings programme incentives implemented by the cantons, the acceleration of the adoption of the buildings energy performance standards by cantons (faster than what is assumed in WWB) and the updated vehicle emissions standards for the post-2030 period (please see also Figure 5 for the policies implemented in the BAU and CLI scenarios).

These developments target near-term energy consumption and emissions, reducing energy demand in the BAU and CLI scenarios compared to WWB and Zero Basis. In contrast, towards 2050, the BAU and CLI scenarios come closer to the levels of WWB and Zero Basis. In addition, it should be noted that the CLI scenario aims at net-zero in 2050 with only domestic mitigation measures, while ZERO-Basis foresees compensation abroad, leading to additional efficiency gains in CLI.

The fuel mix between the POLIZERO and EP2050+ scenarios is largely the same, although BAU and CLI show more electrification of the demand than WWB and ZERO Basis. A major difference is the very prominent penetration of biogas in the ZERO Basis scenario by 2050, while in CLI, the clean molecules for industry and other uses are mainly found in solid biomass and hydrogen.

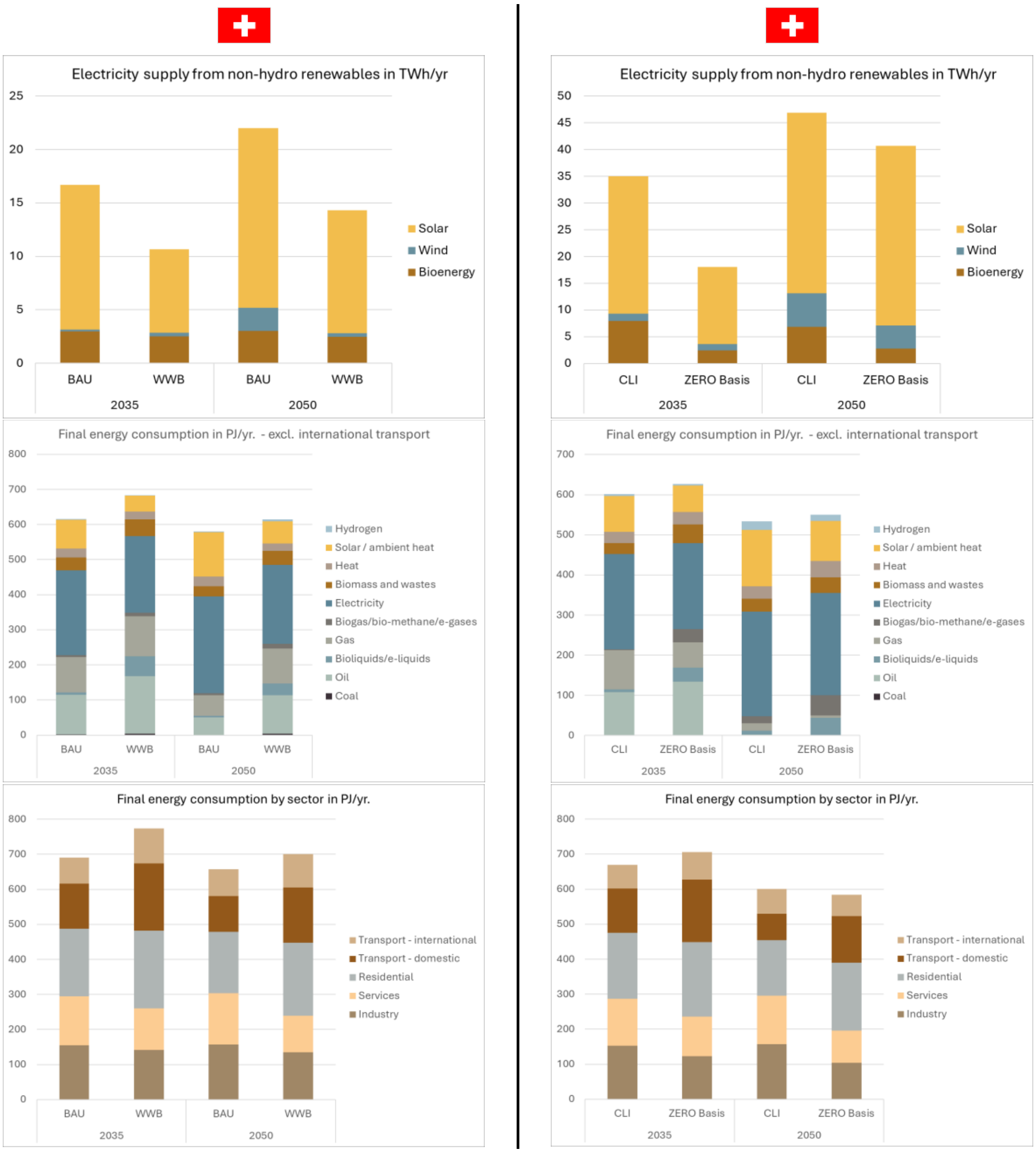

Figure 15: Comparison of electricity generation from renewables (top), final energy consumption by fuel (middle) and final energy consumption by sector (bottom) between the POLIZERO and EP2050+ scenarios

3.2.7.GHG emissions in BAU and CLI scenarios

The GHG emissions trajectories for the BAU and CLI scenarios for the EU-27 and Switzerland are shown in Figure 16 per sector of activity. In both regions, energy supply emissions are reduced most, underlining the large potential for emissions cuts through renewable energy deployment. From the demand side sectors, the highest reductions can be observed in the building and transport sectors. However, there is a more limited scope for transport in the near term than in the long term.

In the EU-27, the buildings sector achieves deep emissions cuts as the current stock is relatively old and inefficient, with large renovation potential at a relatively low cost. The emissions reduction in the industry develops until 2030 at the annual rates observed over the last decade, which signals the high effort the sector has already put in place to reduce its carbon footprint due to the strengthening of the emissions trading system. CO2 emissions from combustion decrease faster than CO_2 process emissions in the industrial sectors, and it is likewise for non-CO_2 emissions from other sectors outside the energy system. It should be noted here that the trajectory of the non-CO_2 GHG is an assumption.

Figure 16: GHG emissions and CO_2 captured in the EU and Switzerland in BAU and CLI scenarios

In Switzerland, the CO_2 emissions from fuel combustion and industrial processes, excluding international aviation, peaked around 2010. Achieving net-zero emissions in 2050 requires reductions in the cumulative CO_2 emissions budget of more than 230 Mt CO_2 from 2020 to 2050 compared to the BAU scenario. The residential, services and transport sectors are decarbonised, while the remaining CO_2 emissions from the energy system in 2050 are from industry and industrial processes. Agriculture is one of the largest emitting sectors of GHG in the CLI scenario in the EU-27 and Switzerland by 2050, based on the assumptions of the scenarios derived from the sector's emissions reduction targets stated in the

EU Green Deal (EC, 2024)and the Swiss Long-Term Climate Strategy (SFOEN, 2021). This development necessitates the uptake of negative emissions technologies that enhance the natural carbon sinks of LULUCF.

The CLI scenario foresees about 10 Mt CO_2 being captured by 2050 in Switzerland. About half of it is captured in the power and heat generation sector, via CCS in waste incinerator plants and some limited deployment of other bioenergy with CCS (wood and biogas). CCS from industrial processes amounts to about 2.6 Mt CO_2, and there are additional contributions from Direct Air Capture (1.5 Mt CO_2) and LULUCF (in addition to the current (2020) of about 0.6 Mt CO_2). The deployment of Direct Air Capture in Switzerland is driven by the requirement of the CLI scenario for deploying 100% domestic GHG emissions mitigation measures. In the CLI90 scenario, no Direct Air Capture or additional carbon sinks from LULUCF are deployed (please see section 3.2.9).

3.2.8. Trade implications in BAU and CLI scenarios for Switzerland

Figure 17 shows the annual Swiss net imports in the BAU and CLI scenarios. However, it excludes fuel imports for the nuclear reactors (approx. 412 metric tons of Uranium per year for the four reactors in 2024[15]). Overall, the BAU scenario has a higher import dependency than the CLI scenario. **In BAU**, import dependency increases over time, driven by the demand for natural gas and the need for electricity after the nuclear phase-out, as the domestic renewable energy sources do not scale up to the levels required to fill the nuclear electricity gap. At the same time, oil imports are halved, reflecting the shift in the transport sector to electro-mobility. In the BAU scenario, some limited imports of hydrogen and e-fuels are also needed to support industry aviation transport needs.

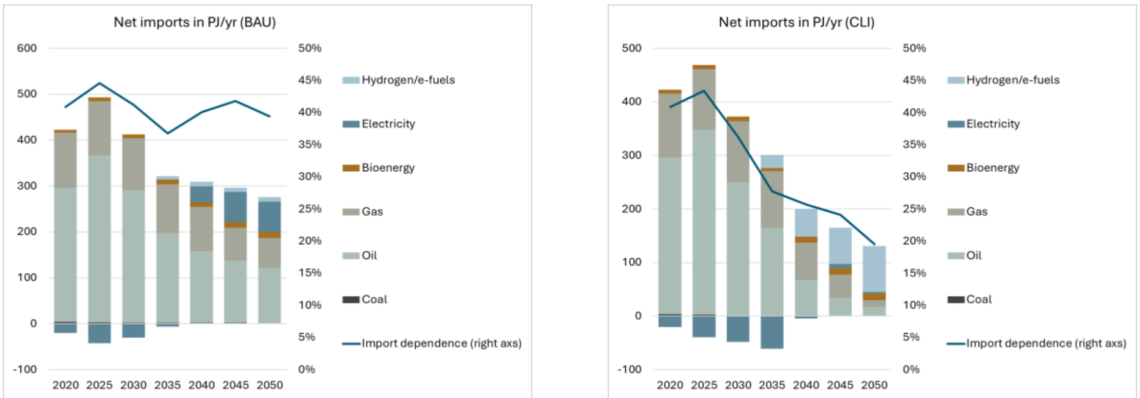

Figure 17: Net imports and import dependency in Switzerland in BAU and CLI scenarios.

In the **CLI** scenario, the import dependency reduces over time from today's level. However, after 2035, import dependency remains relatively stable because of the need for increased electricity imports, hydrogen, and synfuels to decarbonise the demand as the ambition for climate change mitigation increases. Oil imports in 2050 are a fraction of today's level, together with gas imports. Instead, imports of biofuels emerge that complement the imported e-fuels in providing zero-carbon molecules to the Swiss energy system. As mentioned in the section 3.2.3, the electricity imports reduce to annual net-zero by 2050, if the renewable electricity supply targets and the electricity savings per capita targets foreseen in the Swiss Energy Strategy are achieved. Table 7 presents an estimation of the evolution of the average day-ahead electricity price in Switzerland (in real CHF of 2023), based on the levelized cost of electricity. The lower import dependency is associated with a shift away from traditional energy carriers. This shift requires new connections to the European and international trade routes. New agreements between Switzerland and regions that can be potential exporters of alternative low-carbon fuels

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[15] See https://world-nuclear.org/information-library/facts-and-figures/world-nuclear-power-reactors-and-uranium-requireme

will be needed as soon as possible to secure access to these markets. According to the analysis, the critical trade routes Switzerland would require to pursue in the future are the hydrogen and CO_2 backbone grids in Europe, as well as the trade of synfuels and hydrogen with North Africa, the Middle East and Latin America.

Table 7: Evolution of the average electricity day ahead prices (without VAT) in CHF/MWh

Scenario	**2020**	**2030**	**2040**	**2050**
BAU	37.8	85.7	87.1	88.9
CLI	37.8	86.1	92.5	101.3
CLI90	37.8	86.0	92.3	97.7

Note: The 2020 price is the EPEX Spot day-ahead price (annual average). The future price evolution is solely based on increases in the levelized cost of electricity production across Europe and Switzerland, accounting for the trade costs and the origin of the imported electricity. This means that this table does not include any costs incurred due to market inefficiencies, market power, or any other market effect seen in the real markets, as the JRC-EU-TIMES modelling framework cannot capture these. In addition, as the levelized cost approach has been followed for the price calculation, any congestion or re-dispatching costs are also not accounted for in the above calculations.

3.2.9. Compensation of GHG emissions in Switzerland abroad

The variant CLI90 of CLI assumes that up to 10% of the Swiss GHG emissions in 1990—that is, up to 5.4 Mt CO_2-eq—can be compensated abroad in 2050, following a “cost-supply” curve from 50 to 800 CHF per Mt CO_2 (please see the Appendix “8.5 Main assumptions of the POLIZERO long-term energy transformation scenarios” and the accompanying EXCEL file with the main assumptions of POLIZERO scenarios). The compensation takes the form of Internationally Transferred Mitigation Options (ITMOs), which entail a combination of mitigation measures and investments in negative emissions technologies deployed outside the EU, e.g., Sub-Saharan Africa, Southeast Asia, etc. As the JRC-EU-TIMES is not a global model, it cannot specify exactly how the compensation of the emissions abroad is achieved. In addition, it should be noted that the potential of 5.4 Mt CO_2-eq refers to emissions that can be compensated abroad on top of the current bilateral agreements that Switzerland has (e.g., with Peru, Ghana, Senegal, Georgia, Dominica, Vanuatu, Thailand, Ukraine, etc.) or will sign until 2035. This is because the GHG emissions reduction target for 2030 and 2035 has already been adjusted to account for the share of the emissions that can be compensated abroad, as foreseen in the Swiss NDC.

Figure 18 compares the main developments of the Swiss energy system between the two scenarios. The emissions compensated abroad in 2030 are already accounted for in the overall GHG emissions target (as both CLI and CLI90 pass through the emissions reductions of the Swiss NDC), and they are not shown in the figure. This implies that in the figure under the category “Compensation abroad”, the incremental compensation from 2030 levels is shown, which is deployed in the post-2040 period.

Interestingly, the model does not exhaust the 5.4 Mt CO2-eq potential for compensating emissions abroad. This is mainly because of spillovers from the European policy, as stringent EU-ETS regulations by 2050 push the hard-to-abate sector to deploy EU-domestic decarbonisation measures early enough, including not only the manufacturing sector but also the waste incineration plants (in the POLIZERO scenarios, waste incineration plants are part of the EU-ETS). The GHG emissions compensated abroad in 2045 (in addition to those already compensated in 2030/2035) are 3.2 Mt CO_2-eq, increasing to 4.2 Mt CO_2-eq by 2050. Compared to CLI, the possibility of compensating emissions abroad eliminates the need for domestic deployment of Direct Air Capture and additional carbon sinks from LULUCF. Moreover, the total CO_2 captured is about 40% less than in the CLI scenario. The final energy consumption developments in CLI90 are similar to the ones observed in CLI, which is attributable to the sectoral emissions mitigation targets implemented in CLI, as foreseen in KiG. However, the electricity supply mix in the CLI90 scenarios shows less reliance on domestic bioenergy with CCS. The need for carbon-free, low-temperature heat is also lower in CLI90 than in CLI, because no domestic Direct Air Capture (Solid sorbent-based) is deployed. In 2050, the need for district heating in CLI90 is about 2 TWh less than in CLI.

CLI-90 | **CLI**

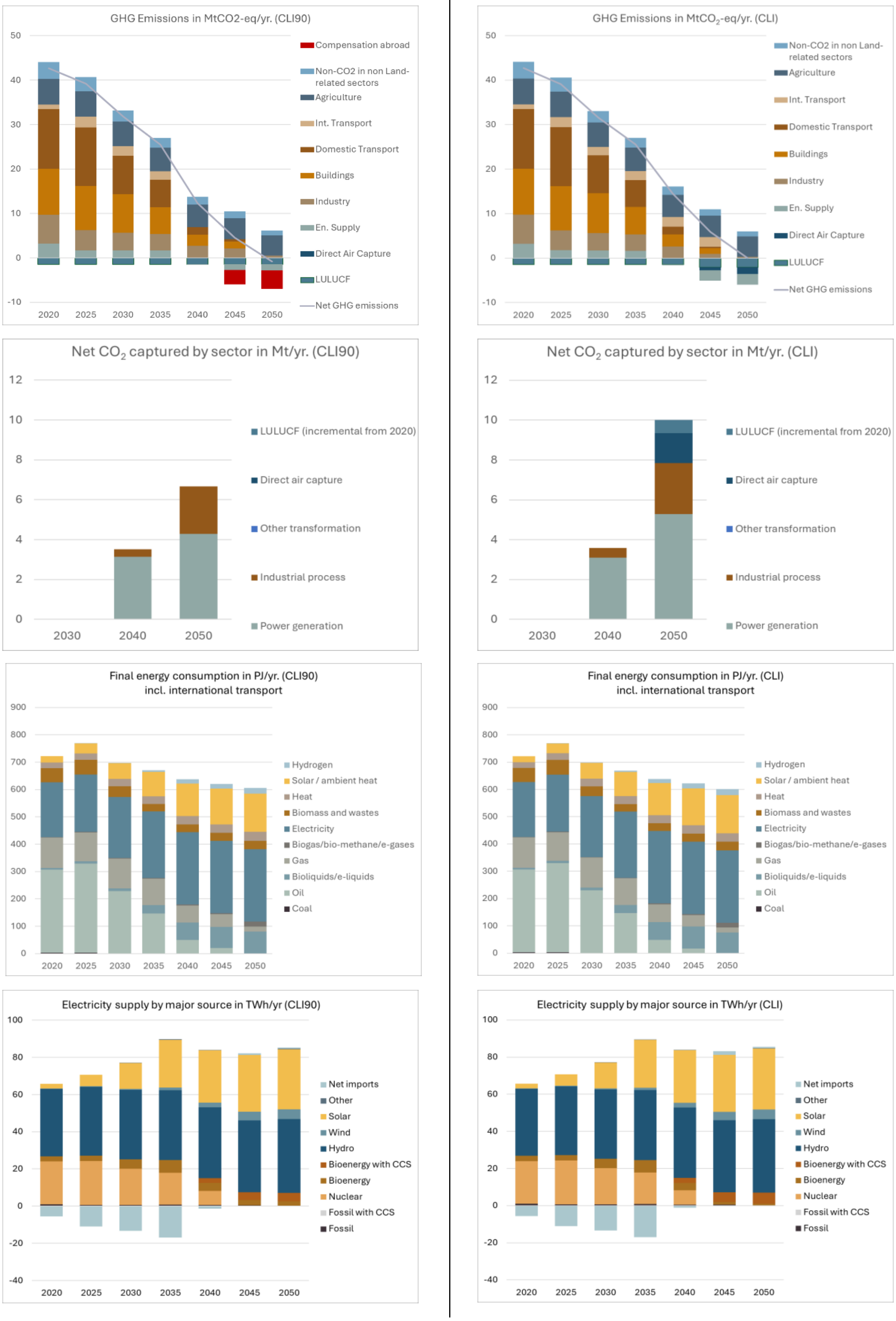

Figure 18: Comparison of the CLI90 and CLI scenarios for Switzerland

3.3 Dynamic Policy Adaptive Pathway Analysis

The Dynamic Adaptive Policy Pathway Analysis explores possible policy pathways to achieve the Swiss energy and climate targets. The four identified policy packages and their combinations, together with the 20 uncertainty contexts and three intensities per policy package, resulted in 30^6 possible pathways to be explored. However, by excluding those that are not meaningful from the policy implementation perspective, e.g., for example, policy pathways starting with bans and continuing with subsidies, and by narrowing further down to those that achieve net-zero emissions from fuel combustion and industrial processes (as there are no policy packages targeting agriculture or international aviation in the analysis), five pathways were identified, which are discussed below.

The policy exploration was performed using the AIM model. AIM is a meta-analysis tool, agnostic to the underlying model that provides the simulation data (in this case, the JRC EU TIMES). AIM has a limited foresight logic, which means that the policies are applied in a forward-looking, sequential manner, and the policy outcome of each policy affects the outcome of the following policies. This logic mimics real-world situations of a policy planner. Nevertheless, perfect foresight on policy implementation is also valuable for a social planner with clear long-term strategic goals. For these reasons, the identified policy pathways from AIM were also implemented in the JRC-EU-TIMES model in a second step. However, due to the foresight philosophy of the JRC-EU-TIMES and the policy implementation methodology of AIM, in some cases, the policy impacts produced by the two models slightly differ. The main gain from linking the two models is that it allows exploring many pathways and guides additional targeted simulation with the JRC EU TIMES. In this section, the results from both models are discussed.

Finally, it should be noted that the pathways discussed in the next sections are implemented on top of the BAU scenario. Policies in the pathways could overlap with the ones the BAU scenario, however, the intensities in the pathways would overwrite the ones in the BAU scenario. In the discussion that follows, the reader is also directed to Tables 3-6 for the intensities of the different policy packages, while the four policy packages are labelled as “Subsidies”, “Levies”, “EU harmonisation” and “Obligations”.

3.3.1. Pathway 1 – Subsidies, EU Harmonisation and Obligations

This pathway examines the combined role of “Subsidies”, harmonisation of the Swiss policy with EU measures, “EU Harmonisation”, and implementing “Obligations” (mandates, bans) in achieving net-zero CO_2 emissions in the Swiss energy system. Three variations of this pathway were identified with AIM, which are discussed below.

Variation 1 – Discontinuation of subsidies

At its 1st variation, Pathway 1 applies high intensity in the policy package of “Subsidies” from 2025 until 2035, while the “EU harmonisation” and “Obligations” policy packages are at medium intensity (according to the definitions in Table 3, Table 4, Table 5 and Table 6). “Subsidies” are reduced to their low values from 2035 until 2040, while the “EU harmonisation” and “Obligations” are set at the highest intensity. After 2040, ”Subsidies” are phased out, leaving only the application of the “EU harmonisation” and “Obligations” at their highest intensity. Figure 19 visualises the 1st variation of Pathway 1. In this figure, and the next ones in this section, on the Y axis, policies in **blue** are implemented at their low intensity, policies in **yellow** are implemented at their medium intensity, and policies in **red** are implemented at their high intensity. The selection of the policy sequence was based on the following observations deriving from the policy exploration. The “EU harmonisation” of Swiss policies and the application of “Obligations” should start immediately with medium intensity. Lower intensity in these two policy packages, even 5 years following the policy status quo, eliminates all possible routes to net zero until 2050. Only with high “Subsidies” accompanying medium intensity of the “EU harmonisation” policies and ”Obligations” at the start, can the pathway reach net-zero. This means that high “Subsidies” can act as “smoothing” transition factors from the status quo to the “EU harmonisation” regime. Then, the phase out of “Subsidies” after 2035 should be gradual, maintaining at least a low level of “Subsidies” for 2035-2040 before they are completely phased out. Any consideration for a decrease in “Subsidies” before

2035 should be followed by an even higher stringency of “EU harmonisation” and “Obligations” from 2025 and onwards, for the achievement of the 2050 net-zero target.

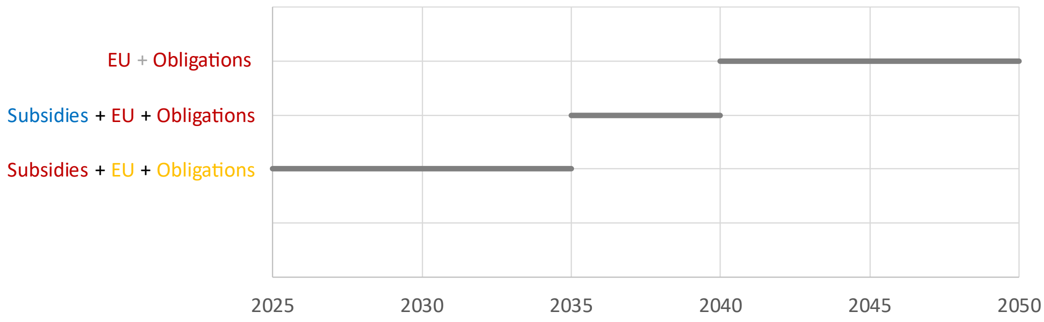

Figure 19: Dynamic Adaptive Policy Pathway 1 - Variation 1

The policy pathway in Figure 19 achieves the 2050 net-zero target in 75% of the assessed contextual scenarios (or in 15 out of the 20 scenarios shown in Appendix “8.6 Probability distributions and correlation matrix of the random variables representing key uncertainties surrounding the evolution of the Swiss energy system “. Figure 20 shows a steep decline in emissions until 2040, implying that “EU harmonisation” policies and “Obligations”, combined with ”Subsidies”, can accelerate the net-zero transition. All sectors contribute to decarbonisation until 2035. At the forefront of the transition is the domestic transport sector, which, driven by vehicle standards, has the potential to reach net-zero emissions[16] by the 2040s. During the same period, this combination of policies also has the potential to reach net zero in the residential and services sectors.

However, from 2040 and onwards, the decline in emissions decelerates, attributable to the nuclear phase-out that is associated with increased electricity costs and the introduction of gas backup generation until renewable energy scales up to fill the gap from the decommissioning of the existing nuclear reactors, as well as the need to abate emissions in sectors with limited decarbonisation options such as industry and long-distance road transport.

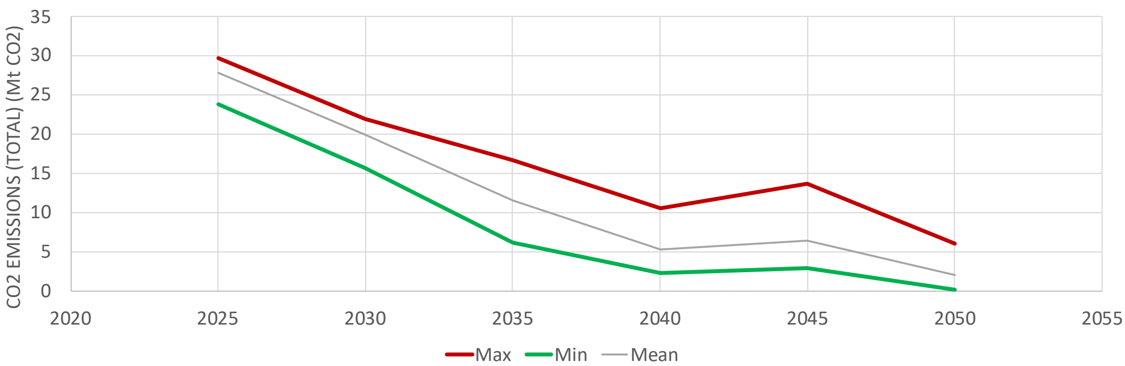

Figure 20: Total CO_2 emissions of the Policy Pathway 1- Variation 1 from the policy exploration with AIM

[16] The phrase that a sector “has the potential to reach net-zero emissions” is stated in this manner as the context affects the performance of each policy package.

Table 8: Context values affecting the performance of Pathway 1 - Variation 1 according to AIM policy exploration

Contextual factor	Simulated range in 2050	Range for pathway success in 2050
Solar PV potential (TWh)	30 -88	30 – 76.1
Biomass potential (PJ)	101.0 -113	101.6 -113
Gasoline import price (EUR10/GJ)	3.5 – 26.3	8.8 – 26.3
Natural gas price (EUR10/GJ)	1.4 – 11.7	2.9 – 11.7

It was mentioned above that this pathway achieves the 2050 net-zero emissions target with 75% probability. This implies that 75% of the contextual scenarios, i.e., the scenarios accounting for the main evolving uncertainties surrounding the future energy system configuration in Switzerland, achieve the target, given the specific timing and sequence of policy implementation. However, if the context evolves differently, there is a 25% chance that the Policy Pathway 1 will miss the net-zero target. Table 8 shows the values of important context variables, as identified by the AIM clustering algorithm, that lead to the achievement of the net-zero target in 2050. Important context variables are those for which AIM identified at least one value in the simulated scenario range, leading the policy pathway to miss the net-zero target. This implies that: (i) other context variables still affect the performance of the policy pathway but don't lead it to failure, and (ii) it can be that some value of these contexts plays a critical role in the achievement of the 2050 net-zero target, because it appears in combination with another context that AIM cannot report with clustering rules. To this end, further exploration was performed in all variations of the assessed pathways to identify why AIM reported the different contextual factors shown in the respective tables as critical ones.

The bounds shown in the second column of Table 8 are the lowest and highest values sampled from the contextual factors' probability distributions, which lead the pathway to success. At this point, it should be noted that we mandated all context values to change simultaneously during the context sampling via Latin Hypercube, as we sampled the joint distribution of the random variables. Moreover, the sample size plays an important role in the reported critical contexts from the clustering algorithm. For this reason, in those scenarios where the net-zero target was not met, the sampled context resulted in a solar PV potential above 76.1 TWh and a wind potential also close to its highest simulated value (i.e., 26 - 30 TWh), but at the same scenarios, biofuel or e-fuel imports had their lowest sampled value, which was 5 PJ and 0 PJ, respectively. This leads us to conclude that despite the efforts to expand renewable energy sources, the net-zero target cannot be achieved without the contribution of imported biofuels and e-fuels. This is highly correlated to the domestic biomass potential, which appears as an important context to be monitored for the success of the policy pathway.

In the scenario where, based on the sampling of the joint probability distributions of the random variables, the biomass potential takes a value below 101.6 PJ, the imported biofuels take their lowest simulated value, equal to 5 PJ. So, for the success of this pathway, the biofuel potential (imported and domestically produced) needs to be above about 107 PJ in 2050. At the same time, gasoline import prices should not drop more than 8.7% compared to 2020 (i.e., not to be less than 8.8 EUR/GJ or roughly 0.30 EUR/lt), and natural gas import prices should not drop more than 56.4% (i.e., not to be less than 2.9 EUR/GJ or roughly 10.4 EUR/MWh) compared to 2020. Of course, any increase in fossil fuel prices cannot negatively affect the performance of this policy pathway. Such an increase could be controlled via further increased taxes on fossil fuels. Between the two, the price of gasoline is a more important variable to monitor than the price of natural gas, indicating that the transport sector needs stronger price signals than the residential sector to achieve its decarbonisation. In this regard, a potential reduction in the price of natural gas from its 2020 levels could still lead to the 2050 decarbonisation target.

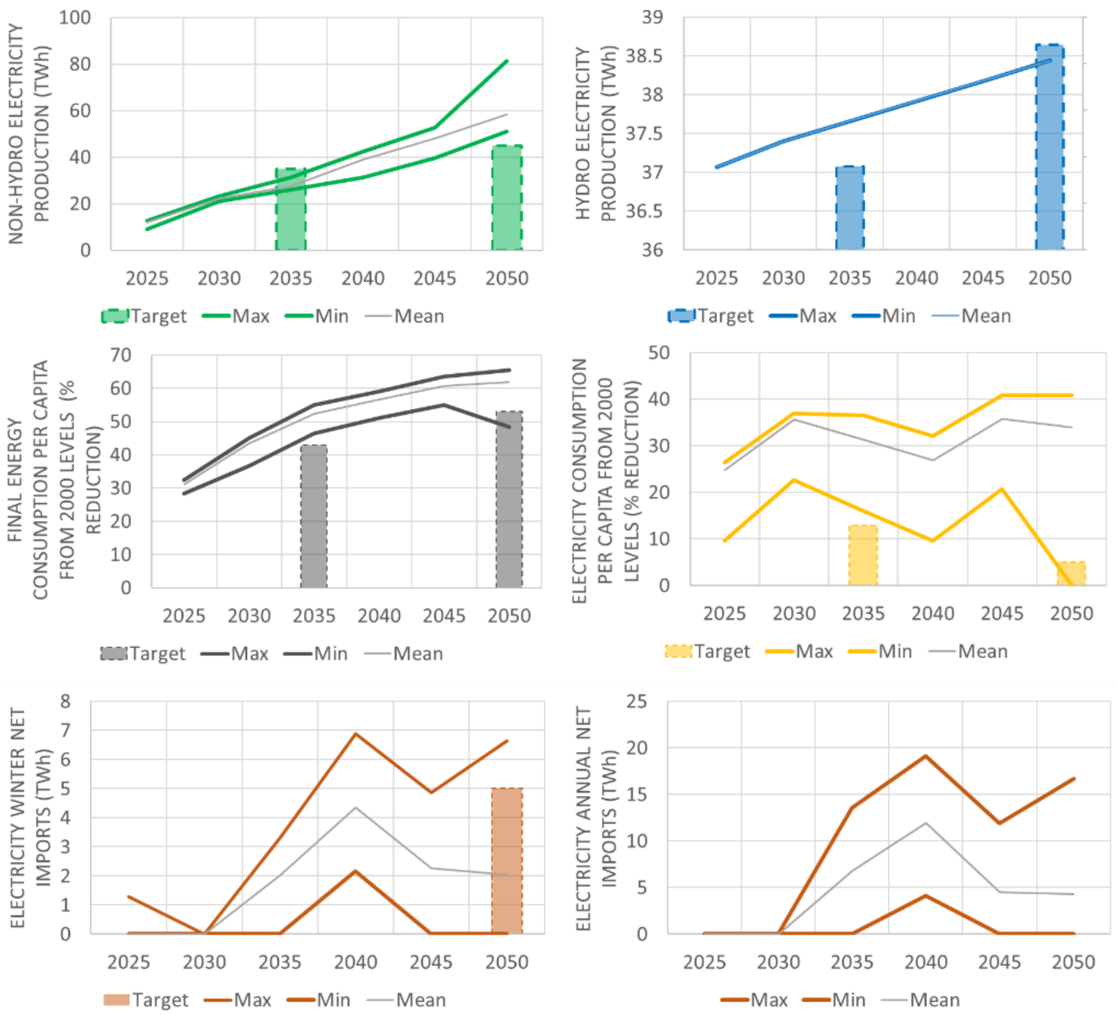

Figure 21: Performance of Policy Pathway 1- Variation 1 concerning targets other than CO_2 emissions, as derived from the policy exploration with AIM

With respect to the other Swiss energy and climate policy targets (Table 1), as shown in Figure 21, the average result of the Policy Pathway 1 - Variation 1 (i.e., mean of the result under the effect of all context values - indicated with the thin grey lines) shows that the pathway is robust in achieving most of these targets. The only exception is the 2035 non-hydro renewable electricity production, which is missed in all scenarios and may be attributed to the delay in the renewable capacity expansion. This exception highlights the need for streamlined licensing procedures for RES, which is also a suggestion raised by the stakeholders during the stakeholder workshops to be able to accelerate RES deployment. Finally, the cases where the minimum/maximum (depending on the target) simulated output fails to achieve the respective target correspond to the 25% context scenarios analysed above, for which the net-zero target is missed.

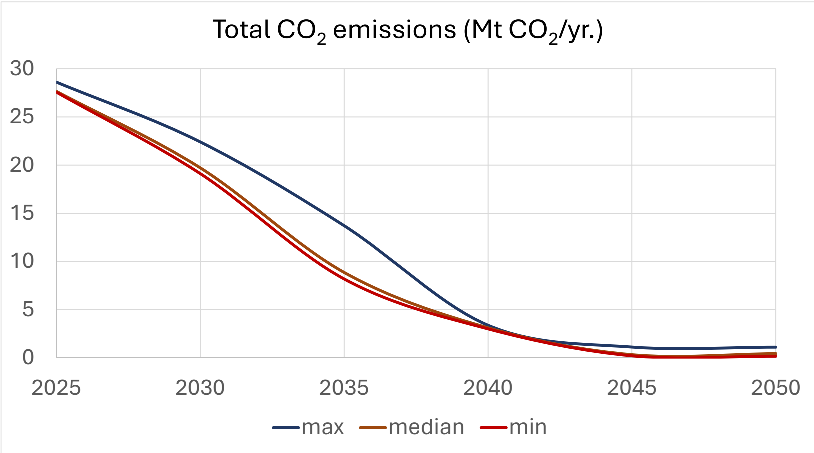

Figure 22: CO_2 emissions by implementing the Pathway 1 – variation 1 in the JRC-EU-TIMES model

In implementing the policy pathway in JRC-EU-TIMES, the CO_2 emissions trajectory of Figure 22 is obtained. Implementing the policy pathway with perfect foresight eliminates the kink in the 2045 emissions, providing stronger long-term signals to investors. At the same time, policy interactions across sectors result in a steeper acceleration of emissions until 2040. Any deceleration of emissions in the post-2040 period occurs because industry also reaches net zero. This is driven by the strengthening of the “EU harmonisation” (especially the EU-ETS) and the “Obligations” policies in the sector. Hence, to fulfil these requirements in a cost-optimal way, the industry will need to replace ageing equipment with equipment compatible with the emissions requirements to avoid creating stranded assets. These assets occur when decisions are made with limited foresight.

Variation 2 – Continuation of subsidies until 2050

In its 2nd variation, Pathway 1 still applies high ”Subsidies” from 2025 until 2035, and the “EU harmonisation” and “Obligations” policy packages are applied at medium intensity. From 2035, ”Subsidies” are reduced to their lowest values, while the intensity of the “EU harmonisation” and “Obligations” is increased to its highest level. This setup continues until 2050, which constitutes the main difference to variation 1; “Subsidies” are not phased-out in 2040, but their application continues at a low intensity until 2050. This pathway is generated following the same policy exploration observations that were presented in the previous variation and is graphically illustrated in Figure 23.

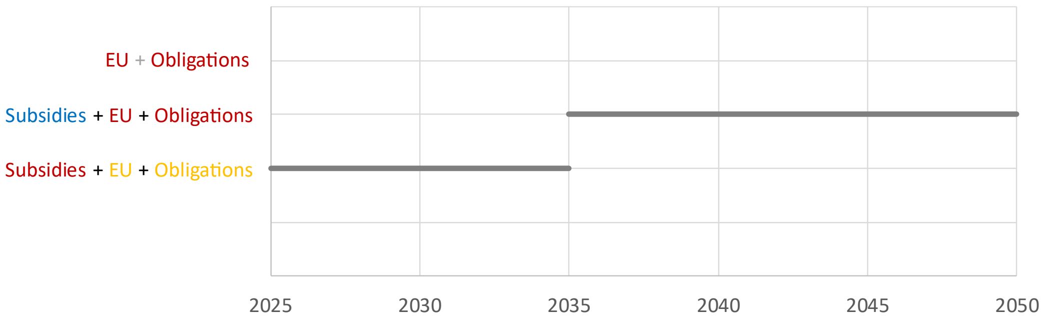

Figure 23: Dynamic Adaptive Policy Pathway 1 - Variation 2

This pathway still achieves the 2050 net-zero target in 75% of the assessed contextual scenarios, with only small differences to Variation 1 after 2040, as shown in the results from AIM in Figure 24. The transport, residential, and services sector developments are similar to those described in Variation 1 of this pathway.

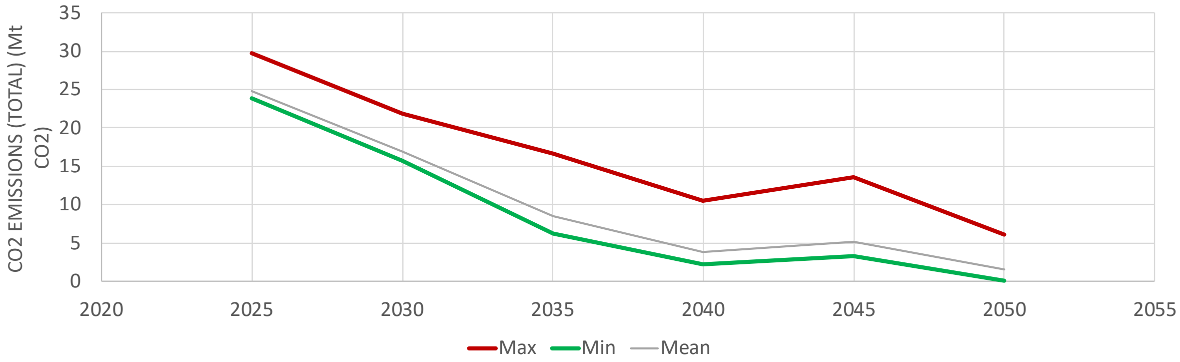

Figure 24: Total CO_2 emissions of Pathway 1- Variation 2 from the policy exploration with AIM

However, there is a slightly lower rebound effect of the nuclear phase-out in 2045 and a better response from the industry sector, which can be attributed to the prolonged subsidies for clean energy generation technologies and clean technologies in industrial process heating and efficient equipment. Especially for the latter, prolonged “Subsidies” give the industry more time to respond to the incentives provided by the government, given the low stock turnover in the sector because of the long-lived assets. The main difference compared to variation 1 is that with prolonged “Subsidies”, the average CO_2 emissions (thin grey line in Figure 24) are closer to the minimum emissions achieved by the pathway (thick green line), which means there is a higher probability of achieving closer-to-zero emissions if subsidies are kept until 2050. In a nutshell, the provision of “Subsidies” beyond 2040 is subsidiary to “EU harmonisation” and “Obligations”. While “Subsidies” are not a “game changer” towards achieving a close-to-net-zero target, their prolongation still facilitates the transition for those sectors facing high upfront costs in investing in clean technologies or having long-lived assets that imply low capital stock turnover.

In terms of contexts, the same variables remain important in the affecting context, as described in Variation 1. This means that applying “Subsidies” beyond 2040 does not enhance the robustness of the pathway, which could have been the case if some of the critical contexts in Variation 1 had not occurred in Variation 2. Table 9 shows the context values affecting the performance of Pathway 1 - Variation 2.

Table 9: Context values affecting the performance of Pathway 1 - Variation 2 according to AIM policy exploration

Contextual factor	**Simulated range in 2050**	**Range for pathway success in 2050**
Solar PV potential (TWh)	30 -88	30 – 76.1
Biomass potential (PJ)	101.0 -113	101.6 -113
Gasoline import price (EUR10/GJ)	3.5 – 26.3	8.8 – 26.3
Natural gas import price (EUR10/GJ)	1.4 – 11.7	2.9 – 11.7

Regarding the other Swiss targets, the same observations as in the case of Variation 1 apply (Figure 25). The only difference with the continuation of “Subsidies” until 2050 is the higher probability of achieving the target for imported electricity in winter, as even the maximum electricity imports achieved by this pathway are very close to the target limit. This is because these “Subsidies” also target technologies that can directly provide electricity in winter (such as wind or geothermal), which are needed most by 2050, and technologies that can be indirectly used for this purpose such as those related to hydrogen or e-fuels production that can be used in fuel cells or thermal power plants in winter. Prolonged “Subsidies” can accelerate technology maturity and uptake.

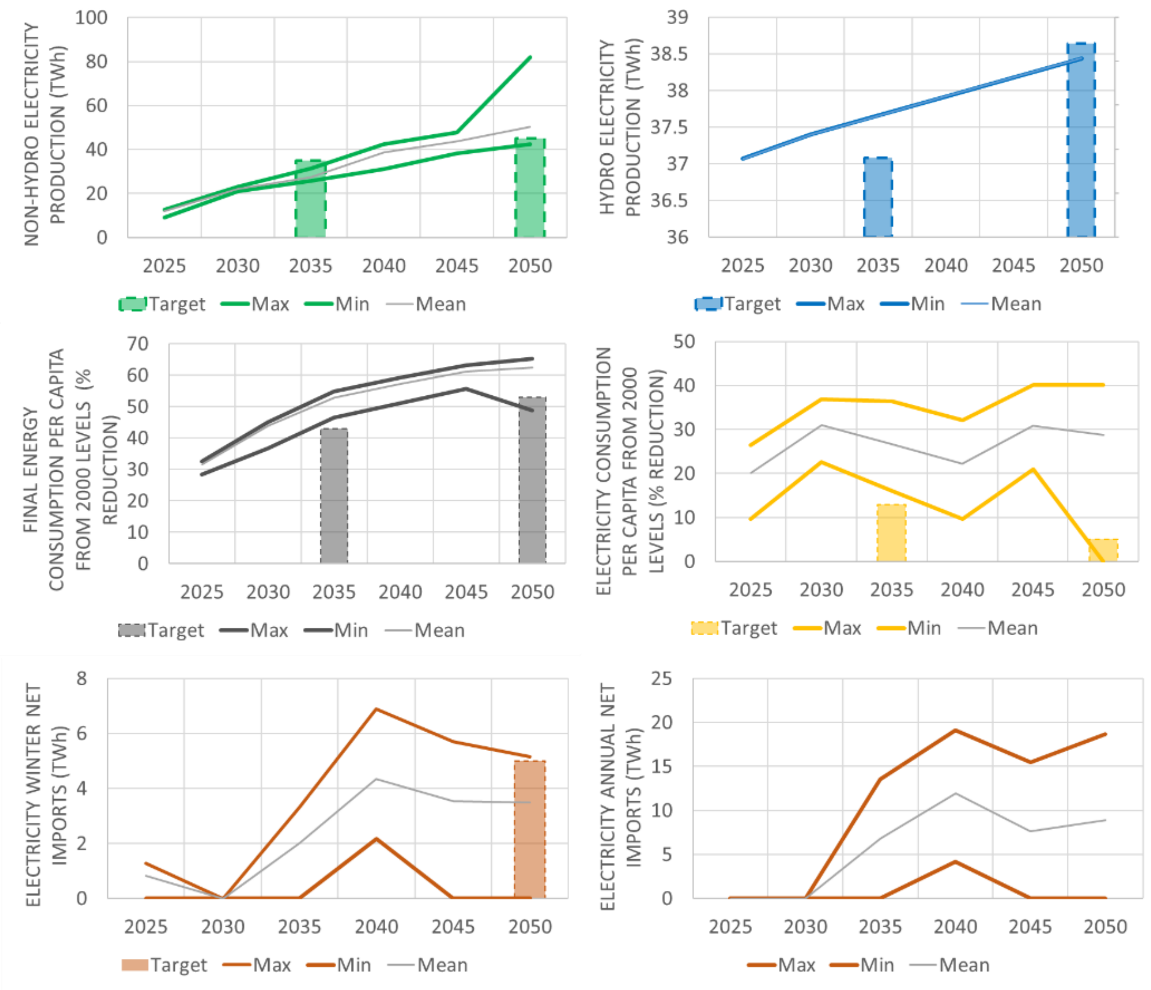

Figure 25: Performance of Policy Pathway 1- Variation 2 with respect to targets other than CO_2 emissions, as derived from the policy exploration with AIM

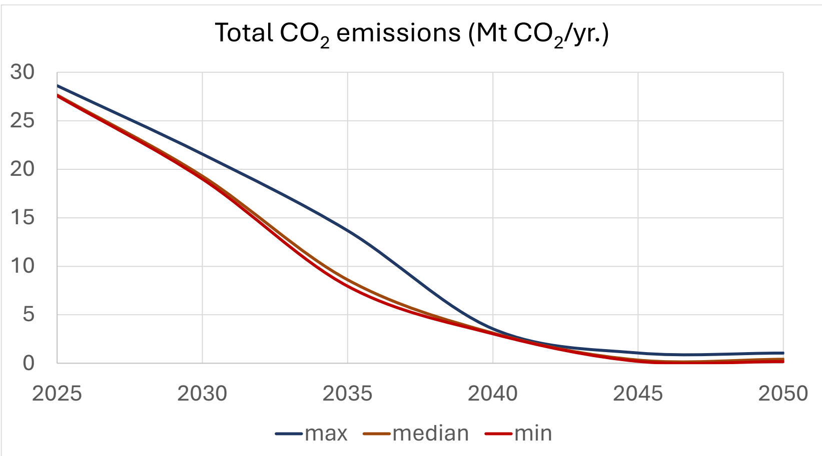

Figure 26: CO_2 emissions by implementing the Pathway 1 – Variation 2 in the JRC-EU-TIMES model

In implementing Variation 2 in JRC-EU-TIMES, the resulting CO_2 emissions trajectory is shown in Figure 26. The trajectory is very similar to the one obtained for Variation 1, except that in 2030 – 2040, the emissions abatement rate is higher in Variation 2. Also, in line with the findings from AIM, the deceleration of the abatement rate in the post-2040 period is lower in Variation 2 than in Variation 1. Again, the perfect foresight of the JRC-EU-TIMES model and the cost-optimisation of the energy system configurations try to avoid generating stranded assets in the electricity and industry sectors. In this regard, the kink in the 2045 emissions shown in Figure 24 does not occur when the pathway is implemented in the JRC-EU-TIMES model.

Variation 3 – Constant policy implementation

The 3rd variation of this pathway is to keep the intensity of policies constant throughout 2025-2050. The pathway analysis revealed that such a strategy can lead to net-zero emissions until 2050 in 95% of the contextual scenarios, with any intensity of "Subsidies" or even without "Subsidies". This implies that if "EU harmonisation" and "Obligations" are implemented with high intensity from the beginning, "Subsidies" are not necessary for the success of the pathway per se.

Nevertheless, for this to happen, the "EU harmonisation" and "Obligations" policy packages should be implemented at their highest intensity as soon as possible. In fact, this is the case discussed in the previous two variations, where if any "Subsidies" with intensity lower than their highest values (Table 3) were to be chosen for the period 2025-2035, then the ambition for "EU harmonisation" and application of "Obligations" in the same period should be high (Tables 5 and 6), and continue at this high intensity until 2050. Any decreased ambition in these two policy packages does not lead to net-zero emission by 2050. The "EU harmonisation" includes policies such as the EU-ETS, EU-ETS2, and vehicle emissions standards, which target a part of the industry, the energy transformation sectors, and the buildings and transport sectors.

Hence, "Obligations" with bans and mandates for the sectors not covered by the EU-ETS and EU-ETS2 complement the "EU harmonisation" policy package, and combined, the two packages can achieve net-zero emissions when they are at their highest intensity. In this case, "Subsidies" play a role in mitigating the financial burden of the upfront investments required to comply with the emissions reduction targets, or technology bans and other mandates implied by the two other packages. Figure 27 visualises all possible options of the 3rd Variation of Pathway 1, i.e., "EU harmonisation" and "Obligations" alone, as well as "EU harmonisation" and "Obligations" with low, medium and high "Subsidies".

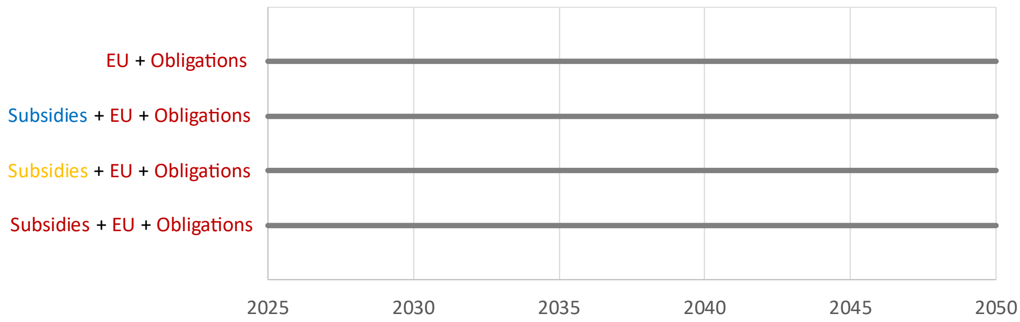

Figure 27: Dynamic Adaptive Policy Pathway 1 - Variation 3

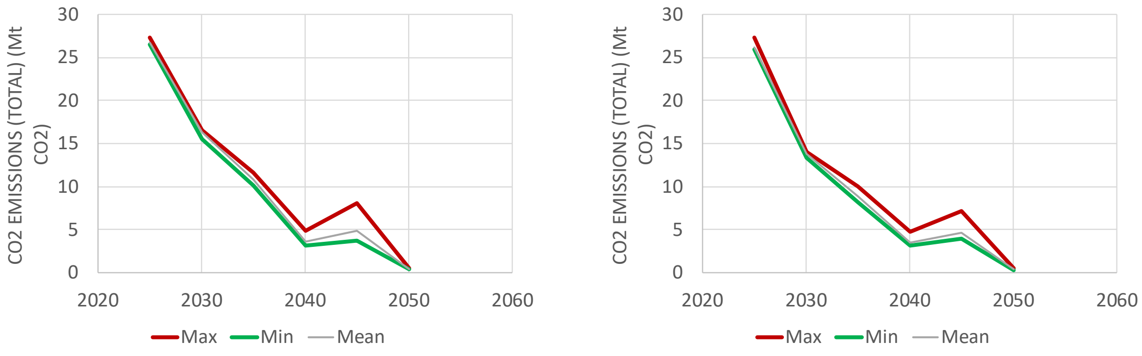

Figure 28. Total CO_2 emissions of Pathway 1- Variation 3 from the policy exploration with AIM. Left**:** Without subsidies. Right**:** With "High Intensity" subsidies.

Figure 28 presents the evolution of total emissions in the two cases with high “Subsidies and without ”Subsidies”. The results suggest that “Subsidies” play a complementary role in the emissions abatement effort until 2040, but from 2040 onwards, the difference in the emissions trajectories between the two cases is small. The residential and services sectors are most responsive to “Subsidies”, while the transport sector is not sensitive to them. This is because the vehicle emissions standards requiring zero-emissions new vehicles drive the transformation of the road transport sector - however, it should be noted that the formation of the policy package “Subsidies”, in line with the Swiss policy developments, does not include direct subsidies to clean vehicles but only to alternative fuel infrastructure. In contrast, it does include direct subsidies to clean heating technologies. The same applies to the electricity and industry sectors, which are targeted by the EU-ETS and need to undergo a significant transformation to comply with the elimination of emissions allowances foreseen by the high intensity of the future EU-ETS. After 2040, the residential and services sectors have reached net-zero emissions and cannot further contribute to emissions reductions. Therefore, and given the lower response to subsidies for the rest of the sectors, the overall emissions reduction between 2040 and 2050 remains the same, either with or without subsidies.

The policy exploration with AIM reveals two key policy outcomes for this pathway. Firstly, “Obligations” are catalytic policy instruments for achieving net-zero emissions by 2050, and their absence can lead to policy failure despite the intensity of the other policy packages. Secondly, this variation of the pathway confirms that “Subsidies” have a complementary role in “Obligations” and “EU harmonisation” policy packages in the post-2035 period, but are crucial for the decade 2025 – 2035 as they can accelerate the transition. In this regard, “Subsidies” are “front-loading” the decarbonisation effort of the residential and services sector.

Analysing the contexts affecting the emissions trajectories of this policy pathway revealed only the solar PV potential as a critical one (Table 10), which is correlated to the sampling procedure (as discussed in Variation 1) and the absence of imported biofuels and e-fuels in the scenarios featuring very high solar potential. Nevertheless, the tolerance to the absence of imported biofuels and e-fuels is better, justifying the higher success rate of this pathway (i.e., 95%) “Obligations” in this policy pathway are set to their highest intensity from the beginning, which implies rapid emissions reductions and defossilisation of the demand. If solar PV scales up in this policy pathway, biomass potential does not appear as a critical context without implying that it is unimportant. Furthermore, as the use of fossil fuels is reduced significantly due to the high intensity of “EU harmonisation” and “Obligations” in this pathway, their price is no longer a critical context. Nevertheless, despite the lower number of critical contexts affecting such a variation of Pathway 1, where constant and immediate high ambition for “EU harmonisation” and “Obligations” takes place, it should be noted that they could constitute abrupt changes to the Swiss status quo (due to the implementation of “EU harmonisation” and “Obligations” at their highest intensity), which might not be desirable from a policymaking perspective.

Table 10: Context values affecting the performance of Pathway 1 - Variation 3 according to AIM policy exploration

Contextual factor	Simulated range in 2050	Range for pathway success in 2050
Solar PV potential (TWh)	30 -88	30 – 83.9

Regarding the other Swiss targets, (Figure 37) the picture remains more or less the same as in the previous variations. The only difference is that the application of “EU Harmonisation” and “Obligations” at high intensity from the beginning has the potential to make Switzerland a net exporter of energy as early as of 2030 and until 2050. This can be justified by the high pressure applied by the ambitious ETS2, and the high subsidies for alternative fuel backbone infrastructure pipelines, which push new generation technologies into the Swiss energy system.

Figure 29: Performance of Policy Pathway 1- Variation 3 (without subsidies) with respect to targets other than CO_2 emissions, as derived from the policy exploration with AIM

Implementing the 3d Variation of Pathway 1 in JRC-EU-TIMES resulted in the emissions trajectory shown in Figure 30, for the case when high “Subsidies” are applied. In this case, the role of “Subsidies” in accelerating decarbonisation is more prominent than in the results from AIM, as “Subsidies” enable industry to faster replace ageing fossil-based equipment with more environmentally friendly equipment; a result attributable to the perfect foresight of the model that tries to avoid creating many stranded assets in the future by taking replacement decisions that would result in lock-in to carbon intensive options. Interestingly, in this Variation of Pathway 1, the JRC-EU-TIMES might fail the net-zero target by a small amount of remaining emissions in the transport sector if the context develops differently. This insight was not present in the analysis of AIM, and it is justified by the cross-sectoral policy interactions triggered by the implementation of mandates, bans and obligations.

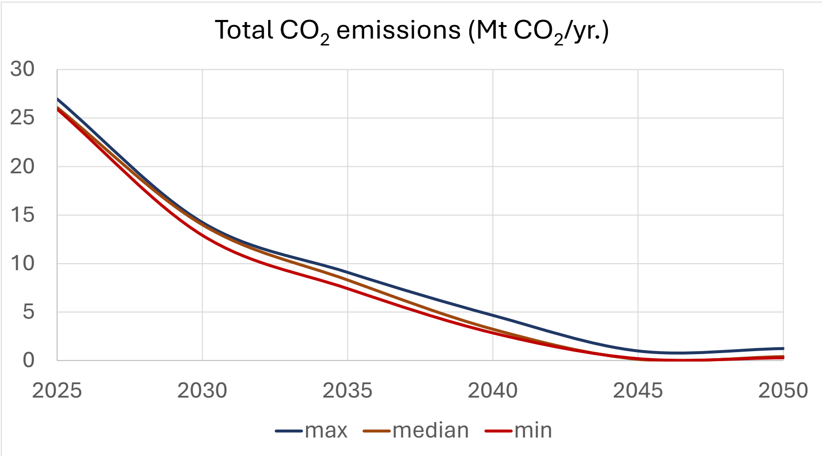

Figure 30: CO_2 emissions by implementing the Pathway 1 – Variation 3 in the JRC-EU-TIMES model

3.3.2. Pathway 2 – Subsidies, Levies and Obligations

This pathway examines the combined role of “Subsidies”, “Levies”, and the implementation of “Obligations” (mandates, bans) in achieving net-zero CO_2 emissions in the Swiss energy system. With AIM, two variations of this pathway are identified that can achieve the target with a high probability, which are discussed below.

Variation 1 – Gradual decline of subsidies

At its 1st Variation, Pathway 2 applies high “Subsidies” from 2025 until 2030, while “Levies” and “Obligations” are at their medium intensity. From 2030 until 2040, ”Subsidies” are reduced to medium intensity, while “Levies” and “Obligations” intensity is increased to its highest level. After 2040, “Subsidies” are reduced to lower intensity, leaving only the application of “Levies” and “Obligations” to continue at their highest intensity. Figure 31 visualises the 1st Variation of Pathway 2. This pathway is generated respecting the following observations coming out of the policy exploration. If “Levies” combined with “Obligations” were to be chosen, they should be implemented at least at their medium intensity, starting as soon as possible, and with high subsidies to support them. Then, the ambition of “Levies” and “Obligations” should be further increased after 2030, even if high ”Subsidies” remain.

Any ambition lower than the high-intensity definition of “Levies” and “Obligations” beyond 2030 (even for just a few years) misses the 2050 net-zero target. Once the ambition of “Levies” and “Obligations” has been increased to their highest intensity after 2030, “Subsidies” can be either reduced in a stepwise manner, as shown in Figure 31, or they can be reduced to their lowest intensity right after 2030, without altering the success percentage of the pathway. Nevertheless, any reduced ambition in ”Subsidies” (i.e., medium or low intensity) before 2030, should be followed by high intensity implementation of “Levies” and “Obligations” as soon as possible (which is the case presented in Variation 2 of this pathway), to ensure the achievement of the 2050 net-zero target.

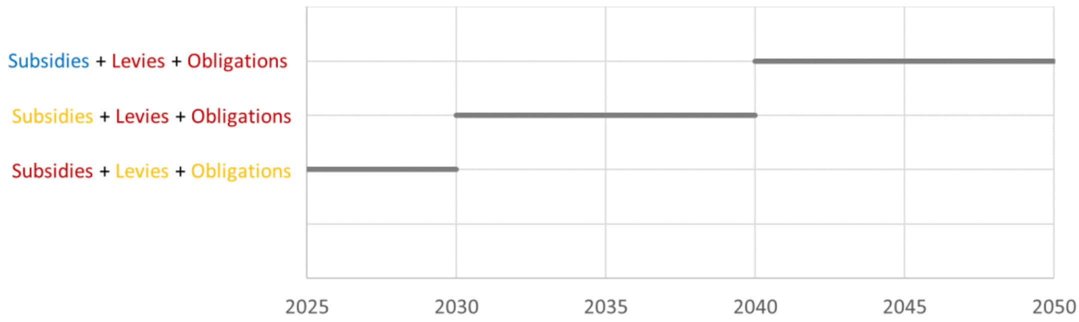

Figure 31: Dynamic Adaptive Policy Pathway 2 - Variation 1

This variation of Pathway 2 achieves the 2050 net-zero target in 80% of the assessed contextual scenarios (or in 16 out of the 20 contextual scenarios). Still, the overall trajectory of emissions is similar to Pathway 1 (Figure 31). However, the sectors of the energy system respond differently individually than in Pathway 1.

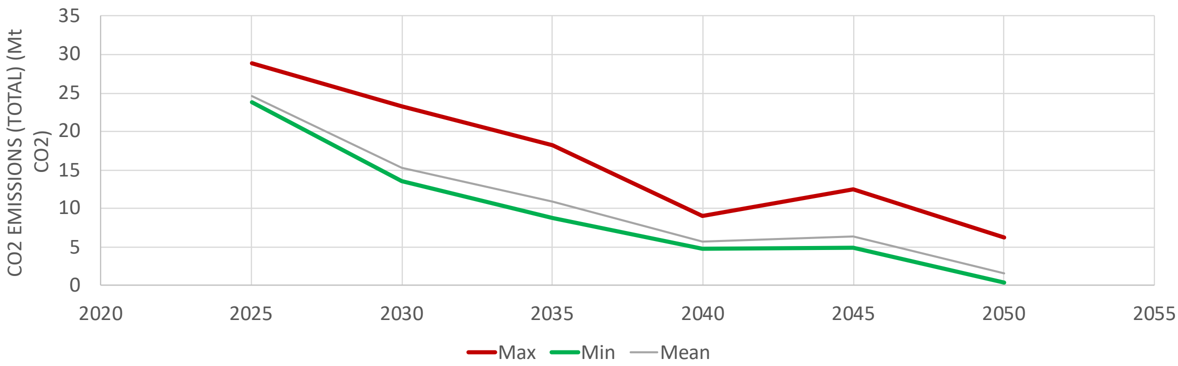

Figure 32: Total CO_2 emissions of Pathway 2- Variation 1 from the policy exploration with AIM

More specifically, the industrial sector follows a similar trajectory to Pathway 1 until 2035, followed by a steep reduction in emissions in the post-2040 period. Looking at the sectoral developments implied by the emissions trajectories shown in Figure 32, the uncertainty in the emissions reductions (which is the range between the max and min emissions trajectories) in industry is lower in Pathway 2 – Variation 1 than in Pathway 1. A similar behaviour is observed in the residential and services sector. This implies that the industrial, residential, and services sectors may be more responsive to "Levies" applied to fossil combustible fuels rather than a strengthened ETS applied to industry and buildings, which is included as a policy in the "EU harmonisation" policy package. On the contrary, the transport sector seems to perform poorly over the years, leading to higher uncertainty regarding achieving the net-zero target in 2050. This is because the levies applied to the transport sector include taxes on fuels and emissions (through registration and circulation taxes). On the other hand, stricter emission standards and policies for banning internal combustion engine vehicles "push" the transport sector towards decarbonisation. Finally, the electricity generation sector presents a similar overall picture with "EU harmonisation" (Pathway 1) or "Levies" (Pathway 2).

In terms of contexts affecting the performance of Pathway 2 - Variation 1 (Table 11), in Pathway 2 we see another important context variable, which is a product of the scenario sampling, during which the contexts change simultaneously. The clustering of AIM highlighted that failure towards net zero may occur, even if the biomass use is at 111.5 PJ. In those scenarios, the e-fuel imports have their lowest modelled value. Therefore, this suggests that despite having high domestic renewable energy potential, the net-zero target cannot be achieved if imported e-fuels don't contribute – and this is a limitation imposed by the need for domestic C-atoms that can be used for producing e-fuels inside Switzerland. Also, gasoline prices appear to be an influencing factor in this pathway. Still, in this case, the tolerance towards reduced gasoline prices compared to the monitored 2020 price is nearly zero to compensate for the lower performance of 'Levies' in decarbonising the domestic transport sector compared to the "EU harmonisation" policy package. This means that if "Levies" are chosen instead of the "EU harmonisation" policy package, they should be followed by policies ensuring high gasoline prices as an incentive for vehicle fleet substitution with more environmentally friendly ones.

Table 11. Context values affecting the performance of Pathway 2 - Variation 1 according to AIM policy exploration

Contextual factor	**Simulated range in 2050**	**Range for pathway success in 2050**
Solar PV potential (TWh)	30 -88	30 – 76.1
Biomass potential (PJ)	101.0 -113	101.0 -111.5
Gasoline price (EUR10/GJ)	3.5 – 26.3	9.6 – 26.3

Regarding the other Swiss targets, compared to Pathway 1 (which applies "EU Harmonisation"), this pathway (which applied "Levies" from the beginning) leads to a high probability of zero imports of electricity by 2050 – please see Figure 33.

This means that a gradually intensified CO_2 tax (included in the "Levies" policy package) may have a more positive effect than a gradually intensified EU-ETS (included in the "EU harmonisation" policy package) with respect to the target of electricity imports, even if they are applied gradually. For the rest of the targets, the observations of Variations 1 and 2 apply in this case, too.

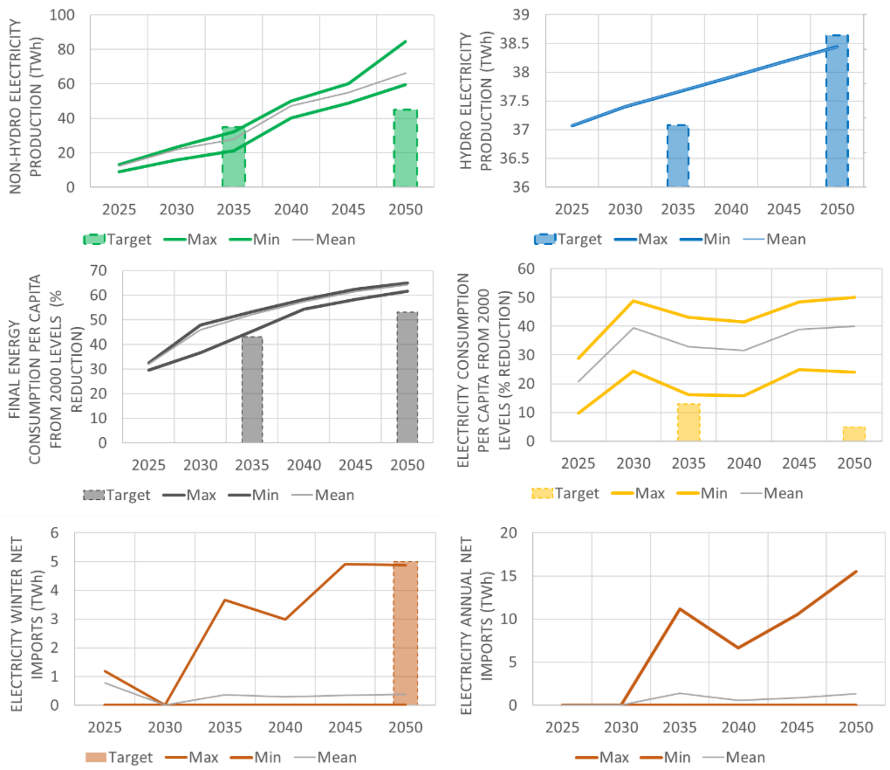

Figure 33: Performance of Policy Pathway 2- Variation 1 with respect to targets other than CO_2 emissions, as derived from the policy exploration with AIM

The implementation of this policy pathway into the JRC-EU-TIMES model resulted in the CO_2 emissions trajectory shown in Figure 34. Although the model's perfect foresight and cost-optimisation for finding the future energy system configuration mitigate the kinks in the emissions, the trajectory is very similar to the one obtained by AIM. In this regard, the same policy-related conclusions derived from the AIM analysis are also valid for the analysis with the JRC-EU-TIMES model.

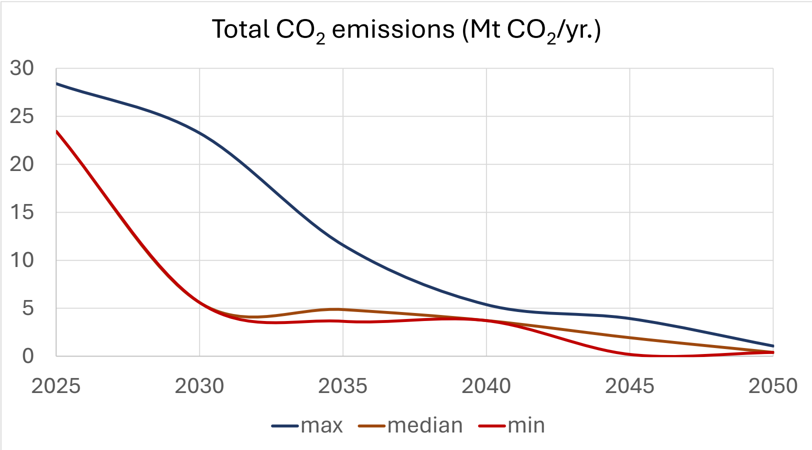

Figure 34: CO_2 emissions by implementing the Pathway 2 – Variation 1 in the JRC-EU-TIMES model

Variation 2 – Constant policy implementation

The 2nd variation of this pathway is to keep the intensity of policies constant throughout 2025-2050. The pathway analysis revealed that such a strategy can lead to net-zero emissions until 2050, with any intensity of “Subsidies”, but given that “Levies” and “Obligations” are implemented at their highest intensity from the beginning. Still, despite the high ambition for the implementation of “Levies” and “Obligations” as soon as possible, the success percentage of the pathway remains 80%. Figure 35 visualises all possible options of the 2nd variation of Pathway 2. The figure shows Variation 2 with all possible combinations of the intensity for “Subsidies” and the high intensities for “Levies” and “Obligations”. A variation with “Levies” and “Obligations” but without “Subsidies” was not simulated by the JRC-EU-TIMES, since a policy pathway without financial incentives is unlikely to be a realistic option.

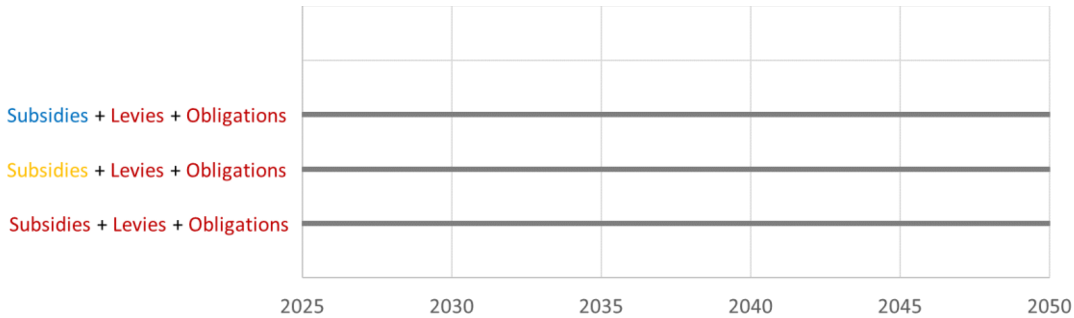

Figure 35. Dynamic Adaptive Policy Pathway 2 - Variation 2

Figure 36 presents the evolution of total emissions in the two cases of this variation, namely with low intensity for “Subsidies” (left) and with high intensity for “Subsidies” (right). It is found that the intensity of the policy package “Subsidies” is not a game changer for the success of the pathway. The only contribution of “Subsidies” in a scenario where “Levies” and “Obligations” are implemented at their highest intensity from the beginning could be in the speed of decarbonisation of the residential and services sectors, just like in the case of Pathway 1. Nevertheless, the contribution would still be negligible, justifying the barely visible difference between the two cases of Figure 36. The same variables remain important in the affecting context as described in Variation 1 - please see Table 11.

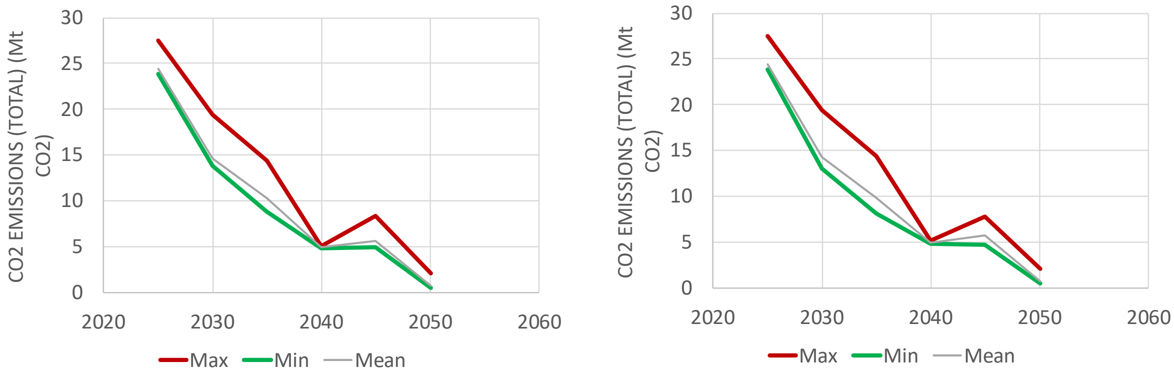

Figure 36. Total CO_2 emissions of Pathway 1- Variation 2 from the policy exploration with AIM. Left**:** With"Low Intensity" subsidies. Right: With "High Intensity" subsidies

Table 12. Context values affecting the performance of Pathway 2 - Variation 2 according to AIM policy exploration

Contextual factor	**Simulated range in 2050**	**Range for pathway success in 2050**
Solar PV potential (TWh)	30 -88	30 – 76.1
Biomass potential (PJ)	101.0 -113	101.0 -111.5
Gasoline price (EUR10/GJ)	3.5 – 26.3	9.6 – 26.3

Regarding the other Swiss targets (Figure 37), similarly to the case of applying "EU harmonisation" at high intensity from the beginning (i.e., Pathway 1 – Variation 3), the application of "Levies" and "Obligations" at high intensity from the beginning also has the potential to make Switzerland a net exporter of energy as early as of 2030 and until 2050.

Finally, Figure 38 presents the CO_2 emissions trajectory when the 2^{nd} Variation of this Pathway is implemented in the JRC-EU-TIMES model for the case when high "Subsidies" are applied. In contrast to the trajectory shown in Figure 36, the emissions control rate, in this case, does not significantly decelerate in the post-2040 period compared to the case when "Subsidies" are removed or applied to at a reduced intensity. This enforces the conclusion that "Subsidies" can help accelerate the decarbonisation effort.

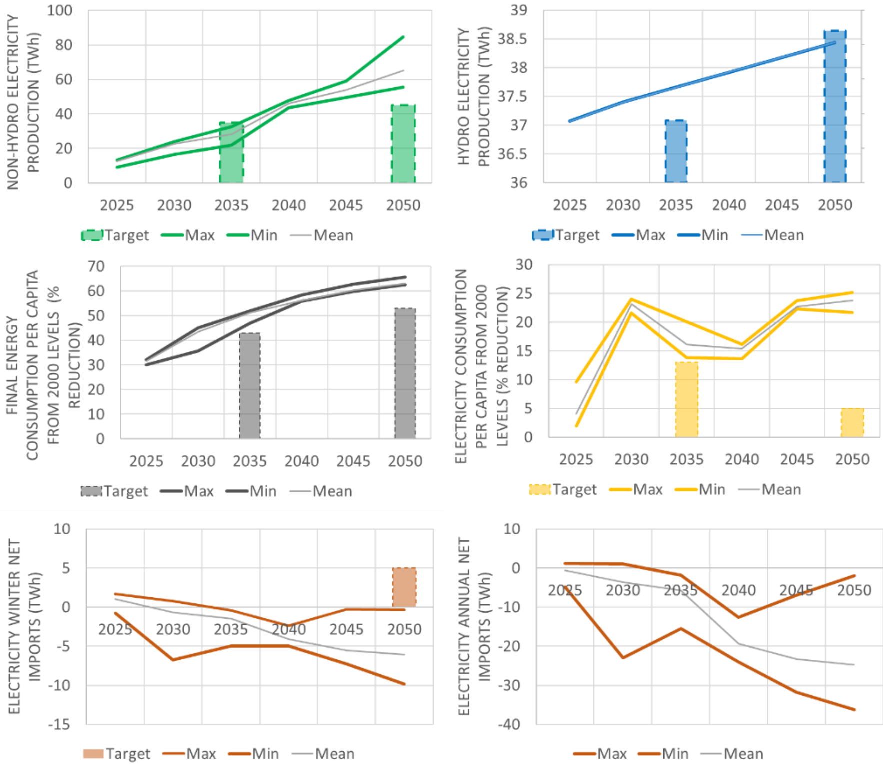

Figure 37: Performance of Policy Pathway 2- Variation 2 (without "Subsidies") with respect to targets other than CO_2 emissions, as derived from the policy exploration with AIM

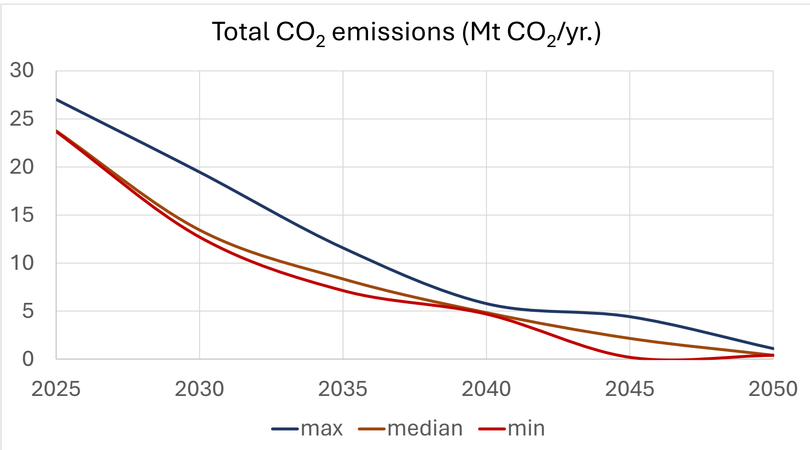

Figure 38: CO_2 emissions by implementing the Pathway 2 – Variation 2 in the JRC-EU-TIMES model

3.3.3. Observations on the timing of policies and the factors affecting the pathways' success

The timing of policy implementation is crucial in achieving the 2050 net-zero target. The analysis confirms that policies such as **"EU harmonisation", "Levies", and "Obligations" should be implemented as soon as possible and at least with medium ambition (intensity)**. Lower ambition, even briefly until 2030, eliminates possible pathways to net-zero until 2050, signifying that immediate and ambitious action is needed. **“Obligations” should always accompany “Levies” or “EU harmonisation”**, to force the response change in the various sectors.

Whether Switzerland chooses the “EU harmonisation” pathway or not, further policy timing considerations must be taken into account.

If “**EU harmonisation” combined with “Obligations”** is to be chosen, two main approaches lead to achieving the 2050 decarbonisation target:

- Medium-intensity implementation of the “EU harmonisation” and “Obligations” starting immediately, accompanied by high ”Subsidies” until 2035. After 2035, “Subsidies” can be gradually phased out, maintaining at least low “Subsidies” until 2040. Any reduction in “Subsidies” before 2035 must be offset by even higher ambition in the “EU harmonisation” and “Obligations” policy packages from 2025 onward.
- High-intensity implementation of the “EU harmonisation” and “Obligations” from the outset, where ”Subsidies” become optional as complementary measures rather than key transition factors.

Similar observations apply if “**Levies” combined with “Obligations”** are chosen instead. They should be implemented at least at medium intensity from the outset, supported by high “Subsidies” until 2030. Beyond 2030, the ambition of “Levies” and “Obligations” should be increased to the maximum, even if “Subsidies” remain high after 2030. Any delay in the high-intensity implementation of “**Levies” combined with “Obligations”** beyond 2030 risks the achievement of the 2050 net-zero target. On the other hand, following the increase in ambition of “Levies” and “Obligations” after 2030, ”Subsidies” can either be gradually or immediately reduced to their lowest intensity without affecting the success rate of the pathway. **In both cases**, if a constant policy intensity from 2025 to 2050 were to be chosen, “EU Harmonisation” or “Levies”, combined with “Obligations”, should be implemented at their highest intensity immediately. That way, the high ambition of these policies in the starting period 2025-2030 can compensate for any reduced ambition in subsidies.

It becomes apparent that the timing and intensity of policy package implementation are thus crucial for the achievement of the 2050 net-zero target, and any deviation from the 5 presented pathways bears a high risk of failure. Nevertheless, even if the time- and intensity-wise implementation of the pathways presented in this report is followed, the achievement of the 2050 net-zero target is conditional on crucial contexts. Achieving the net-zero target requires the **contribution of imported biofuels and e-fuels, alongside domestic biomass and renewable energy production**. The biomass potential is a critical factor that must be monitored, as it directly influences the availability of imported biofuels. If biomass potential falls below **101.6 PJ**, imported biofuels should be higher than **5 PJ**, in order to maintain the combined potential of domestically produced and imported biofuels higher than about **107 PJ by 2050**. **An immediate high ambition in the implementation of the “EU harmonisation” combined with “Obligations”** could exhibit better tolerance to the absence of imported biofuels and e-fuels, because this strategy leads to rapid emissions reductions and defossilisation. Therefore, if solar and wind scale up quickly under such a policy choice, the biomass potential becomes less critical for the success of the pathway. Nevertheless, it is still worth monitoring. **The same tolerance increase, however, does not apply if high intensity “Levies” are applied in the place of high intensity “EU harmonisation”**.

Gasoline and natural gas prices should also be monitored as significant impact factors on the outcome of the presented policy pathways, as they particularly affect the response of the transport and building sectors. In fact, transport requires stronger price signals than the residential sector to drive decarbonisation. **If “EU harmonisation” is chosen**, the gasoline import prices should not drop more than 8.7% compared to 2020 (i.e., the gasoline import price should not be below 8.8 EUR/GJ or 0.30 EUR/lt), and natural gas prices should not drop more than 56.4% compared to 2020 (i.e., the gas import price should not be below 2.9 EUR/GJ or 10.4 EUR/MWh). However, if “EU harmonisation” is applied with high intensity as soon as possible, fossil fuel prices are no longer a critical context to monitor, as the relevant policies push the transport sector to decarbonisation more efficiently. But **if “Levies” are chosen instead of the “EU harmonisation”**, the tolerance towards reduced gasoline prices compared to the monitored 2020 price is nearly zero to compensate for the lower performance of “Levies” in decarbonising the domestic transport sector compared to the “EU harmonisation policy package”.

Therefore, choosing a pathway that features “EU harmonisation” instead of “Levies” may result in fewer restrictions from the context for the achievement of the 2050 net-zero target. In fact, **if “EU harmonisation” is implemented with high ambition as soon as possible, it can lead to more robust results towards the 2050 net-zero target, with minimum impact from the context**.

3.4 Limitations of the POLIZERO Methodology

Though the stakeholder workshops aimed to complement the results from topic modelling, which was wide in scope in terms of stakeholder coverage to gain depth in the analysis, we recognise that not all stakeholders from every step of the energy transition had a presence in them. In the topic modelling method, we mainly treated umbrella associations and institutional stakeholders, which are representative for the sectors and important actors of the energy transition, such as the houseowner association, Swiss District Heating Association, Association of the Swiss Paint and Coatings Industry and Interest Group For Energy Intensive Industries etc. (see Appendix “8.2 Stakeholders Included in Topic Modelling “ for the full list). However, the topic modelling analysis lacked those stakeholders who did not participate in the consultation phases: these are often experts in key areas for the implementation of the energy transition. Additionally, due to COVID-19 restrictions, along with time and budget constraints, the workshops did not cover all aspects relevant to energy transition comprehensively. By acknowledging this limitation, we abstained from formulating policy packages which reflected only the opinions of the stakeholders who were part of the POLIZERO analysis, but we aimed to implement policy packages that are broader in scope and entail policy-making or academic research interest, while at the same time serve well the policy exploration analysis (i.e., they are cross-sectoral and with different intensities) and can be implemented and quantified by the modelling tools we employed in the project.

The JRC-EU-TIMES is a partial equilibrium framework. The implications of the policy instruments do not include feedback to the rest of the economy sectors and do not account for energy service demand responses to its own price, a response often induced by policy implementation. Further, we do not account for policy transaction costs, policy financing, or other policy implementation costs other than those incurred within the boundaries of the energy sector driven by technology and fuel switch. At the same time, we do not account for recycling policy revenues within the economy. Such an analysis would have required the employment of a Computable General Equilibrium model. Having such a model available, additional policies like Carbon Border Adjustment Mechanisms for carbon pricing of imported goods (CBAM) could have been assessed. However, because of time, resources, and budget constraints in POLIZERO, as well as the uncertainties in developing the JRC-EU-TIMES model and its coupling with AIM, we abstained from adding one more modelling framework to the project. It follows that by only employing an energy system model, the discussion of the policy packages' implications remains at the level of the energy system, covering areas such as emissions from fuel combustion and industrial processes, energy trade, or energy technology uptake and fuel switches. In addition, the adoption of the policy is considered ex-ante, which means that there is no social opposition to implementing the policy instruments of the packages, while a rational decision maker is assumed to be targeted by the policy, which reacts in an economic rational way.

During policy exploration with AIM, the user can identify deviations of a policy from the set targets and, therefore, search for an alternative that can be implemented at the right timing in order to allow the policy pathway to achieve the set targets. This means that a policymaker following a policy pathway generated with AIM will need to plan ahead all the policy changes, to let them take full effect as much as possible at the beginning of their implementation. In other words, due to the explorative planning logic of AIM, the lead-in and lead-out effects of policies, i.e., the transaction time needed to implement the policy or the time needed to phase out the policy, cannot be captured. Instead, AIM assumes that the planning has been made ahead in time, in order to allow a smooth transition from one policy to another. While this logic, helps in planning policy change procedures to smoothen, for example, social opposition or prepare the required regulatory background, it cannot highlight instances where such parameters affect the policy outcome at the transition phase.

Furthermore, AIM has a limited foresight logic, which means that the policies are applied in a forward-looking, sequential manner, and the policy outcome of each policy is added to the outcome of previously implemented policies. Often, such additive effects in policy implementation are not observed in reality, due to cross-policy interactions that are not explicitly accounted for in AIM. Still, the logic of AIM provides useful insights as it implements a myopic approach in decision making, closer to what is actually applied in reality. However, it also lacks the ability to apply optimisations in a backward manner (i.e., starting from the target and reaching the start). For example, when implementing “EU harmonisation”, some sectors have quicker decarbonisation responses than others. Those that respond quickly stop contributing after some point (as they cannot go to negative emissions), and the emissions mitigation burden to reach net zero falls on those that have delayed responses. Opposite response rates can be observed with “Levies”. So, with the forward-looking, sequential policy implementation manner of AIM, changing from “EU harmonisation” to “Levies” would need some sectors to go negative to compensate for those sectors whose slow response has only been taken into account during the entire pathway. Since this is not possible, the analysis with AIM could not find a pathway that starts with “Levies” and then switches to “EU harmonisation”, or vice versa. Nevertheless, this should not be treated as a deterministic result, as when simulating with the JRC-EU-TIMES, which has perfect foresight, it is possible that an optimised sectoral response could be found in which starting with “Levies” and continuing with the “EU harmonisation” can transition the Swiss energy system to net-zero GHG emissions.

The uncertainty analysis of the performance of the different policy instruments is based on a rather limited number of 20 contexts (i.e., the size of the random sample), while the number of random variables is 22. We acknowledge that a larger number of contexts would have further benefited the clustering algorithm of AIM and generated richer insights as to which of them need to be monitored towards achieving the decarbonisation of the Swiss energy system. However, it was not possible to increase the number of contexts because this would have required an exponentially increased number of simulations with the JRC-EU-TIMES, the computational time for which might not have been available in the PSI computer cluster within the project time frame. To this end, we opted to narrow down the context variables to the number of contexts that were feasible to simulate with the available computational resources by employing Latin Hypercube Sampling to ensure that at least the full spectrum of the contexts is sampled.

4 Conclusions and Outlook

The POLIZERO project was an innovative research initiative that integrated stakeholder analysis, energy system modelling using the JRC-EU-TIMES model, and dynamic adaptive policy pathway approaches using the AIM model to assess the transformation of the Swiss energy system towards achieving net-zero emissions by 2050 while accounting for multi-level interactions with the EU energy system. The primary objective of POLIZERO was to provide insights to policymakers and stakeholders on what Switzerland needs to do to achieve its long-term energy and climate goals and how this can be achieved by carefully selecting and implementing suitable policy packages from today to 2050. In this regard, the POLIZERO analysis included a stakeholder elicitation to identify relevant policies for Switzerland, a normative energy system analysis, in which specific targets are requested to be met by the Swiss energy system, and an explorative and policy-driven energy system analysis. The combination of these three types of analyses formed the basis for dynamic policy exploration under uncertainty to identify robust policy implementation pathways and critical uncontrolled contextual factors that could affect policy performance with respect to achieving the long-term goals of the Swiss energy and climate strategy. POLIZERO assessed the transition of the Swiss energy system to net-zero emissions and performed the dynamic adaptive policy exploration by accounting for the interactions between the Swiss and the EU energy systems and policies. This is important because the Swiss energy system will be increasingly interconnected to the European energy infrastructure, beyond electricity and gas, and because Switzerland is implementing many of the European regulations and market schemes by transposing the relevant regulations into its national legislation. This section summarises the main conclusions from the analysis of POLIZERO, the research collaborations and main outcomes achieved, and provides an outlook for addressing limitations identified in the current research.

The POLIZERO **stakeholder analysis** was conducted via physical workshops and Natural Language Processing algorithms on published position papers of key stakeholders during the COVID-19 period of

2020-2021, where restrictions on physical meetings and social interactions were in force. Still, the findings from this analysis are very relevant to Swiss policymaking for energy transition. Many of these findings are now hot topics in the discourse for the post-2030 policy measures. Stakeholders advocated for a **stronger integration into the EU emissions mitigation schemes** by expanding Swiss participation in the European Emissions Trading Scheme for buildings and transport and pursuing further EU-CH agreements across all energy markets, not only electricity. They also supported **technology-neutral support schemes,** in which financial incentives are agnostic to any energy supply technology that can help meet climate change mitigation targets by **avoiding technology bans**, including nuclear power. To this end, **simplifying permitting, construction, and licensing regulations** is a key multiplier for new technology deployment at the speed required by the net-zero emissions transition. Stakeholders generally asked for more **secure financing** of energy projects and building renovations, which can be provided via soft loans. Related to the trade-offs between technology versus behavioural switches, stakeholders considered the behaviour changes as a long-term option after making a technology switch: for example, first to switch to clean heating and electromobility and then to adopt behaviours of reducing indoor temperatures, diets or mobility habits. Finally, the main **concerns** for almost all stakeholders were the **energy security of supply,** which is beyond electricity imports, the **household income impacts** from the increased energy costs, the **reduction of GHG emissions from the hard-to-abate sectors** such as agriculture and industrial processes, and the **environmental protection** such as securing biodiversity and heritage sites. All these perceptions were used in POLIZERO to inspire the formation of post-2025 policy packages that are also relevant for academic research, can be implemented and assessed by the energy system model employed in the project, and can provide useful insights to the Federal Administration.

The **energy system analysis of three scenario pathways of the Swiss energy system** with the JRC-EU-TIMES model identified several areas where the policy focus should be, among which the most important are:

- The clean energy transition has been accelerated recently, but the decade **2025-2035 represents a critical window for Switzerland**. By 2030, the analysis shows that most energy demand technologies we use today for heating, mobility and industrial processes will need to be replaced as they approach their technical or economic lifetime. Supporting a switch to electric heating and mobility, without extensive reliance on electricity imports, would require by 2035 a build-up of 3x the solar-based electricity capacity of today and a realisation of increased efficiency gains in the demand sectors to reduce the overall final energy consumption by 15% from today.
- If the phase-out of the current nuclear power plants is to be completed by 2050, about 12 TWh of **wind and bioenergy electricity will be needed** to achieve electricity import independence annually, of which around 6 TWh will need to be available in the winter half-year.
- The recently observed deceleration of electromobility needs to be a parenthesis; **electric cars need to regain their momentum** and account already for 50% of the total passenger car fleet by 2035, especially if Switzerland would need to comply with the newest vehicle emissions standards from the EU commission that would be in place at that time.
- The **expansion of the district heating network** needs to be accelerated, and the challenge is to supply the district heating with enough clean energy sources. By 2035, **large-scale heat pumps will start having a role in this** by accounting for more than 10% of the total district heating supply, with their share increasing to one-third by 2050.
- The industry and aviation's participation in the European Emissions Trading Scheme (EU-ETS) would require **Switzerland to include sustainable fuels and hydrogen in its energy mix**. About 6 TWh of hydrogen as an energy carrier will be needed in the Swiss industry by 2050, of which the bulk will be in the chemicals sector. At the same time, about 90 PJ of sustainable synthetic fuels of biogenic or electric origin will be required to cover the needs of aviation, industrial processes and space heating (biomethane). Around two-thirds of the hydrogen demand in 2050 can be domestically produced via electrolysis. Still, the consumption of sustainable synthetic fuels mainly relies on imports from the Middle East, North Africa, and Latin America; imports from Europe primarily occur until the 2040s, when the rest of the world's regions develop enough export capacity.

- Capturing CO_2 emissions will be needed to **compensate for emissions from the hard-to-abate sectors,** i.e., industry, waste incineration and agriculture**.** Depending on whether the emissions are to be compensated abroad or mitigated with domestic measures only, **Switzerland will need to capture from 6 to 10 Mt CO_2/yr.** by 2050, of which up to 5-5.5 Mt is from power generation and up to 2.5-3 Mt from industrial processes. The rest must be captured via Direct Air Capture or compensated abroad. Given the limited domestic storage potential for captured emissions, these need to be exported to the Northern Sea by developing appropriate connections to the European CO_2 transport backbone network by the 2040s

The stakeholder analysis, desk research, the insights from the energy system analysis of the three scenarios' pathways, and further exchanges with the Federal Administrator (SFOE, FOEN, ASTRA) inspired the formation of four policy packages underlying different philosophies. Each policy package included several policies spanning all sectors of the energy system to account for both cross-policy and cross-sectoral interactions as well:

- The first policy package focuses on **subsidies** in the form of capital, one-time subsidies on clean technologies for energy supply and use, and new clean fuels infrastructure. This policy package entailed the philosophy of “awarding the new.”
- The second policy package focused on policies related to **harmonisation with EU regulations**, such as emissions trading schemes or vehicle emissions and other energy performance standards that are Europe-wide and imposed by European legislation. This policy package entailed the philosophy of “let the market play.”
- The third policy package included policies focusing on taxing emissions, such as CO_2 levies for heating, or CO_2-based registration and circulation taxes. This policy package entailed the philosophy of “penalising the old”
- The fourth policy package included regulatory **mandates and obligations** applicable only to Switzerland. This means that Europe-wide mandates are included in the EU harmonisation policy package. Examples of policies relevant to the fourth policy package are maximum requirements for buildings for energy consumption or direct CO_2 emissions, minimum requirements for roof-top or building-integrated solar photovoltaic installations in new buildings, or a minimum number of electric car chargers in buildings. This policy package entails the philosophy of “forcing the change”.

In the following discussion, the above policy packages are referred to as “Subsidies”, “EU harmonisation,” “Levies”, and “Obligations”. These packages were used in the exploration of the policy pathways with the AIM model.

The exploration of the policy pathways with the AIM model aimed to identify how the transformation of the energy system suggested by a normative scenario analysis via the JRC-EU-TIMES model can be achieved by evaluating the performance of the policy packages identified in POLIZERO and by accounting for uncertain contexts within which the policy implementation takes place. The analysis showed that **the timing of policy implementation** is crucial in achieving the Swiss 2050 net-zero target.

The analysis confirmed that policy packages containing either:

- **Strong “EU harmonisation”:** including the enhanced EU-ETS2, stricter emissions standards, bans on internal combustion engines, and subsidies for alternative fuel and CC(U)S pipelines.
- **“Levies” penalising polluting technologies:** including strengthened CO_2 levies for buildings, industry and the energy sector, increased CO_2 tax for motor and aviation fuels, and increased CO_2-based vehicle registration and circulation taxes,

should be implemented as soon as possible and with significant ambition. Inadequate ambition in implementing such policies, even for a brief period until 2030, eliminates possible pathways to net-zero emissions until 2050.

Policies containing **“Obligations”**, including:

- CO_2 emissions requirements, minimum energy performance, RES and storage capacity requirements, and banning of new installations of fossil-based heating systems in buildings,
- carbon budgets and mandates for minimum EV charging stations in buildings, and
- CO_2 emissions requirements in industry

should always accompany "Levies" or "EU harmonisation" to force a response change in the various sectors.

Whether Switzerland chooses the "EU harmonisation" policy pathway or not, further policy timing considerations need to be taken into account. If "**EU harmonisation" combined with "Obligations"** are to be chosen, two main approaches would lead to the 2050 decarbonisation target:

- Medium ambition in implementing the "EU harmonisation" and "Obligations" starting immediately, accompanied by high capital "Subsidies" for clean technologies in all sectors until 2035. After 2035, subsidies can be gradually phased out, maintaining at least low subsidies until 2040. Any reduction in "Subsidies" before 2035 must be offset by even higher ambition in "EU harmonisation" and "Obligations" from 2025 onward.
- High ambition in implementing "EU harmonisation" and "Obligations" from the outset, where "Subsidies" become optional as complementary measures rather than key transition factors.

In both cases, "Subsidies" play a main role in front-loading the decarbonisation effort for the residential and services sectors and acting as accelerators for the transformation to a net-zero energy system, especially in the short term. Also, prolonged "Subsidies" may allow more time for the industry to respond, given the long-lived assets and the capital intensity required to decarbonise the sector.

Similar observations apply if "**Levies" combined with "Obligations"** are chosen instead. They should be implemented at least with medium intensity from the outset, supported by high subsidies until 2030. Beyond 2030, the intensity of "Levies" and "Obligations" should be further increased, even if subsidies remain high after 2030. Any delay in the high-intensity implementation of "**Levies" combined with "Obligations"** beyond 2030 risks the achievement of the 2050 net-zero target. On the other hand, following the intensity increase of "Levies" and "Obligations" after 2030, subsidies can either be slowly or quickly reduced without affecting the success rate of the pathway. **In both cases**, if a constant policy intensity is preferable compared to changing intensities from 2025 to 2050, "EU Harmonisation" or "Levies", combined with "Obligations", should be implemented with high ambition. That way, the high ambition of these policies in the starting period 2025-2030 can compensate for any reduced "Subsidies" intensity.

These observations make it clear that the timing and intensity of policy package implementation are crucial parameters for achieving the 2050 net-zero target. Nevertheless, even if the aforementioned presented pathways' time- and intensity-wise implementation is followed, the achievement of the 2050 net-zero target is conditional on crucial contexts, which are elaborated below.

Achieving the net-zero target requires the **contribution of imported biofuels and e-fuels, alongside domestic biomass and renewable energy production**. The biomass potential is a critical factor that must be monitored. If biomass potential falls below about **100 PJ**, imported biofuels should be higher than **5 PJ**, to maintain the combined potential of domestically produced and imported biofuels higher than about **105 PJ by 2050**. **An immediate high ambition in implementing "EU harmonisation" combined with "Obligations"** could exhibit better tolerance to the absence of imported biofuels and e-fuels because this strategy leads to rapid emissions reductions and defossilisation. Therefore, if renewable energy sources scale up quickly under such a policy choice, the biomass potential becomes less critical for the success of the pathway, but it is still worth monitoring. **The same tolerance increase however does not apply if high intensity "Levies" are applied in the place of high intensity "EU harmonisation" from the beginning**.

Gasoline and natural gas prices should also be monitored as significant impact factors to the outcome of the presented policy pathways, as they particularly affect the response of the transport and heating sectors. Transport requires stronger price signals than the residential sector to drive decarbonisation. **If the pathway with gradual ambition in "EU harmonisation" is chosen**, gasoline prices should not drop more than 8.7% compared to 2020 (i.e., 8.8 EUR/GJ or 0.3 EUR/lt), and natural gas prices should not drop more than 56.4% (i.e., 10.4 EUR/MWh) compared to 2020. However, **if "EU harmonisation" is implemented with high ambition as soon as possible**, fossil fuel prices are no longer a critical context to monitor, as the relevant policies push the transport sector to decarbonisation more efficiently. On the other hand, **if "Levies" are chosen instead of "EU harmonisation"**, the tolerance towards reduced gasoline prices, compared to the monitored 2020 prices, is nearly zero. High gasoline prices are needed to compensate for a lower-than-required performance of financial counter-incentives through levies in decarbonising the domestic transport sector, compared to the vehicle standards in the "EU harmonisation" policy package. This is because levies offer price certainty but do not guarantee emissions reductions, in contrast to standards. Therefore, in case that levies fail to achieve the reductions needed for net-zero, additional measures need to complement them. A critical one is to ensure high gasoline and gas prices, even if by implementing additional taxation on them.

As an overall remark from the presented conclusions, choosing a pathway that features "EU harmonisation" instead of "Levies" may result in fewer contextual factors that could lead to a failure in the achievement of the 2050 net zero target. In fact, **if "EU harmonisation" is implemented with high ambition as soon as possible, it can lead to robust results towards the 2050 net-zero target, with minimum negative impacts from the context, i.e. policy failures**. Substituting "EU harmonisation" with "Levies" (always with the support of obligations) can be an alternative, but only when the levies are high enough to trigger the transport sector response, and with potential higher vulnerability to contextual uncertainties.

In terms of academic outputs, POLIZERO delivered a comprehensive European energy systems model that included a bottom-up representation of the Swiss energy system alongside the energy systems of 35 additional countries. This model, built upon the JRC-EU-TIMES open-source framework, significantly enhances the capacity of researchers to analyse the challenges and opportunities associated with Switzerland's long-term energy transformation. Additionally, POLIZERO pioneered novel approaches using Natural Language Processing to efficiently analyze stakeholder positions, improving the ability to interpret diverse perspectives on energy policy. Finally, the project developed a new version of the Adaptive policymaking Model (AIM), an agnostic machine-learning tool capable of evaluating policy pathways by considering evolving uncertainties and identifying robust strategies that maximize the likelihood of achieving policy objectives.

POLIZERO also led to two PhD theses, one in Switzerland at ETH/PSI and one in Greece at UPRC. In addition to 2 peer-reviewed publications and 4 conference talks based on the project's results, POLIZERO insights and tools were also integrated into university lectures in Switzerland at ETH and Greece at UPRC. Finally, the project provided data and results and seed funding for further development of the JRC-EU-TIMES and AIM models for several national and European projects.

Acknowledging that the work in the past 4 years should not be archived, but should be continued and further advanced, the teams of PSI and UPRC have prepared an outlook for further research:

- The topic modelling algorithm can be extended to sentiment analysis so that the analysed stakeholders' views on future policies can also be labelled positive, negative, or neutral. If more comprehensive political opinions on the "elite" level are desired, textual data in Switzerland is not limited to position papers but also Federal Council and parliamentary transcripts and reports. If more "unofficial" views are of interest, lobbyists can be identified, and their published texts utilised. Future research could explore the temporal evolution of stakeholder coalitions or examine how insights from different text sources might differ. Topic modelling could serve as a basis method for further methods to enhance energy strategies, such as Multi-objective optimisation (MOO) or Multi-criteria Decision-making (MCDA). The policy priorities from topic modelling can be concluded as other "objectives" for optimisation beyond the classic cost objective. Similarly, these priorities can be used as the criteria for MCDA. The proportions of stakeholders under each priority could be converted into weights for MCDA. Other ways to integrate topic modelling with MOO and MCDA could be explored further.
- The current version of the JRC-EU-TIMES model lacks sufficient intra-annual resolution to capture the variability of energy supply and demand at sub-annual levels. This underestimates the

need for storage and dispatchable generation capacity and can overestimate the uptake of renewable energies. In addition, the energy service demands in the model are inelastic to their prices, while endogenous modal shifts in transport are also not captured. The model can be further improved to include endogenous non-CO_2 GHG emissions from the energy system, which currently are given as assumptions. Finally, the model can be further expanded to include more demand sectors and granularity in the investment decisions.

- The AIM model is planned to be further improved to account for the lead-in and lead-out effects of policy implementation and support pathway-long fine-tuning of policy implementation. This will require a learning algorithm which will be trained based on the simulations provided by a simulation model (in this case, the JRC-EU-TIMES). This algorithm will serve as a surrogate to actual simulations, which will provide estimates for the transitional effects during a policy change. Furthermore, the algorithm will capture the pathway-wide interactions during policy shifts, therefore minimising instances of infeasibilities, which are a product of mathematical implementation rather than actual limitations.
- In future work on this topic, the use of complementary models and methods could further enrich the value-added of this research. For example, policy exploration with AIM was solely based on the response from the energy system, ignoring feedback to the rest of the economy. Including, for example, a computable general equilibrium model, additional results on the economic implications and financing of the policy packages explored could have been integrated into the AIM clustering algorithm and the energy system transformation pathways from JRC-EU-TIMES. Or, going beyond the energy sector, policy packages targeting agriculture or international aviation (and maritime) could have also been evaluated. It should be acknowledged that the POLIZERO methodology is flexible enough to integrate additional models and tools into the normative scenario analysis and dynamic policy exploration.

Building on the knowledge gained through PSI's collaboration with TEESLab and the improved understanding of the opportunities and challenges in linking an energy systems model with a machine learning agnostic tool for policy exploration, we seek further opportunities to amplify such research to achieve a more comprehensive assessment of the implications of energy policy and long-term energy sector development pathways.

5 National and international cooperation

With PSI and UPRC as partners, the project team represents international cooperation. In addition, both research teams are involved in different national and international activities based on other ongoing research projects related to deep decarbonisation pathways for Switzerland and European countries.

The policy inventory and the findings from the Stakeholder Workshops of POLIZERO are available to other Swiss researchers and national experts. The long-term energy system scenarios for Europe and Switzerland assessed in the project also provide necessary boundary conditions regarding the evolution of the European energy system to the “JI Synfuel” project, a partnership between PSI and EMPA regarding the role of low-carbon synthetic fuels in Europe and aviation, in which also the JRC-EU-TIMES model was used. In addition, POLIZERO scenarios provide boundary conditions regarding the European developments in the SWEET SURE project[17] and the SWEET Refuel.ch project[18]. POLIZERO also uses input from the “SWEET CROSS” project[19] regarding main future socio-economic assumptions for Switzerland, resource potentials and technology-performance assumptions for the scenarios assessed with the JRC-EU-TIMES. The policy inventory has also been utilised in the context of UPRC's ongoing H2020 research projects, e.g., “Energy Citizens for Inclusive Decarbonisation (ENCLUDE)”[20], etc., related to

[17] https://sweet-sure.ch
[18] https://www.admin.ch/gov/en/start/documentation/media-releases.msg-id-97292.html
[1919] https://sweet-cross.ch
[20] https://encludeproject.eu

modelling energy transition scenarios for decarbonisation in different European contexts and scales. The JRC-EU-TIMES model developed in POLIZERO and the scenarios of POLIZERO BAU and CLI are also used in the SFOE project SHELTERED[21] that specifically looks at the role and potential of synfuels in decarbonising the Swiss energy system.

Furthermore, the updated AIM model has been used in the H2020 TIPPING+[22]and SENTINEL[23] projects in which UPRC participated, for the design of adaptive pathways for the transition of the power sector in Greece, and the transformation of a former lignite-dependent city into a green energy centre.

PSI is involved in the IEA-ETSAP energy modelling community. Since last year, the POLIZERO inventory has been available to all IEA-ETSAP members through the POLIZERO website. At the same time, the improvements made in the JRC-EU-TIMES model have already been communicated to the ETSAP community.

Finally, it should be noted that POLIZERO provided seed funding to bring in Switzerland and further develop the JRC-EU-TIMES energy system model, enabling the assessment of energy system transformation pathways for Switzerland by accounting for the interactions with EU policy and energy markets. Therefore, the project contributed to the capacity building of the European energy system modelling, and the version of the JRC-EU-TIMES developed in POLIZERO is now being used in other research projects also funded by the European Commission, such as the EU Horizon 2020 project WIMBY[24] and the iDesignRES[25]PSI's participation with the JRC-EU-TIMES model in EU H2020 projects strengthens Switzerland's position within the European energy systems analysis research community.

6 Publications and other communications

The POLIZERO project led to two PhD theses, one at PSI and one at UPRC:

- PhD thesis of Meixi Zhang (to be completed within 2025) on “Climate and Energy Policies for Switzerland’s Energy Transition in View of the European Decarbonisation Landscape” focusing on how Europe's decarbonisation efforts could shape Switzerland’s path to net-zero emissions by 2050, using an enhanced version of the JRC-EU-TIMES energy model. Model improvements include refined cross-border energy trading, updated technologies, and alignment with EU and Swiss climate targets. These enhancements enable the analysis of new policy tools, offering insights into effective strategies for Switzerland’s decarbonisation within the European context
- PhD thesis of Serafeim Michas (completed in 2024) on “Exploratory assessment of adaptive pathways toward renewable energy systems: a modelling framework facilitating decision making under deep uncertainty”, focusing on the energy transition of Greece by addressing the topics of consumer engagement in the energy transition, minimum waste of renewable energy, and shielding the electricity system from external disruptions (Michas, 2024)

In addition, the following open-access scientific publications were produced:

- Michas, S., & Flamos, A. (2024). “Least-cost or sustainable? Exploring power sector transition pathways”. Energy, 296, 131086. https://doi.org/10.1016/j.energy.2024.131086 (Michas & Flamos, 2024)
- Meixi, Z., Patt, A., Kober, T., Panos, E. (2024) “Mapping Policy Priorities Across Diverse Stakeholder Groups in the Swiss Energy and Climate Subsystems”, Submitted to Energy Strategy reviews, Pre-print available at https://doi.org/10.21203/rs.3.rs-5395974/v1 (Zhang et al., 2024)

[21] https://www.aramis.admin.ch/Texte/?ProjectID=49507
[22] https://tipping-plus.eu
[23] https://sentinel.energy
[24] https://wimby.eu
[25] https://idesignres.eu

One more joint publication between PSI and UPRC is being prepared with the tentative title: Panos, E., Zhang M., Michas, S., and Flamos, A. (2025) "Efficient Swiss Policy Pathways for the net-zero transition and their alignment with the European decarbonisation policy"

Finally, the methodology and project results were communicated at international scientific conferences:

- Zhang, M. et al (2023) "Identification of Stakeholder Interests in the Energy Transition with Topic Modeling: A Swiss Case Study", 3rd Swiss Social Science and Humanities Energy Workshop, 2 June 2023[26]
- Panos, E., et al. (2024) "Climate change mitigation policy spillovers in the EU's neighbourhood", 17th Integrated Assessment Modelling Consortium meeting, Seoul, 4th – 6th November 2024
- Panos, E. (2025) "Swiss Policy towards Zero CO_2 Emissions compatible with European Decarbonisation Pathways ", ETH-CEPE seminar, Zurich, 27th March 2025
- Panos, E. et al. (2021) "Energy and climate policies in major European Countries: insights from the POLIZERO project", ETSAP Winter Workshop, November 29th- 30th, 2021[27]

In addition to the above, POLIZERO was announced at IRENA's communication event within the International Energy Workshop 2022 in Fribourg, Germany, on May 25, 2022. The event was organised in the context of IRENA's Long-Term Scenarios Network (LTES Network), which aims to facilitate knowledge-sharing between scenario practitioners in the government sectors through the exchange of good practices to plan for the clean energy transition (link to the proceedings of the event).

In addition, the following communication activities have taken place:

- POLIZERO brand: From the early stages of the project, a POLIZERO logo was created and embedded in the POLIZERO document and presentation templates, which were used in all events where POLIZERO content was presented.
- Organisation of the Stakeholder Workshop on June 1, 2022, in Kreuz Bern Modern City Hotel. Participants from more than 20 organisations, associations, administrative offices and the energy industry gave valuable insights regarding relevant decarbonisation policies and measures for Switzerland in the post-2020 period (see https://polizero.ch/stakeholder-workshop)
- The design and deployment of a dedicated POLIZERO website (www.polizero.ch) that includes news and posts about POLIZERO, information about the Energy and Climate Policy Inventory developed in the project and a link to download it, download links of POLIZERO reports, papers, and conference presentations, and summary scenario results from the model runs of JRC-EU-TIMES and AIM model. Since December 2021, the POLIZERO website has achieved 1752 sessions, 2268 page views, 1601 new and 26 returning users, and 72 downloads of the policy inventory.
- Following the completion of the project's research activities (which coincide with the preparation of the final report), posts on the website and social media will be prepared to raise the visibility of the POLIZERO outputs further. The posts will concern the final report and its main outputs, participation in conferences, publication of relevant publications, etc.

Finally, research from POLIZERO is included in two undergraduate university courses in Switzerland and Greece:

- The undergraduate course "Introduction to Systems Modelling, Simulation and Optimisation", taught at the University of Piraeus, is enhanced with principles derived from the modelling activities of POLIZERO.

[26] https://www.psi.ch/en/eem/conferences

[27] https://www.slideshare.net/IEA-ETSAP/energy-and-climate-policies-in-major-european-countries-insights-from-the-polizero-project

- The undergraduate course “Introduction to Energy Systems” taught in the Spring semester at ETH Zurich Department of Mechanical and Process Engineering (D-MAVT) includes a lecture on Energy Policy with insights from the analysis in POLIZERO.

7 References

Abrell, J., Eser, P., Garrison, J. B., Savelsberg, J., & Weigt, H. (2019). Integrating economic and engineering models for future electricity market evaluation: A Swiss case study. *Energy Strategy Reviews*, *25*, 86–106. https://doi.org/https://doi.org/10.1016/j.esr.2019.04.003

Alberini, A., Bareit, M., & Filippini, M.-S. im A. des B. (2015). *Economic analysis of policy measures to reduce CO2 emissions of passenger cars in Switzerland*. https://www.bafu.admin.ch/dam/bafu/en/dokumente/klima/externe-studien-berichte/economic_analysisofpolicymeasurestoreduceco2emissionsofpassenger.pdf.download.pdf/economic_analysisofpolicymeasurestoreduceco2emissionsofpassenger.pdf

BFE. (2017). *Energy Strategy 2050 after the Popular Vote*. Bundesamt für Energie (BFE). http://www.bfe.admin.ch/php/modules/publikationen/stream.php?extlang=en&name=en_210755710.pdf&endung=Energy Strategy 2050 after the Popular Vote

Blei, D. M., Ng, A. Y., & Jordan, M. I. (2003). Latent Dirichlet Allocation. *J. Mach. Learn. Res.*, *3*(null), 993–1022.

Bloch, L., & Sauter, Y. (2023). *Photovoltaikmarkt: Preisbeobachtungsstudie*. https://pubdb.bfe.admin.ch/de/publication/download/11768

Díaz, P., Adler, C., & Patt, A. (2017). Do stakeholders’ perspectives on renewable energy infrastructure pose a risk to energy policy implementation? A case of a hydropower plant in Switzerland. *Energy Policy*, *108*, 21–28. https://doi.org/https://doi.org/10.1016/j.enpol.2017.05.033

EC. (2022). *REPowerEU Plan*. https://eur-lex.europa.eu/resource.html?uri=cellar:fc930f14-d7ae-11ec-a95f-01aa75ed71a1.0001.02/DOC_1&format=PDF

EC. (2024). *The European Green Deal*. https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF

FOEN. (2020). *Revision of the CO2 Act*. Swiss federal office for environment - BAFU. https://www.bafu.admin.ch/dam/bafu/de/dokumente/klima/praesentation/totalrevision-co2-gesetzes-nach2020.pdf.download.pdf/Musterpräsentation nach Schlussabstimmung_de.pdf

Gutzwiller, L. (2006). *21. Excursion: 2000-Watt-Society (21. Exkurs: 2000-Watt-Gesellschaft)*.

Haasnoot, M., Kwakkel, J. H., Walker, W. E., & ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, *23*(2), 485–498. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2012.12.006

Heim, S., Hellwig, M., Schober, D., & Woll, O. (2017). *Market integration, renewable energy expansion, interconnector capacity investment, and their impact on the Swiss Electrcity Market*. https://www.aramis.admin.ch/Default.aspx?Docum

Hettich, P., Thaller, P., Camenisch, L., Hoffman, B., Petrovich, B., & Wüstenhangen, R. (2020). *Europeanisation of the Swiss Energy System*. Dike Verlag. https://www.dike.ch/Hettich-et-al-Europeanization

Kirchner, A., Kemmler, A., Ess, F., Althaus, H.-J., Jacob, M., & et. al. (2021). *Energieperspektiven 2050+*. https://www.bfe.admin.ch/bfe/de/home/politik/energieperspektiven-2050-plus.exturl.html/aHR0cHM6Ly9wdWJkYi5iZmUuYWRtaW4uY2gvZGUvcHVibGljYX/Rpb24vZG93bmxvYWQvMTAzMjM=.html

Kwakkel, J. H., & Pruyt, E. (2013). Exploratory Modeling and Analysis, an approach for model-based foresight under deep uncertainty. *Technological Forecasting and Social Change*, *80*(3), 419–431. https://doi.org/https://doi.org/10.1016/j.techfore.2012.10.005

Loulou, R., Goldstein, G., Kanudia, A., Lettila, A., & Remme, U. (2016). *Documentation for the TIMES Model*. Energy Technology Systems Analysis Programme. https://iea-etsap.org/docs/Documentation_for_the_TIMES_Model-Part-I_July-2016.pdf

Luh, S., Kannan, R., McKenna, R., Schmidt, T. J., & Kober, T. (2023). How, where, and when to charge electric vehicles – net-zero energy system implications and policy recommendations. *Environmental Research Communications, , 5*(9).

Marcucci, A., Panos, E., Guidati, G., Schlecht, I., & Giardini, D. (2020). *JASM Framework and Drivers Definition*. https://sccer-jasm.ch

Michas, S. (2024). *Exploratory assessment of adaptive pathways toward renewable energy systems: A modelling framework facilitating decision making under deep uncertainty* [PhD Thesis]. University of Piraeus.

Michas, S., & Flamos, A. (2024). Least-cost or sustainable? Exploring power sector transition pathways. *Energy*, *296*, 131086. https://doi.org/https://doi.org/10.1016/j.energy.2024.131086

Michas, S., Stavrakas, V., Papadelis, S., & Flamos, A. (2020). A transdisciplinary modeling framework for the participatory design of dynamic adaptive policy pathways. *Energy Policy*, *139*, 111350. https://doi.org/https://doi.org/10.1016/j.enpol.2020.111350

Panos, E., Kannan, R., Hirschberg, S., & Kober, T. (2023). An assessment of energy system transformation pathways to achieve net-zero carbon dioxide emissions in Switzerland. *Communications Earth & Environment*, *4*(1), 157. https://doi.org/10.1038/s43247-023-00813-6

Panos, E., Kober, T., & Wokaun, A. (2019). Long term evaluation of electric storage technologies vs alternative flexibility options for the Swiss energy system. *Applied Energy*, *252*. https://doi.org/10.1016/j.apenergy.2019.113470

Papadelis, S., & Flamos, A. (2019). *An Application of Calibration and Uncertainty Quantification Techniques for Agent-Based Models BT - Understanding Risks and Uncertainties in Energy and Climate Policy: Multidisciplinary Methods and Tools for a Low Carbon Society* (H. Doukas, A. Flamos, & J. Lieu, Eds.; pp. 79–95). Springer International Publishing. https://doi.org/10.1007/978-3-030-03152-7_3

Patturpara, R. (2016). *Long term evolution of the Swiss electricity system under a European electricity market*. https://doi.org/10.3929/ethz-a-010635090

Schmidt, T. S., & Sewerin, S. (2019). Measuring the temporal dynamics of policy mixes – An empirical analysis of renewable energy policy mixes' balance and design features in nine countries. *Research Policy*, *48*(10), 103557. https://doi.org/https://doi.org/10.1016/j.respol.2018.03.012

SFOEN. (2021). *Long term Climate Strategy of Switzerland*. https://www.newsd.admin.ch/%0Anewsd/message/attachments/65081.pdf

Sidler, C., & Humm, O. (2019). *Besser planen, besser bauen - Optimieren mit Minergie*. https://www.minergie.ch/media/planer_d.pdf

Simoes, S., Nijs, W., Ruiz, P., Sgobbi, A., Radu, D., Bolat, P., Thiel, C., & Peteves, E. (2013a). The JRC-EU-TIMES Model. In *Scientific and Policy Reports*. "Joint Research Centre, European Commission." http://publications.jrc.ec.europa.eu/repository/bitstream/JRC85804/jrc_times_ eu_overview_online.pdf

Simoes, S., Nijs, W., Ruiz, P., Sgobbi, A., Radu, D., Bolat, P., Thiel, C., & Peteves, E. (2013b). *The JRC-EU-TIMES model - Assessing the long-term role of the SET Plan Energy technologies*. https://publications.jrc.ec.europa.eu/repository/handle/JRC85804

Sperscha, A., Stucki, & T, Wörter. M. (2016). *Policy Spillovers: How foreign energy policy affects green energy innovation Switzerland*. https://www.aramis.admin.ch/Texte/?ProjectID=36927

Swiss Parliament. (2024a). *Bundesgesetz über die Ziele im Klimaschutz, die Innovation und die Stärkung der Energiesi-cherheit (KlG)*. https://www.fedlex.admin.ch/eli/fga/2022/2403/de

Swiss Parliament. (2024b). *Verordnung über die Förderung der Produktion von Elektrizität aus erneuerbaren Energien*. https://www.fedlex.admin.ch/eli/oc/2024/279/de

Zhang, M., Patt, A., Kober, T., & Panos, E. (2024). Mapping Policy Priorities Across Diverse Stakeholder Groups in the Swiss Energy and Climate Sub-systems. *Energy Strategy Rev*.

8 Appendix

8.1 Stakeholders Participated in the POLIZERO Workshop

In June 2022, the POLIZERO team organised a workshop with 21 stakeholders representing Administrative Offices, Industry Associations, Consumer Associations and NGOs (Table 6) to identify efficient policies for Switzerland to help deliver the net-zero GHG emissions target by 2050.

Table 13: List of stakeholders who participated in the POLIZERO workshop in alphabetical order

Name	Stakeholder type
Amt für Umwelt und Energie (Kanton Bern)	Canton Administration Office
Amt für Wasser und Energie (Kanton St.Gallen)	Canton Administration Office
BKW Energie AG	Power production and distribution utility
Bundesamt für Energie (BFE)	Federal Administration Office
Bundesamt für Raumentwicklung (ARE)	Federal Administration Office
Bundesamt für Umwelt (BAFU)	Federal Administration Office
Cemsuisse	Association of the Swiss cement industry

energie-cluster.ch	Association promoting innovation in the energy sector
Interessengemeinschaft Energieintensive Branchen (IGEB)	Association of the energy-intensive industry (Paper and pulp, non-metallic minerals other than cement, metals)
Klimastreik	Association promoting renewable energies
ProClim	Forum for Climate and Global Change
Prognos AG	Energy-economy research and consulting company
Schweizerische Energie-Stiftung (SES)	Think-tank foundation for energy and renewable sources
Schweizerischer Bauernverband (SBV)	Association of Swiss farmers
Schweizerischer Gewerkschaftsbund (SGB)	Association representing employee interests
Swisscleantech	Business association
Swisspower AG	Strategic alliance of 22 Swiss municipal and regional utilities
Verband der Schweizerischen Gasindustrie	Association of the gas industry
Verband freier Autohandel Schweiz (VFAS)	Association of car sellers in Switzerland
Verband Schweizerischer Elektrizitätsunternehmen (VSE)	Association of the electric utilities
WWF Switzerland	Non-Governmental Organisation

8.2 Stakeholders Included in Topic Modelling

The Natural Language Processing algorithm of Topic Modelling was applied to the position papers of the stakeholders, shown in Table 14. In total, more than 250 stakeholders participated in the consultation rounds of the EnG 2020 and CO_2 Act 2021 revisions, covering a broad spectrum of different interests and action areas. The table also presents the categorisation of each stakeholder based on function, organisation or interest, and their classification (grouping) to the topics identified by the algorithm.

Table 14 The stakeholder groups identified by using clustering based on topics they belong to for the EnG 2020 and CO_2 Act 2021 revisions. The category refers to the type of stakeholder they are.

Stakeholder	Group	Category
Bauernverbände Nidwalden, Obwalden und Uri	Topic 1. Strong Climate Mitigation	Agriculture
Schweizerische Vereinigung für Sonnenenergie	Topic 1. Strong Climate Mitigation	solar
Schweizerische Energiestiftung	Topic 1. Strong Climate Mitigation	Energy/Climate/ Landscape
Junglandwirtekommission	Topic 1. Strong Climate Mitigation	Agriculture
PUSCH Stiftung	Topic 1. Strong Climate Mitigation	Energy/Climate/ Landscape
Klimaallianz	Topic 1. Strong Climate Mitigation	Energy/Climate/ Landscape
Koalition Luftverkehr Umwelt und Gesundheit	Topic 1. Strong Climate Mitigation	Aviation
Bauernverband Appenzell Ausserrhoden	Topic 1. Strong Climate Mitigation	Agriculture
Greenpeace Schweiz	Topic 1. Strong Climate Mitigation	Energy/Climate/ Landscape
Naturfreunde Schweiz	Topic 1. Strong Climate Mitigation	Energy/Climate/ Landscape
Oeku Kirchen für die Umwelt	Topic 1. Strong Climate Mitigation	Energy/Climate/ Landscape
Pro Natura	Topic 1. Strong Climate Mitigation	Energy/Climate/ Landscape
Cleantech Agentur Schweiz	Topic 1. Strong Climate Mitigation	Energy/Climate/ Landscape
Pro Velo Schweiz	Topic 1. Strong Climate Mitigation	Energy/Climate/ Landscape
Protect our Winters	Topic 1. Strong Climate Mitigation	Energy/Climate/ Landscape

Stakeholder	Group	Category
Aerztinnen und Aerzte für Umweltschutz	Topic 1. Strong Climate Mitigation	Energy/Climate/ Landscape
Insight Providers Climate Change Switzerland (IPCCS)	Topic 1. Strong Climate Mitigation	Energy/Climate/ Landscape
Solarspar	Topic 1. Strong Climate Mitigation	solar
Helvetas	Topic 1. Strong Climate Mitigation	International Development
Stiftung für Konsumentenschutz	Topic 1. Strong Climate Mitigation	Commerce
Bund Schweizer Architektinnen und Architekten	Topic 1. Strong Climate Mitigation	Building
Association Climat Genève	Topic 1. Strong Climate Mitigation	Energy/Climate/ Landscape
Campax	Topic 1. Strong Climate Mitigation	Energy/Climate/ Landscape
Alpen-Initiative	Topic 1. Strong Climate Mitigation	Energy/Climate/ Landscape
Der Gewerbeverein	Topic 1. Strong Climate Mitigation	General Political Consulting
Alliance Sud	Topic 1. Strong Climate Mitigation	International Development
Eidgenössische Kommission für Lufthygiene EKL	Topic 1. Strong Climate Mitigation	Aviation
Energie-wende-ja	Topic 1. Strong Climate Mitigation	Energy/Climate/ Landscape
Fastenaktion	Topic 1. Strong Climate Mitigation	International Development
Verkehrs-Club der Schweiz	Topic 1. Strong Climate Mitigation	Mobility
WWF Schweiz	Topic 1. Strong Climate Mitigation	Energy/Climate/ Landscape
Verband Schweizer Gemüseproduzenten	Topic 1. Strong Climate Mitigation	Energy/Climate/ Landscape
Grands-parents pour le Climat	Topic 1. Strong Climate Mitigation	Energy/Climate/ Landscape
Gruppe Grosser Stromkunden (GGS)	Topic 1. Strong Climate Mitigation	Industry
Swiss Textiles	Topic 1. Strong Climate Mitigation	Industry
HEKS	Topic 1. Strong Climate Mitigation	International Development
St. Galler Bauernverband	Topic 1. Strong Climate Mitigation	Agriculture
Berner Bauern Verband	Topic 1. Strong Climate Mitigation	Agriculture
The Branch	Topic 1. Strong Climate Mitigation	Building
Bauernverband (SBV)	Topic 1. Strong Climate Mitigation	Agriculture
Swissaid	Topic 1. Strong Climate Mitigation	International Development
Terre des hommes	Topic 1. Strong Climate Mitigation	International Development
SP	Topic 1. Strong Climate Mitigation	Political Party
EVP	Topic 1. Strong Climate Mitigation	Political Party
Swissrail	Topic 1. Strong Climate Mitigation	Mobility
Swiss Association for Zero Emission Boat	Topic 1. Strong Climate Mitigation	Mobility
Swisssolar	Topic 1. Strong Climate Mitigation	solar
Vereinigung für erträglichen Flugverkehr (VeFeF)	Topic 1. Strong Climate Mitigation	Aviation

Stakeholder	Group	Category
Verband historischer Eisenbahnen Schweiz (HECH)	Topic 1. Strong Climate Mitigation	Mobility
Verein Klimaschutz Schweiz	Topic 1. Strong Climate Mitigation	Energy/Climate/ Landscape
Suissetec	Topic 1. Strong Climate Mitigation	Building
Verband freier Autohandel Schweiz (VFAS)	Topic 2. Subsidy-oriented	Mobility
Verband Fernwärme Schweiz	Topic 2. Subsidy-oriented	Heating
Gebäudehülle Schweiz	Topic 2. Subsidy-oriented	Building
Swisscleantech	Topic 2. Subsidy-oriented	Energy/Climate/ Landscape
Swiss International Airports Association (SIAA)	Topic 2. Subsidy-oriented	Aviation
Thurgau	Topic 2. Subsidy-oriented	Canton/Municipality/Commune
Holzbau Schweiz	Topic 2. Subsidy-oriented	Biomass
Schweizerischer Verband der Bürgergemeinden und Korporationen (SVBK)	Topic 2. Subsidy-oriented	Canton/Municipality/Commune
Gastrosuisse	Topic 2. Subsidy-oriented	Commerce
Verband Schweizer Flugplätze	Topic 2. Subsidy-oriented	Aviation
Schweizerische Bankiervereinigung (SBVG)	Topic 2. Subsidy-oriented	Commerce
Verband Schweizerischer Elektrizitätsunternehmen	Topic 2. Subsidy-oriented	Energy/Climate/ Landscape
Verein Green Building Schweiz	Topic 2. Subsidy-oriented	Building
Flughafen Basel-Mulhouse	Topic 2. Subsidy-oriented	Aviation
Verein Kettenreation	Topic 2. Subsidy-oriented	Nuclear
Energie Wasser Bern (ewb)	Topic 2. Subsidy-oriented	Energy Supply
Nidwalden	Topic 2. Subsidy-oriented	Canton/Municipality/Commune
Schwyz	Topic 2. Subsidy-oriented	Canton/Municipality/Commune
Alpiq	Topic 2. Subsidy-oriented	Energy Supply
Citizens' Climate Lobby Schweiz (CCL Schweiz)	Topic 2. Subsidy-oriented	Lobby
Carnot-Cournot Netzwerk	Topic 2. Subsidy-oriented	Nuclear
Luzern	Topic 2. Subsidy-oriented	Canton/Municipality/Commune
Bern	Topic 2. Subsidy-oriented	Canton/Municipality/Commune
Axpo group	Topic 2. Subsidy-oriented	Energy Supply
Verband für die Schweizer Luftfahrt (Aviations...	Topic 2. Subsidy-oriented	Aviation
Flughafen Zürich AG	Topic 2. Subsidy-oriented	Aviation
HotellerieSuisse	Topic 2. Subsidy-oriented	Commerce
Swiss International Air Lines Ltd. (SWISS)	Topic 2. Subsidy-oriented	Aviation
Dachverband der schweizerischen Luftfahrt (Aer...	Topic 2. Subsidy-oriented	Aviation
Schweizerischer Ingenieur- und Architektenverein	Topic 2. Subsidy-oriented	Building
Mobility Genossenschaft	Topic 2. Subsidy-oriented	Mobility
Geothermie-Schweiz	Topic 2. Subsidy-oriented	Energy Supply
Raiffeisen Schweiz	Topic 2. Subsidy-oriented	Commerce
Holzwirtschaft Schweiz (Lignum)	Topic 2. Subsidy-oriented	Biomass

Stakeholder	Group	Category
Regionalkonferenz Bern-Mittelland (RKBM)	Topic 2. Subsidy-oriented	Canton/Municipality/Commune
Infrawatt	Topic 2. Subsidy-oriented	Energy/Climate/ Landscape
Bauenschweiz	Topic 2. Subsidy-oriented	Building
Schweizerische Bundesbahn (SBB)	Topic 2. Subsidy-oriented	Mobility
GLP	Topic 2. Subsidy-oriented	Political Party
Verband der Schweizer Unternehmen (Economiesuisse)	Topic 2. Subsidy-oriented	Energy/Climate/ Landscape
Konferenz der kantonalen Ausgleichskassen	Topic 2. Subsidy-oriented	Federal Entity
Schweizer Tourismus-Verband (STV FST)	Topic 2. Subsidy-oriented	Commerce
JUSO	Topic 2. Subsidy-oriented	Political Party
Schweizerischer Baumeisterverband	Topic 2. Subsidy-oriented	Building
Senke Schweizer Holz	Topic 2. Subsidy-oriented	Biomass
Synhelion	Topic 2. Subsidy-oriented	Energy Supply
Clean Fuel Now	Topic 3. Building Culture	Energy/Climate/ Landscape
EIT.swiss	Topic 3. Building Culture	Commerce
Berner Heimatschutz	Topic 3. Building Culture	Heritage Building Protection
Edelweiss Air AG (siehe SWISS)	Topic 3. Building Culture	Aviation
Vereinigung Zürcher Immobilienunternehmen	Topic 3. Building Culture	Building
Schweizerische Vereinigung Beratender Ingenieurunternehmungen	Topic 3. Building Culture	Commerce
Empa	Topic 3. Building Culture	Academia
Climeworks	Topic 3. Building Culture	Carbon Removal/Offset
Schweizerische Vereinigung der Eigentümer Historischer Wohnbauten	Topic 3. Building Culture	Building
Satom AG	Topic 3. Building Culture	Energy Supply
Transitgas AG	Topic 3. Building Culture	gas
Entwicklung Schweiz	Topic 3. Building Culture	International Development
Verband Schweizerischer Isolierfirmen (ISOLSUISSE)	Topic 3. Building Culture	Industry
Stadt Zürich	Topic 3. Building Culture	Canton/Municipality/Commune
Varo Energy AG	Topic 3. Building Culture	Energy Supply
H2 Energy AG	Topic 3. Building Culture	Energy Supply
Verband der Schweizerischen Lack- und Farben	Topic 3. Building Culture	Industry
Verband der Schweizerischen Schmierstoffindust...	Topic 3. Building Culture	Industry
Verband der Waldeigentümer (WaldSchweiz)	Topic 3. Building Culture	Biomass
Stiftung KMU Clima	Topic 3. Building Culture	Energy/Climate/ Landscape
Genève Aeroport	Topic 3. Building Culture	Aviation
Swissgas	Topic 3. Building Culture	gas
Förderverein H2 Mobilität Schweiz	Topic 3. Building Culture	Mobility
Konferenz der Gebäudetechnik Verbände (KGTV)	Topic 3. Building Culture	Building
Konferenz der kantonalen Delegierten des öffentlichen Verkehrs (KKDöV)	Topic 3. Building Culture	Mobility

Stakeholder	Group	Category
Föderation der Motorradfahrer der Schweiz (FMS)	Topic 3. Building Culture	Mobility
Swiss Krono AG	Topic 3. Building Culture	Biomass
Powerloop	Topic 3. Building Culture	Energy Supply
Kleinbauern-Vereinigung	Topic 3. Building Culture	Agriculture
Union suisse des professionnels de l'immobilier Suisse	Topic 3. Building Culture	Building
Zürcher Handelskammer	Topic 3. Building Culture	Commerce
Association économique romande pour une infrastructure	Topic 3. Building Culture	Building
Schweizerischer Verband der Umweltfachleute (SVU/ASEP)	Topic 3. Building Culture	Energy/Climate/ Landscape
Schweizerischer Nutzfahrzeugverband (ASTAG)	Topic 3. Building Culture	Mobility
Konferenz kantonaler Energiedirektoren	Topic 3. Building Culture	Canton/Municipal-ity/Commune
Regierungskonferenz der Gebirgskantone	Topic 3. Building Culture	Mountainous Region
JardinSuisse	Topic 3. Building Culture	Energy/Climate/ Landscape
Electrosuisse	Topic 3. Building Culture	Commerce
Dachverband der Wirtschaft für erneuerbare Energiepolitik für die Schweiz	Topic 3. Building Culture	Energy/Climate/ Landscape
Casafair Schweiz	Topic 3. Building Culture	Building
Carbura	Topic 3. Building Culture	Energy Supply
Biofuels Schweiz	Topic 3. Building Culture	Energy/Climate/ Landscape
Bau-, Planungs- und Umweltdirektoren-Konferenz	Topic 3. Building Culture	Canton/Municipal-ity/Commune
Avenergy Suisse	Topic 3. Building Culture	Energy Supply
Schweizerischer Gewerkschaftsbund (SGB)	Topic 3. Building Culture	Union
Schweizerischer Gewerbeverband (SGV)	Topic 3. Building Culture	Commerce
SVP	Topic 3. Building Culture	Political Party
Die Mitte	Topic 3. Building Culture	Political Party
Schweizerische Arbeitsgemeinschaft für die Bergebiete (SAB)	Topic 3. Building Culture	
Uri	Topic 3. Building Culture	Canton/Municipal-ity/Commune
Obwalden	Topic 3. Building Culture	Canton/Municipal-ity/Commune
Glarus	Topic 3. Building Culture	Canton/Municipal-ity/Commune
Zug	Topic 3. Building Culture	Canton/Municipal-ity/Commune
Freiburg	Topic 3. Building Culture	Canton/Municipal-ity/Commune
Solothurn	Topic 3. Building Culture	Canton/Municipal-ity/Commune
Stiftung Klimaschutz und CO_2-Kompensation (Klik)	Topic 3. Building Culture	Carbon Removal/Off-set
Basel-Stadt	Topic 3. Building Culture	Canton/Municipal-ity/Commune
Appenzell Innerrhoden	Topic 3. Building Culture	Canton/Municipal-ity/Commune
St. Gallen	Topic 3. Building Culture	Canton/Municipal-ity/Commune
Graubünden	Topic 3. Building Culture	Canton/Municipal-ity/Commune
Aargau	Topic 3. Building Culture	Canton/Municipal-ity/Commune

Stakeholder	Group	Category
Tessin	Topic 3. Building Culture	Canton/Municipal-ity/Commune
Neuenburg	Topic 3. Building Culture	Canton/Municipal-ity/Commune
Basel-Land	Topic 3. Building Culture	Canton/Municipal-ity/Commune
Touring-Club Schweiz (TCS)	Topic 3. Building Culture	Mobility
Fachverband landwirtschaftliches Biogasproduzenten	Topic 3. Building Culture	gas
Heimatschutz Basel	Topic 3. Building Culture	Heritage Building Protection
Heimatschutz Schaffhausen	Topic 3. Building Culture	Heritage Building Protection
Solothurner Heimatschutz	Topic 3. Building Culture	Heritage Building Protection
Thurgauer Heimatschutz	Topic 3. Building Culture	Heritage Building Protection
Innerschweizer Heimatschutz	Topic 3. Building Culture	Heritage Building Protection
Züricher Heimatschutz	Topic 3. Building Culture	Heritage Building Protection
Schweizer Heimatschutz	Topic 3. Building Culture	Heritage Building Protection
Aargauer Heimatschutz	Topic 3. Building Culture	Heritage Building Protection
Aargauische industrie- und Handelskammer (AIHK)	Topic 3. Building Culture	Commerce
Allianz Fossilfreie Logistik	Topic 3. Building Culture	Commerce
Berner Heimatschutz	Topic 3. Building Culture	Heritage Building Protection
Arbeitsgruppe Christen und Energie	Topic 3. Building Culture	Heritage Building Protection
Arbeitsgruppe Denkmalpflege	Topic 3. Building Culture	Heritage Building Protection
arv Baustoffrecycling Schweiz	Topic 3. Building Culture	Building
Arbeitsgruppe Berggebiet	Topic 3. Building Culture	Mountainous Region
Biomasse Suisse	Topic 4. Oil Tax	Biomass
ETH-Rat	Topic 4. Oil Tax	Academia
Romande Energie SA	Topic 4. Oil Tax	Energy Supply
Verband der Schweizerischen Cementindustrie	Topic 4. Oil Tax	Industry
Arxada AG	Topic 4. Oil Tax	Industry
Automobil Club der Schweiz (ACS)	Topic 4. Oil Tax	Mobility
Autogewerbe Verband Schweiz (AGVS)	Topic 4. Oil Tax	Mobility
Schweizerischer Burgenverein	Topic 4. Oil Tax	Heritage Building Protection
Akademien der Wissenschaften Schweiz	Topic 4. Oil Tax	Academia
Travail Suisse	Topic 4. Oil Tax	Commerce
Stahl Gerlafingen	Topic 4. Oil Tax	Industry
Swiss eMobility	Topic 4. Oil Tax	Mobility
Schweizerischer Städteverband	Topic 4. Oil Tax	Canton/Municipal-ity/Commune
Swisscofel	Topic 4. Oil Tax	Agriculture
Prométerre	Topic 4. Oil Tax	Agriculture
Centre Patronale	Topic 4. Oil Tax	General Political Consulting

Stakeholder	Group	Category
Verein der H2-Produzenten	Topic 4. Oil Tax	Energy/Climate/ Landscape
Verband öffentlicher Verkehr (VöV)	Topic 4. Oil Tax	Mobility
Waadt	Topic 4. Oil Tax	Canton/Municipal-ity/Commune
Chambre vaudoise du commerce et de l'industrie	Topic 4. Oil Tax	Industry
Umweltfreisinnige St. Gallen (UFS)	Topic 4. Oil Tax	Energy/Climate/ Landscape
Swiss Alliance for Collaborative Mobility (CHACOMO)	Topic 4. Oil Tax	Mobility
Jura	Topic 4. Oil Tax	Canton/Municipal-ity/Commune
Gewerkschaft des Verkehrspersonals (sev)	Topic 4. Oil Tax	Mobility
Pro Bahn Schweiz	Topic 4. Oil Tax	Mobility
Gaz nat	Topic 4. Oil Tax	gas
Scienceindustries	Topic 4. Oil Tax	Industry
Holzenergie Schweiz, Verband für Umwelttechnik...	Topic 4. Oil Tax	Biomass
Verband des Strassenverkehrs FRS (strasseschweiz)	Topic 4. Oil Tax	Mobility
auto-schweiz, Vereinigung Schweizer Automobil-...	Topic 4. Oil Tax	Mobility
Mieterinnen- und Mieterverband Schweiz	Topic 4. Oil Tax	Building
Fédération des Entreprises Romandes (FER)	Topic 4. Oil Tax	Commerce
Lausanne	Topic 4. Oil Tax	Canton/Municipal-ity/Commune
Ligue suisse pour l'organisation rationnelle du trafic	Topic 4. Oil Tax	Mobility
Lonza AG	Topic 4. Oil Tax	Industry
Interessengemeinschaft energieintenisve Branch...	Topic 4. Oil Tax	Industry
Privatperson 1	Topic 4. Oil Tax	
Post AG	Topic 4. Oil Tax	Commerce
Energie-Agentur der Wirtschaft (EnAW)	Topic 4. Oil Tax	Energy/Climate/ Landscape
Partito Comunista	Topic 4. Oil Tax	Political Party
Fédération romande immobilière (FRI)	Topic 4. Oil Tax	Building
ECO SWISS	Topic 4. Oil Tax	Energy/Climate/ Landscape
Privatperson 2	Topic 4. Oil Tax	
metal.suisse	Topic 5. Role of Agriculture	Industry
Coop	Topic 5. Role of Agriculture	Commerce
Infra Suisse	Topic 5. Role of Agriculture	Building
Schaffhausen	Topic 5. Role of Agriculture	Canton/Municipal-ity/Commune
Verband der Schweizerischen Gasindustrie (VSG)	Topic 5. Role of Agriculture	gas
Privatperson 3	Topic 5. Role of Agriculture	
Chambre de commerce, d'industrie et des services de Ge-neve	Topic 5. Role of Agriculture	Commerce
Fachvereinigung Wärmepumpen Schweiz	Topic 5. Role of Agriculture	Heating
Swissmem	Topic 5. Role of Agriculture	Industry
Groupe E	Topic 5. Role of Agriculture	Industry
Swisspower	Topic 5. Role of Agriculture	Energy Supply

Stakeholder	Group	Category
Association des groupements et organisations romandes de l'Agriculture	Topic 5. Role of Agriculture	Agriculture
Handelskammer beider Basel	Topic 5. Role of Agriculture	Commerce
Junge Evangelische Volkspartei (jevp)	Topic 5. Role of Agriculture	Political Party
Twiliner	Topic 5. Role of Agriculture	Mobility
Migros Genossenschafts-Bund	Topic 5. Role of Agriculture	Commerce
Energie Club Schweiz	Topic 5. Role of Agriculture	Nuclear
Wettbewerbskommission (WEKO)	Topic 5. Role of Agriculture	Federal Entity
Energie 360° AG	Topic 5. Role of Agriculture	gas
Grüne	Topic 5. Role of Agriculture	Political Party
FDP	Topic 5. Role of Agriculture	Political Party
Lidl Schweiz	Topic 5. Role of Agriculture	Commerce
UmverkehR	Topic 5. Role of Agriculture	Mobility
Elektrizitätswerk der Stadt Zürich (ewz)	Topic 5. Role of Agriculture	Energy Supply
IG Detailhandel Schweiz	Topic 5. Role of Agriculture	Commerce
Schweizerischer Gemeindeverband	Topic 5. Role of Agriculture	Canton/Municipal-ity/Commune
Genf	Topic 5. Role of Agriculture	Canton/Municipal-ity/Commune
Wallis	Topic 5. Role of Agriculture	Canton/Municipal-ity/Commune
Junge Mitte Schweiz	Topic 5. Role of Agriculture	Political Party
Junge Grüne	Topic 5. Role of Agriculture	Political Party
Hauseigentümerverband	Topic 5. Role of Agriculture	Building
Zürich	Topic 5. Role of Agriculture	Canton/Municipal-ity/Commune

8.3 Databases used for the calibration of the JRC-EU-TIMES model

In the second year of the POLIZERO project, an effort was made to recalibrate the model to the 2019 energy and emissions statistics. This task is data-intensive, requiring the consolidation of statistics from different data sources. An extensive update of the Swiss-related data included in the model was also performed within the context of recalibrating the model to the latest statistics for energy balances and emissions. The re-calibration of the model also required restructuring, e.g., by making years before 2019 not visible to the optimiser, to reduce the computational complexity of the model. The year 2020 is included as a milestone in the new version of the model and reflects the COVID-19 impacts.

The accompanying EXCEL file lists major databases used to recalibrate the model (Table 0).

Please note that the list included in this file is not an exhaustive list of all data sources used, but provides a good overview of the major statistics needed for calibrating the model. All statistics were collected for 2019, the model's base year. It is worth noting that the POLIZERO project also benefited from the recently published CROSSDat data platform[28] in the context of the SWEET CROSS activity in which PSI participated. The platform utilised many of the sources used also for the EP2050+ study from the Swiss Federal Office of Energy (Kirchner et al., 2021)and the SCCER Joint Activity Scenarios and Modelling research project (Marcucci et al., 2020).

[28] https://sweet-cross.ch/crossdat/

8.4 Sectoral representation of the JRC-EU-TIMES model

JRC-EU-TIMES includes 7 Industrial Sectors: Iron and Steel sector, Chemicals (Ammonia production, Chlorine production, and other chemicals), Paper and Pulp (High- and Low-quality paper production), Non-Ferrous Metals (Aluminium production, Copper production, other non-ferrous metals), Non-metallic Minerals (Cement production, Lime demand, Glass Hollow- and Flat-demand, other non-metallic minerals), Other Industries (including the Construction sector) and Non-Energy Uses. In each sector, a detailed Material Flow representation is also included.

In the Residential sector, the model distinguishes between single- and multi-family buildings with a detailed representation of their vintage (construction year). The model can endogenously decide to demolish or build new buildings to meet household demand. For each building type, several end-uses are included: space and water heating, cooking, cooling, lighting, refrigerators, dishwashing, clothes washing and other electrical appliances and uses.

The Services sector is distinguished into buildings for Hospitals, Hotels and restaurants, Sports and recreation, large and Small Shops, and Offices (including Schools, Universities, Museums, etc.). Like the Residential sector, several end uses are identified for each building type: space and water heating, cooking, cooling, lighting, ICT, refrigeration, and ventilation. Also, street lighting is included in the Services sector.

In Transport, the model considers different modes for passenger and freight transport. Domestic passenger transport is divided into private, public, rail and aviation. Freight transport is divided into road and rail transport. There is also explicit accounting for the international aviation sector (intra-EU and extra-EU flights).

On the supply side, the model is very detailed in the electricity, hydrogen, synfuel and biofuel production sectors. In the electricity sector, the vintages of the power plants are explicitly considered, while nuclear power is modelled at the reactor level. In the hydrogen sector, the model explicitly considers the green hydrogen production routes and distinguishes the different colours of hydrogen for tracking and certification purposes. In the synfuel production sector, there is a clear distinction between sustainable and non-sustainable fuels, with the former being tracked so that green electricity and C-atoms from biogenic or direct air capture sources are used for their production. Finally, the biofuel production sector is extensive, as one of the main uses of the JRC-EU-TIMES model in the past was to assess the role of biofuels in the EU energy system's decarbonisation (Simoes et al., 2013a).

Table 15: The end-use sectors of the JRC-EU-TIMES model

Sector	Sub-sector	End-uses
Industry	Iron and Steel	Steel
	Non-metallic minerals	Cement production Lime production Glass production (hollow, flat) Other non-metallic minerals production
	Chemical	Ammonia production Chlorine production Other production
	Non-Ferrous metals	Aluminium production Copper production Other non-ferrous metals production
	Pulp and paper	High-quality paper production Low-quality paper production
	Other industries	Machine drive Process heat Steam
	Non-energy use	Non-energy demand
Agriculture	Agriculture	Agriculture, forestry and fishing
Residential	Apartment buildings Detached houses Semi-detached houses	Space heating, cooling Water heating Cooking Lighting Refrigeration and freezing Dishwashing Clothes washing, drying Other electrical applications
Commercial	Hospitals Hotels and restaurants Sports and recreation facilities large and small shops Offices (Offices, Schools, Universities, Museums, etc.) Streetlights	Space heating, cooling Water heating Cooking Refrigeration and freezing Lighting Ventilation ICT & multimedia Other electrical applications
Transport	Road transport	Passenger: cars, motorcycles, mopeds, buses (urban and long-distance) Freight: light-duty trucks, heavy-duty trucks
	Rail transport	Passenger: Conventional trains, high-speed trains, metro, trams Freight: Rail freight
	Navigation	Inland Coastal
	Aviation	Domestic International

8.5 Main assumptions of the POLIZERO long-term energy transformation scenarios

The accompanying Excel file lists all major assumptions used in the long-term BAU, CLI, and CLI90 scenarios for Switzerland and the EU.

8.6 Probability distributions and correlation matrix of the random variables representing key uncertainties surrounding the evolution of the Swiss energy system

The analysis of the effect of the context on the performance of policy packages is one of the activities that was performed with AIM. To enable this, instead of simulating only a couple of scenarios for the evolution of the context based on best estimates, the simulation of a structured set of context scenarios was needed. A scenario is defined as a set of context variables whose values change simultaneously in each sample. We used the Latin Hypercube Sampling (LHS) methodology to perform such a sampling procedure. In LHS, when choosing to generate N scenarios, each context's value interval is divided by N, and a random value is drawn from each one of the N partitions. This ensures that values from the entire uncertainty space are drawn when sampling. Then, the randomly selected numbers of each parameter are combined in N scenarios. To ensure as realistic results as possible, during the sampling procedure, probability distributions were assigned to each context variable (see the accompanying EXCEL file), and correlations among the different contexts were defined (the correlation matrix is included in the accompanying EXCEL file). The correlations are based on empirical analysis and literature review.

The scenarios of contextual factors' values generated with this procedure are shown in the accompanying EXCEL file. Twenty context scenarios are selected as an optimal number to balance the computational time requirements of the JRC-EU-TIMES model to run all these scenarios for each policy package and policy package intensities (and the combinations of them), as well as the minimum clustering resolution needed for AIM. As in any clustering application, a larger sample could further increase the clustering's accuracy by exploring more contextual factors' value combinations. However, a compromise had to be made considering the computational effort needed to simulate many scenarios with the JRC-EU-TIMES. LHS is specifically designed for such applications to cover the uncertainty space with a reduced number of samples. In a future work, based on the experience gained at POLIZERO, the possibility of having a larger sample will also be explored.

8.7 Additional results from the POLIZERO scenarios BAU and CLI: developments in buildings, industry, electricity and transport sectors

Additional results regarding the fuel consumption in major end-use sectors for Switzerland are shown in Table 16 for the BAU and CLI scenarios.

Table 16: Sectoral energy consumption in Switzerland by fuel in BAU and CLI scenarios

<table>
<tr><th>BAU Scenario</th><th>CLI Scenario</th></tr>
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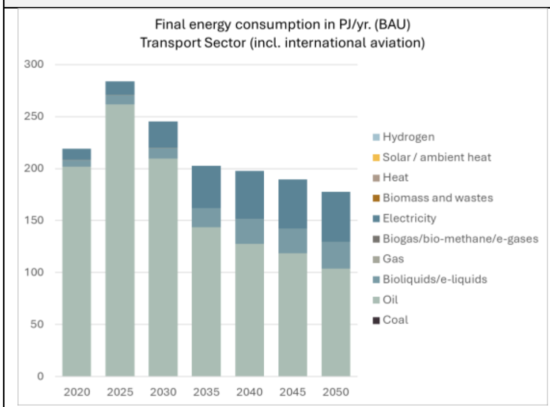

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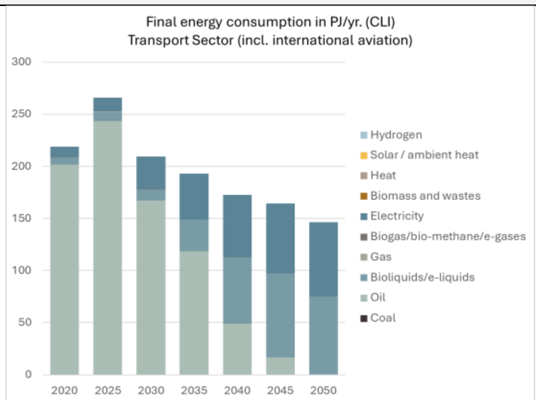

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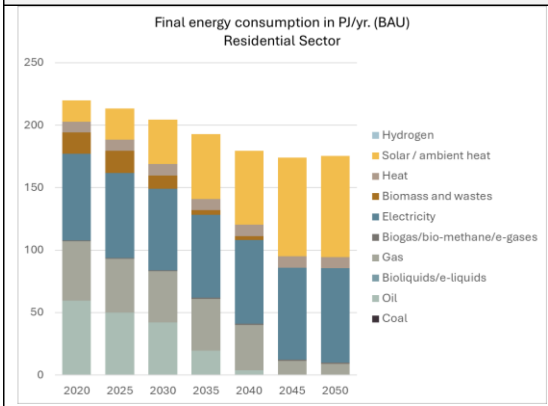
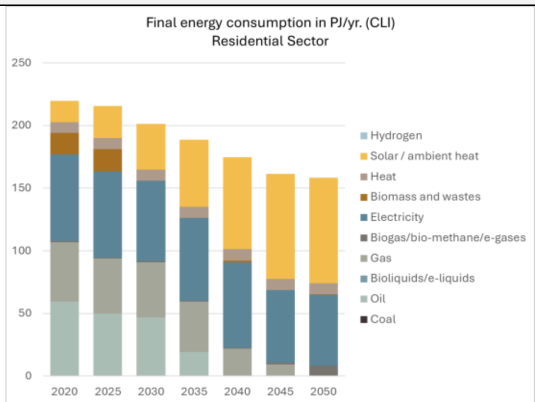
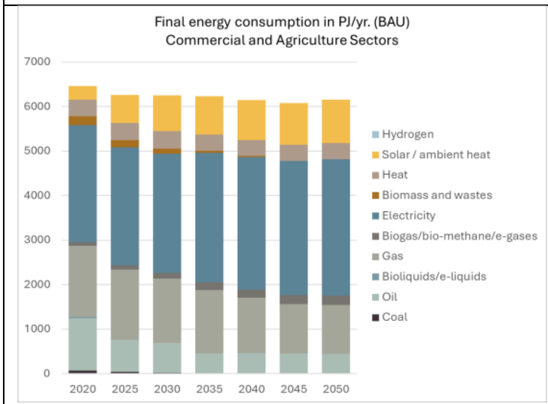
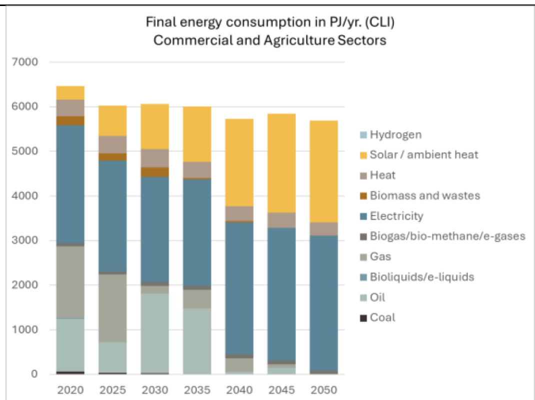
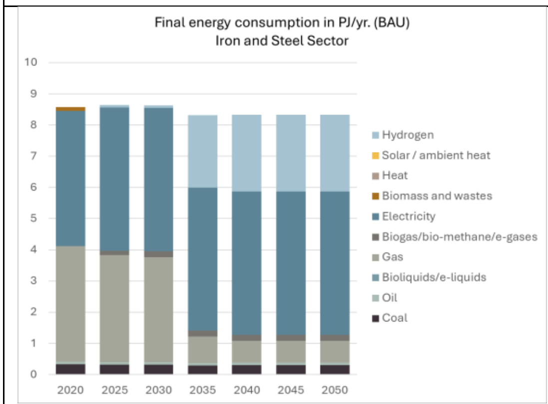
BAU Scenario	CLI Scenario

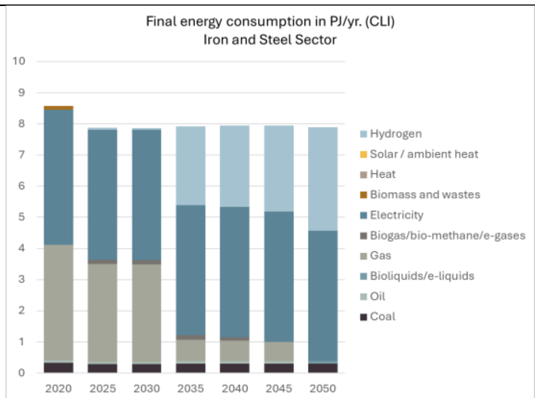


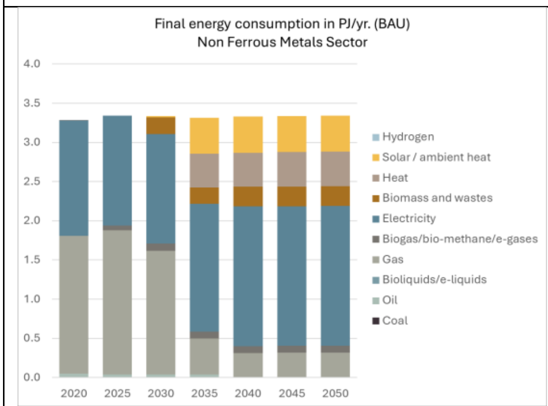


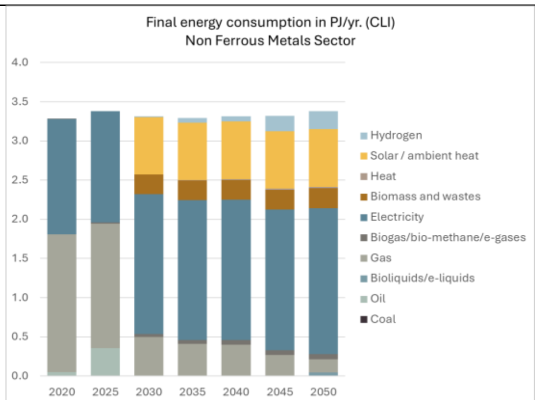




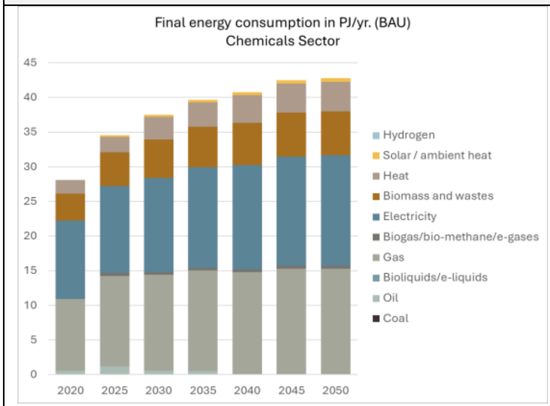


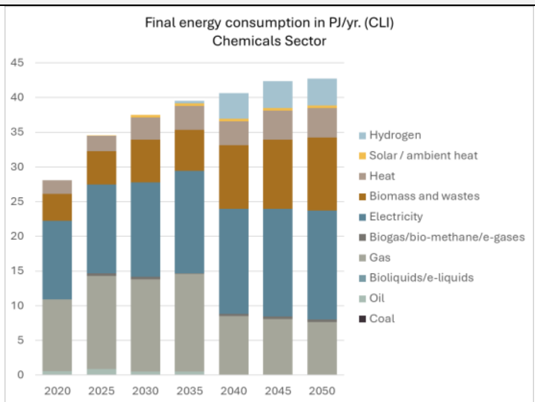


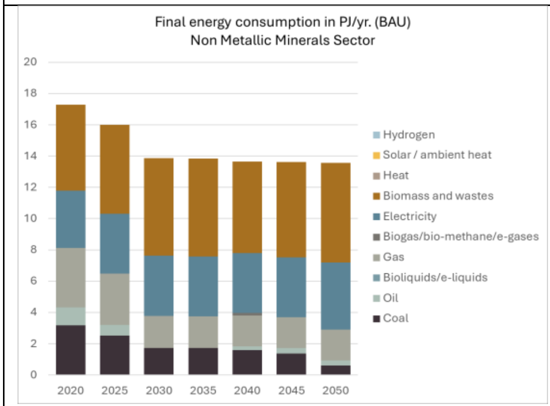


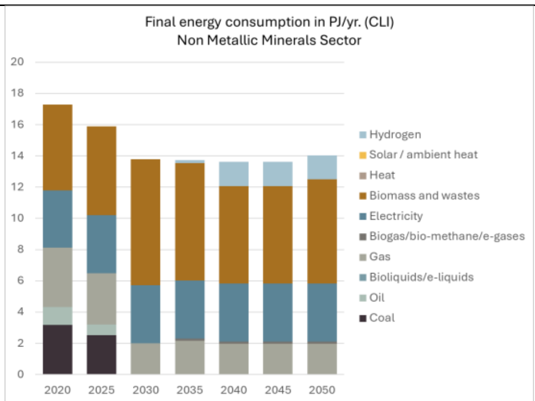


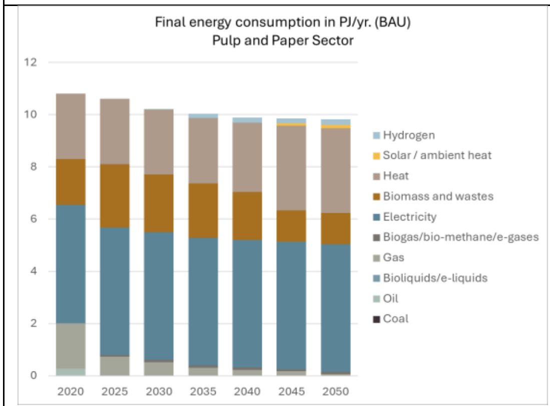
BAU Scenario	CLI Scenario

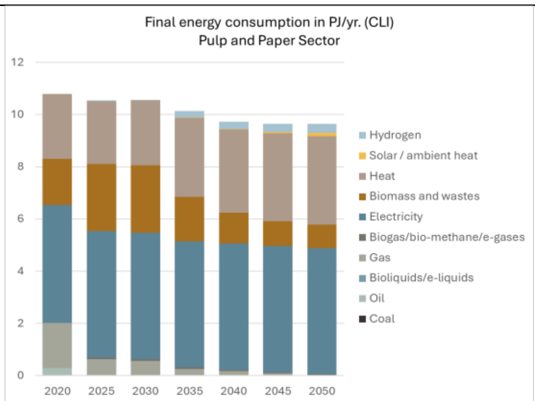


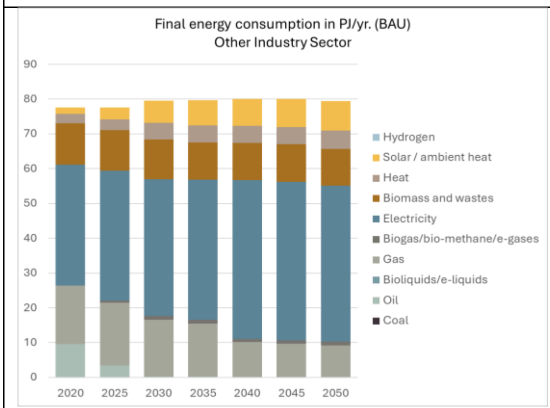


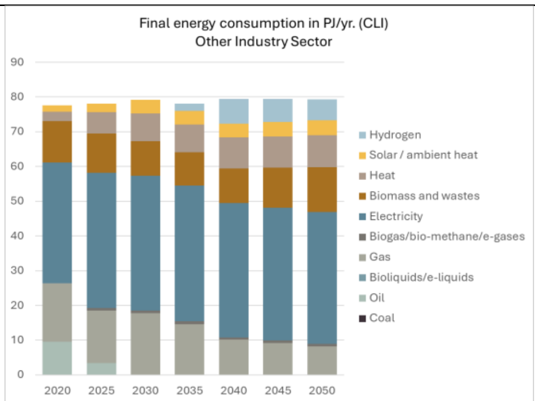












8.8 Investment, construction times and decommissioning in JRC-EU-TIMES

The TIMES framework includes a number of innovations compared to those of more traditional energy models. The objective function of the model is a discounted sum of net annual costs (costs minus revenues), including those incurred after the end of horizon (e.g., salvage values). The model uses a general discount rate, as well as technology specific discount rates. The general discount rate is used to discount fixed and variable operating costs, as well as investment cost payments from the point of time when the investment actually occurs to the base year of the present value of the total system cost. The technology specific discount rate is used to calculate the annual payments resulting from a lump-sum investment in some year.

The investment costs specified in the model are overnight costs, excluding interests paid during construction whenever a construction lead time is explicitly modelled. In such cases, the interests during construction are endogenously calculated by the model. If no lead-in time is specified then the full cost of investment should be used as technology cost, i.e., including interests during construction. Each individual investment physically occurring in a year results in a stream of annual payments spread over several years in the future, depending on the lifetime of the technology. Each stream is equal to the investment cost multiplied by the capital recovery factor. In addition to spreading the investments, TIMES assumes that a physical investment does not occur in a single year but as a series of annual increments. For instance, if the model invests 3 GW of electric capacity from 2030 to 2035, the physical capacity increase may be delayed or spread over several years.

When a technology reaches the end of its lifetime, it can be either decommissioned, extended or retrofitted. When it is decommissioned, decommissioning costs are paid, while any revenues from commodities and materials released during the decommissioning are also accounted for in the objective function. Lifetime extensions and retrofitting can occur after the end of the lifetime of a technology and come at an additional cost. In addition, the model allows a technology to be decommissioned before the end of its lifetime, if continuing to operate this technology proves to be more expensive than investing in and operating a new one.

JRC-EU-TIMES includes different assumptions for the construction times of energy infrastructure projects. These times represent the period from the investment decision until the technology is fully operational and can also refer to permitting or licensing times, as well as other delays that might be experienced in realising energy infrastructure investments. During the period specified by these lead-in times, the interest rate payments are accounted for in the objective function of the model. Table 17 summarises the assumptions for key energy infrastructure and energy technologies in supply and demand that are considered as lead-in times in the current version of the JRC-EU-TIMES model.

Table 17: Assumed construction times, or lead-in times from the moment that an investment decision was made until the technology investment is fully operational

Technology	Construction time
Hydrogen pipleines	5 to 7 years depending if it is transmission or distribution pipeline
Wind turbines	5 years (EU-average) to 15 years (for CH),- when implementing the Wind Express policies, the average time in the EU drops to 2 years , while in CH it drops to 3 years
Geothermal electric	5 to 7 years
New nuclear	12 years
Electricity grid new lines	10 years
Thermal power plants	1 year (gas turbine open cycle), 3 years (bioenergy and gas combined cycle), 5 years (other thermal)
CCS pipelines	5 to 7 years depending if it is transmission or distribution pipeline
Gas pipelines	5 to 7 years depending if it is transmission or distribution pipeline
CCS technologies	5 to 7 years
CO2 sequestration sites	10 years
Industrial processes	1-3 years depending on the sector and process
District heating grids	5 to 7 years
Building heating techs	1 to 2 years (for projects requiring geothermal energy, e.g., ground source heat pumps)

8.9 Additional insights from the Topic Modelling and the assessment of the positions papers of stakeholders

The application of Topic Modelling highlighted the under-representation and asymmetric impacts on diverse social groups in energy and climate policymaking, emphasising the need for inclusive stakeholder engagement. By applying Latent Dirichlet Allocation (LDA) topic modelling to position papers from the consultation phases of the Swiss Energy Law 2020 and CO_2 Act 2021, we provided a novel, data-driven approach to disaggregate stakeholder perspectives. The methodology enables the identification of common and contrasting policy interests, clustering stakeholders into distinct groups based on their priorities.

The main findings from Topic Modelling application in POLIZERO reveal three primary energy policy priorities—environmental protection, subsidies for winter base-load supply, and market-based measures for renewable energy—alongside five key climate policy concerns, including strong climate mitigation, international standard alignment, and sectoral taxation. The analysis also underscores differences in the two types of policies, market-driven mechanisms were favoured for energy policy-making, while climate policy priorities are more varied. These insights highlight critical trade-offs in decarbonisation strategies, particularly the tension between renewable energy expansion and biodiversity and heritage preservation. Additionally, financial incentives, such as subsidies and tax relief, emerge as preferred mechanisms for promoting energy efficiency in the residential sector.

Beyond its empirical contributions, POLIZERO advanced the methodological integration of topic modelling into stakeholder analysis. Compared to traditional survey-based approaches, our method offers greater scalability and efficiency in capturing stakeholder positions. However, some limitations should be acknowledged. Participation in policy consultations is voluntary, and the time and resources required to produce position papers may result in the under-representation of certain stakeholders, particularly those with fewer institutional resources. Additionally, while our findings provide valuable insights into stakeholder interests in Switzerland, their applicability to other countries is limited by differences in political structures and policy processes. Despite these limitations, the versatility of our methodology allows for application beyond Swiss position papers, utilising sources such as parliamentary debates, federal council reports, social media, and lobbying publications.

8.10 Methodology for policy pathways generation with AIM

The generation of policy pathways in POLIZERO is created based on the simulations of JRC-EU-TIMES for individual policy packages implementation and the Swiss targets that need to be achieved by the policy pathways. Let's assume three policy packages which are implemented constantly from 2025 until 2050 in the JRC-EU-TIMES, and the target is to reach zero in 2050 (arbitrary measurement unit). Each policy package has its own outcome trajectory Figure 39. For example, PP1 overperforms after 2040, PP2 nearly reaches the target, while PP3 underperforms.

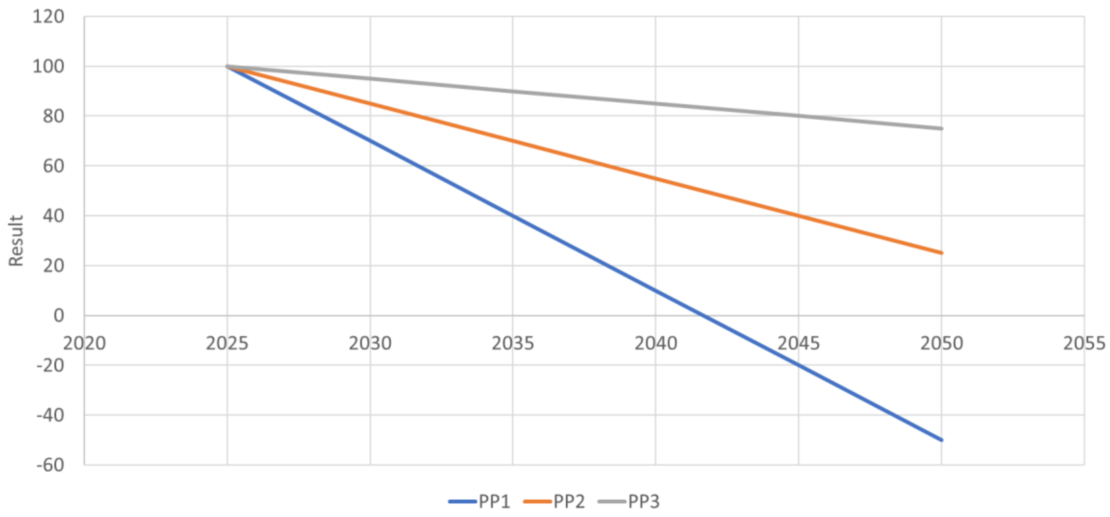


Figure 39. Individual policy packages simulations in JRC-EU TIMES

With AIM, policy package implementation sequences (or policy pathways) can be generated, checking if the desired zero result can be asymptotically reached. First, the user of AIM chooses the sequence of policy packages to be implemented and their duration. Then, the respective outcome segments derived from the JRC-EU-TIMES simulations are filtered as shown in Figure 40.

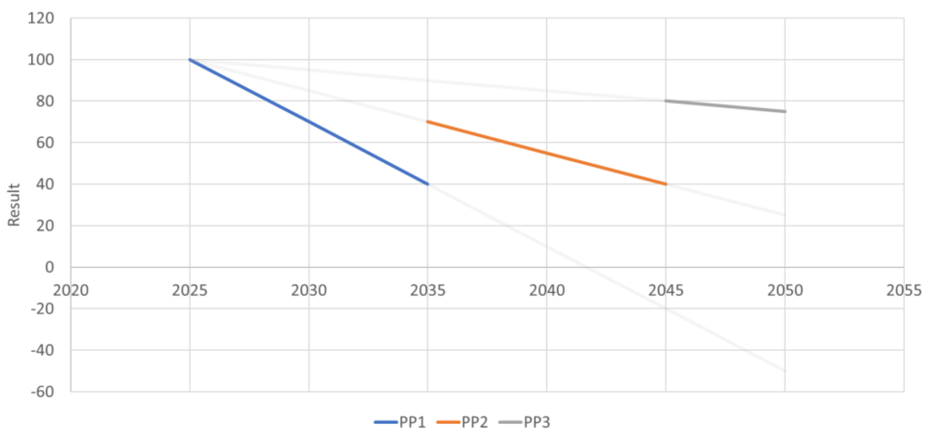


Figure 40. Filtering of selected results from the JRC-EU TIMES

Then, AIM generates the final pathway by adding the outcome of the next policy to the outcome achieved by the previously implemented policies, as shown in Figure 41. At this point, fine-tuning and deepening into this pathway is feasible with AIM, leading, for example, to the final result being closer to the zero target. However, it should be noted here that the linear and additive property of the policy impact that AIM assumes neglects spillovers between policies in the same sector and spillovers between policies in different sectors. These policy interactions can lessen the impacts of individual policies while entailing non-linearities regarding the policy impacts.

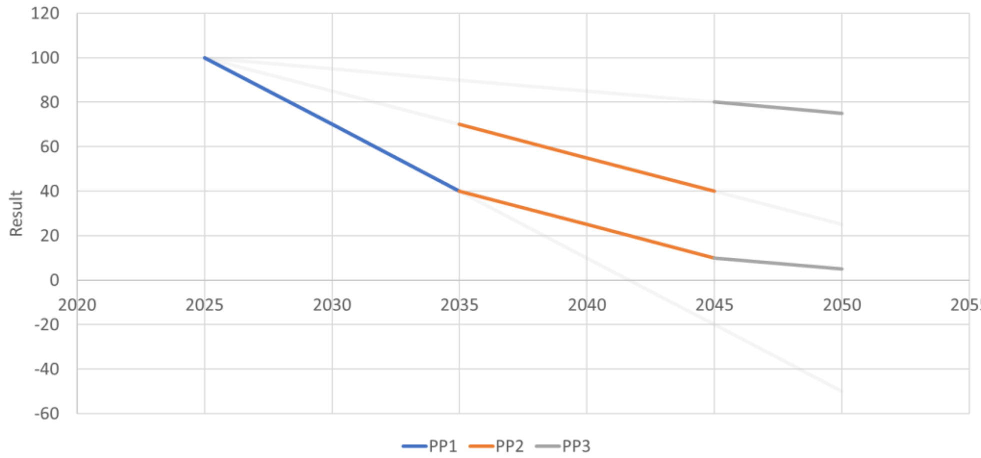


Figure 41. Final pathway generated by AIM

With this example, it is obvious that the development of pathways in AIM can consider time-wise intermediate targets' achievement, as the pathway is being developed by the user. Therefore, each target milestone can serve as the basis for developing shorter policy pathways until the milestone year, setting the initial conditions for the exploratory analysis of longer pathways. Finally, when multiple targets are imposed in parallel, policy pathways are generated respecting as many targets as possible at the same time. If not all targets can be achieved with any of the policy pathways that can be explored, pathways can be generated, sacrificing slightly the achievement of one or more targets, resulting in a group of non-improving policy pathways without sacrificing at least one target.

9 Data management plan and open access/data/model strategy

POLIZERO produced a policy inventory and developed further the JRC-EU-TIMES and AIM model. All outputs are open-source and publicly accessible:

- The POLIZERO policy inventory can already be downloaded from the POLIZERO website
- A Github repository[29] for the enhanced version of the JRC-EU-TIMES
- The source code of AIM is published on GitHub[30] and is free for use under the GNU General Public License v3.0. The open-source version of AIM includes all the updates made during POLIZERO.
- EXCEL files with all the key assumptions and results accompanies the current report[31].

[29] https://gitea.psi.ch/POLIZERO/JRC-EU-TIMES
[30] https://github.com/TEESlab-UPRC/AIM
[31] https://doi.org/10.5281/zenodo.16759092