A quick end to Swiss greenhouse gas emissions

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Principal Investigator: Prof. Anthony Patt,
Climate Policy Lab, ETH Department of Environmental Systems Science
and ETH Energy Science Center

Contributors to the work: Nicoletta Brazolla, Stefan Pfenninger, Bryn Pickering and Jan Wohland (ETH Climate Policy Lab); Jared Garrison and Marius Schwarz (ETH Energy Science Center)

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Executive Summary

1. This project aimed to examine the economic and social consequences for Switzerland, by the time-period 2040 – 50, of achieving climate neutrality. While an increasing number of studies have focused on this question in general, in this project we have focused on two narrow questions.

2. The first question concerns the extent to which behavioural changes – in particular a shift to more plant-based diets and a major reduction in air travel – will ease the economic burden of achieving climate neutrality.

3. A shift towards plant-based diets would alleviate a substantial need for CO_2 removal (CDR) needed to offset the effects of rising meat consumption while achieving climate neutrality. The associated cost savings would correspond to 10 – 20% of the money that Swiss consumers currently spend on beef and dairy products, which we view as significant, but necessarily a game changer. At the global level, however, the associated CDR costs savings would be far higher, up to 100% of the money that is spent on beef. At the global level, the development of plant-based alternatives to meat, which are attractive to consumers, could be a game changer in helping to achieve climate neutrality.

4. A shift towards markedly reduced air travel would alleviate the need for CDR to offset the non-CO_2 emissions from aviation that contribute to global warming, even if there were a complete shift to carbon-neutral fuels. The associated cost savings would correspond to 10 – 15% of the money likely to be spent on aviation by 2050, if there is not a decline in air travel demand. This is significant, but not necessarily a game changer.

5. The second question concerns the extent to which an effort to achieve self-sufficiency in Swiss electricity supply could affect the costs or feasibility of decarbonisation.

6. Compared to a Swiss power system that continues to be integrated into Europe, and where net imports are possible, the shift to self-sufficiency on annual basis would add less than 10% to the cost of electricity, thereby imposing only a small economic penalty. It may, however, require substantial development of solar PV generating capacity, requiring the shift from purely rooftop PV to both rooftop and ground mounted systems.

7. Compared to a well-integrated Swiss power system, a reduction in net transfer capacity with neighbouring countries would impose a small cost penalty, but would require the development of either wind or natural-gas power generation, the latter with carbon capture and storage.

8. Achieving complete electricity autarchy would impose a larger cost penalty, adding roughly 40% to the cost of power relative to a well-integrated Swiss system. It would also require a substantial development of wind energy in Switzerland, comprising several thousand new wind turbines. Achieving this would likely require a revision to the procedures for wind power siting and permitting.

9. Across all scenarios, the overall economic effects of a shift towards a carbon-neutral energy system are likely to be positive, lowering average energy costs and resulting in greater economic growth.

1 Introduction

This project has generated insights into the economics and feasibility of aggressive climate policy, in Switzerland and abroad. We focus on a set of questions that are of high political relevance, and which previous studies have ignored.

Switzerland, along with most wealthy countries, has adopted a target of achieving climate neutrality by 2050 or earlier. Numerous studies have generated scenarios showing how this can be accomplished, and many of these indicate costs estimates for following the least-cost pathway, assumed to be the pathway that policy-makers will follow. In most cases, the aggregate economic effects of achieving climate neutrality have been found to be small, but depending on the particular sets of behavioural and technological assumptions, the results have ranged from showing a small burden on the economy – reducing economic growth by less than one-tenth of one percent per year – to showing small economic boost: lowering the costs of providing energy and energy services by up to 20%, and in turn contributing to slightly faster economic growth.

A common result of all such previous studies is that it is cost-effective to end the burning of fossil fuels, and hence bring CO_2 emissions from energy consumption to zero, rather than offsetting energy-sector emissions. In this project, our aim is to examine the effects of other choices on the costs of climate neutrality. First, we examine the role of behavioural changes that affect emissions other than energy-sector CO_2 emissions. We focus on two sets of behaviour: meat consumption (which results in emissions of methane, CH_4, which is a serious greenhouse gas, GHG), and non-electric flying (which results in emissions of high-altitude water and particulate matter, which combine to cause cloud formation, having s significant warming effect). Such behavioural changes are of global concern, but especially relevant politically in Switzerland. Meat and dairy consumption in Switzerland is higher than the global average, and plays a strong role in Swiss culture. Likewise, Swiss people fly a lot, far more than the global average, and the Swiss tourism sector depends on aviation.

Second, we examine the costs associated with choices as to Switzerland's energy independence. The politics, and popular conception, of Swiss energy supply differ sharply between fuels and electricity. Switzerland has no fossil fuel reserves, and so imports all of its fossil fuels, which constitute the majority of its primary energy supply. This is viewed as normal, and prior to the Russia-Ukraine war was not perceived as compromising Swiss energy security. In the case of electricity, by contrast, Switzerland has historically generated about as much electricity as it consumes, although it both imports and exports electricity depending on time of year and of day. This self-sufficiency is also seen as normal, and a shift towards being a net importer is viewed by many as compromising Swiss energy security. Moreover, international trade in electricity involves the utilization of transmission lines lying outside of Switzerland and inside neighbouring countries, all of which are EU members.

Recent EU legislation places restrictions on the utilization of transmission lines to transmit power to countries that do not belong to the EU or have negotiated special membership in the

EU Energy Union, which Switzerland has not. Thus, there are fears that reliance on importing power from EU countries, even if these imports are matched by exports at other times, would compromise Swiss energy security. These perceptions and fears associated with Swiss self-sufficiency and import dependency with respect to electricity are particularly relevant for the issue of decarbonization, because it is clear that electricity will replace fossil fuels as the primary energy carrier. It is also the case that Swiss renewable energy production is tilted towards production from hydropower and solar, in summer months, leaving a potential shortfall in winter. The development of Swiss renewable energy sources will need to look very different, depending on whether Switzerland can continue to import power in the winter. In this study, we examine the burden of this.

2 Effects of behavioural change or its absence

In the first part of this project, we have examined the effects of Swiss society failing to change its consumption in climate-friendly ways. We see this as politically relevant, because there is a strong political discourse that such behavioural change is not only desirable but also necessary for climate protection goals to be met. At the same time, a common argument against Switzerland taking strong climate action is that this would require us to change our behaviour in undesirable ways; why should we do this, when other countries are not changing their behaviour, and when our own contribution to the greenhouse effect is so small, relative to the rest of the world?

One assumption in this project – which we view as well-founded because it is a common result across integrated assessment modelling – is that all cost-effective pathways to achieve climate neutrality involve ending the use of fossil fuels, and replacing these with carbon neutral energy sources, such as wind and solar power. It is clear that if the energy supply is carbon neutral, then CO_2 emissions from energy use will be completely decoupled from the quantity of energy being used. In this sense, behavioural change with respect to energy usage will have no direct effect on emissions, although of course a reduction in energy demand could make it more feasible, sooner, to provide the renewable energy needed to phase out all fossil fuels. This latter set of interactions is not well understood, and their further investigation lies outside the scope of this project.

Rather, we concentrate on two behavioural patterns that lead to substantial emissions even if the entire energy sector has shifted to carbon neutral energy sources. The first of these is agriculture, which independent of the energy used (for example, for tractors) results in large amounts of non-CO_2 GHG emissions. The second is aviation, which under the most promising pathway for decarbonization – the shift to carbon-neutral fuels – still generates large amounts of non-CO_2 emissions leading to warming.

In both cases, we frame our analysis in terms of calculating the cost of offsetting the non-CO_2 emissions, comparing the costs under conditions of a continuation of current consumption trends with that of large demand reduction. This then yields the additional cost to society of achieving climate neutrality in the absence of behavioural change, or the cost reductions that behavioural change would imply. The project team member working primarily on these questions has been Nicoletta Brazzola, with support from Jan Wohland, within the Climate Policy Lab.

2.1 Agriculture

Agriculture generates a significant portion of current Swiss GHG emissions, and these are divided between CO_2 emissions associated with energy use, N_2O associated with fertilizer use, and CH_4 associated with animal raising, primarily cattle for beef and milk production. For this study we have not focused on N_2O, and assumed that CO_2 will decline through changes to energy supply, and instead have focused primarily on CH_4, which other than CO_2 is the main contributor towards the greenhouse effect. CH_4 is a short-lived GHG, meaning that its effects on the climate are not proportional to total emissions over time, but rather to their rate.

Swiss meat consumption is currently declining, having fallen from 64.4 kg per person in 1980 to 47.3 kg per person in 2020.[1] At the same time, it is above the global average, which is currently 41.3 kg per person.[2] This then poses an ethical question that science cannot answer: can Swiss meat consumption be considered to be climate neutral because it is declining, or should it be viewed as a disproportionately large part of a global agricultural system, in which CH_4 emissions are rising? In the former case, no further analysis is needed. For the latter, however, analysis would be needed to understand the challenge of reaching climate neutrality. Moreover, there has not been a prior study examining the issue in a global context. We have thus analysed the issue in a global context, the paper we have published can be read at this link. (NB: Annex A contains references to all papers from this project.)

We employed a global climate model, allowing us to hold temperature changes to those associated with the Intergovernmental Panel on Climate Change (IPCC) RCP 2.6 scenario, which is consistent with current climate targets, by offsetting CH_4 emissions with direct air capture and storage of CO_2 (DACCS). The reason for choosing DACCS as the offsetting method is that it is the only option for carbon dioxide removal (CDR) that appears to be virtually unlimited in the total volume that could be deployed. DACCS currently costs roughly \$500 per ton CO2, making it far more expensive than other options such as afforestation. Its costs are projected to decline significantly; here, we have assumed a cost of \$200 per ton CO_2 for our central estimate, and generated uncertainty estimates based on range of values from \$100 – 400 per ton CO_2.

The IPCC scenario assumes that agricultural CH_4 emissions would decline between now and 2050, implying a significant behavioural change. We have analysed the quantities and costs of DACCS under scenarios of constant (rather than declining) agricultural CH_4 emissions, as well as a continuation of current trends, namely rising emissions. Constant CH_4 emissions

[1] Statista 2022. Accessed September 2022.
[2] Ibid.

would imply moderate behavioural change, insofar as people fail depart from the historical trend of rising income levels leading to rising meat consumption, even if any given individual would not consume more meat than in the past. The rising meat consumption scenario would imply no behavioural change.

The key result from this work compares the global costs of DACCS needed for offsetting to the quantities of beef, milk, and rice consumed. These can be seen in Figure 1. In the case of beef consumption, the costs of offsetting would be \$2.50 / kg of beef consumed (confidence range: \$0.50 – 4.00) in the constant consumption scenario, and \$5.00 / kg of beef consumed (confidence range: \$1.50 – 7.00) in the rising consumption scenario. Our confidence range incorporates uncertainties with respect to DACCS costs, as well as with respect to CH_4 emissions per unit of agricultural production. The costs would be roughly half as high per kg of milk consumed, and 40% as high per kg of rice consumed. Figure 1 also scales these costs to current commodity prices globally and in the United States, in terms of the percentage price increase for beef, milk, and rice needed to pay for required DACCS offsetting. As food prices in Switzerland are roughly twice those in the United States, the relative price difference for Swiss consumers would be roughly half those shown for the United States. Thus in Switzerland, the price of both beef and milk would have to rise by roughly 10% in the *constant* scenario, and 20% in the *worst-case* scenario. There are, however, wide ranges of uncertainty around these estimates.

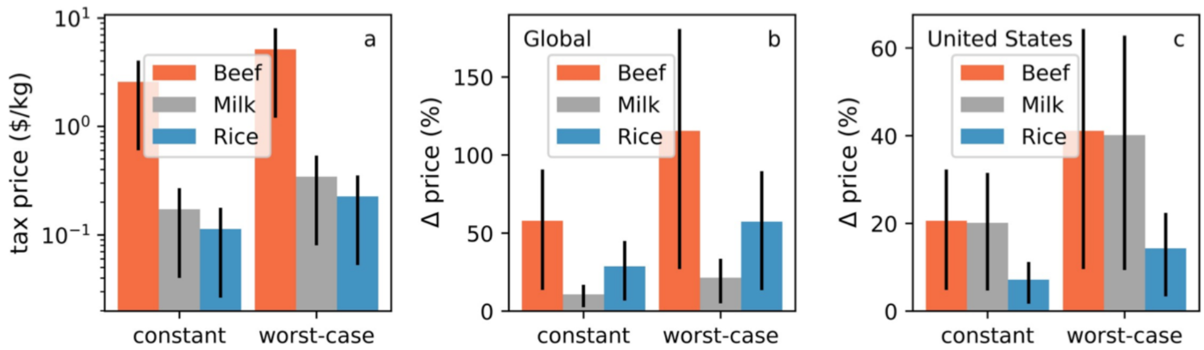

Figure 1: Cost estimates for DACCS offsetting to bring the climate effects of agricultural CH4 emissions in line with those estimated in the IPCC RPC2.6 scenario. The *constant* scenario assumes no further changes in global agricultural CH4 emissions, whereas the *worst-case* scenario assumes these emissions to continue rising at their current rate. Panel (a) scales these costs to the quantities consumed. Panels (b) and (c) scale these to current prices for beef, milk, and rice globally and in the US. Source: Brazzola et al. (2021)

For Swiss consumers, a 10% or even 20% increase in the price of beef and milk may well be politically and socially acceptable. It is less, for example, than the cost difference associated with organic products, which a large segment of the Swiss population consumes. In the global context, however, it is more difficult to imagine policies potentially doubling the prices of these commodities to be politically feasible. That suggests that climate neutrality will in fact depend on major behavioural changes, reducing meat consumption. In turn, the development of attractive meat substitutes, as is beginning to take place, may be a critical technological advancement for the coming decades.

2.2 Aviation

As with agriculture, aviation both accounts for a large share of Swiss GHG emissions, and these are divided between CO_2 and shorter-lived gases. Unlike agriculture, emissions of both are related, as the latter are a product of burning hydrocarbon fuel at high altitude. The primary non-CO_2 forcer is the combination of soot – particulate matter – and water vapour, where the former provides the nucleus for water to condense into cirrus clouds behind the engines, known as contrails. Depending on atmospheric humidity levels, contrails can persist for many hours. While they can have a slight cooling effect during the day – because they reflect sunshine back out to space – their net effect is warming, as they also reflect outgoing longwave radiation back down to the Earth's surface. The uncertainty on their net effect is wide, but many estimates are that they have a net long-term warming effect comparable to that of the CO_2 created from burning the fossil jet fuel.

There are several options for decarbonizing aviation. Demand reduction and efficiency improvements both reduce fuel consumption, causing a drop in both CO_2 and non-CO_2 effects. Hybrid-electric propulsion systems would also lead to a decline in both sets of gases, while full electrification would lead to their complete elimination. There are smaller full-electric airplanes currently being developed, with ranges up to several hundred kilometres. Indeed one of these is planned for commercial operation, between Vancouver and Victoria, British Columbia, crossing a 60 km ocean straight. Analysts are sceptical, however, that full electric propulsion systems will be capable of powering long-haul flights before 2050, simply because the energy-to-weight ratio of batteries is so low. Another technology is the use of hydrogen as a fuel source, which has an energy-to-weight ratio better than that of fossil fuels. However, hydrogen is far less dense, meaning that planes would require a very large storage tank, necessitating their complete redesign. Hydrogen combustion generates more water than does kerosene combustion, per unit of energy, and while there would be no soot produced, their non-CO_2 effects could be large. As with electric planes, analysts are doubtful that hydrogen planes can be developed quickly enough to serve all long-haul flights prior to 2050.

The final option is use of carbon neutral "drop-in" fuels, called this because they can relatively easily substitute for some share of fossil kerosene, with no need for aircraft redesign. These can be both biogenic and non-biogenic, the latter known by their acronym RFNBO, renewable fuels not of biological origin. These can be manufactured at large scale, utilizing CO_2 captured from the air and water, with renewable energy. They burn more cleanly than fossil kerosene, having none of the impurities (so-called aromatics) that lead to much of the soot creation. This suggests that their non-CO_2 effects would be lower, one paper suggesting the non-CO_2 effects would be reduced by more than half. A final note on drop-in fuels is that they currently can only be dropped-in up to 50% of the total fuels. Current jet engines are tuned to run with some aromatics – which provide lubrication – and are only certified to operate on fuels containing 50% or more of the normal aromatic content. That means that to go to 100% drop-in fuels would require either a retuning of jet engines, or would require the active introduction of aromatics. The latter would, of course, negate some of the cleaner-burning benefits that drop-in fuels offer, compared to fossil fuels.

As with CH_4 and agriculture, the non-CO_2 effects of jet engine operation are short-lived. If planes were to stop flying today, there would be an immediate cooling effect, as the non-CO_2 warming effects would quickly vanish. This fact introduces complexity into any effort to analyse flying's being "climate neutral" rather than simply carbon neutral, because neutrality is by definition relative to something. One potential baseline is the climate effect of aviation prior to its becoming climate neutral: additional aviation would not result in any additional warming, from that point forward. That could happen, for example, if CO_2 emissions were eliminated through the use of RFNBOs, and the non-CO_2 effects were to remain constant. Another potential baseline would be a world without any aviation. Imagine that all planes stopped flying, the world cooled, and then flying started up again. In this case it could be climate neutral if the RFNBOs eliminated CO_2 emissions, and CO_2 removal (CDR) were employed to counteract the warming effects of the non-CO_2 emissions. So while the first standard implies, potentially, no offsetting, the latter standard would employ offsetting. And the latter standard would achieve a lower global temperature than the former.

In the work that we have done for this project, we have examined these issues. Essentially, examining how much CDR offsetting, at what cost, would be required to make flying climate neutral, under different assumptions of the baseline for neutrality, and different scenarios for how much we fly. Comparing scenarios where we continue to fly more with ones where we reduce flying, we can estimate the cost of failing to change behaviour. The paper we have published can be read at this link.

Figure 2 portrays a key set of results from the paper. It shows mean global CDR rates required to offset aviation – making it climate neutral – under a range of assumptions about levels of consumption, the baseline, and fuel type. Breaking these factors down, the left-hand side depicts results under SSP1-2.6, which is an IPCC social and economic scenario assuming the volume of flying declines substantially; the right-hand side depicts results under SSP5-8.5, which represents a continuation of current flying trends. Within each side, there are results for the "Gold" climate-neutrality baseline, which represents a world with no aviation, and the "Bronze" baselines, which represents a world with the level of aviation just prior to becoming climate neutral. The "Silver" baseline is in between the two, corresponding to a reduced level of flying. Finally, the dots represent point estimates for the amount of CDR required according to different fuels. CDR would be highest with continued use of fossil fuels, and zero or below for electrification. Values below zero, seen in some of the Bronze scenario results, suggest that even with no offsetting, there would be a net cooling due to the changes in aviation, meaning that positive CO_2 emissions would be allowable elsewhere in the economy.

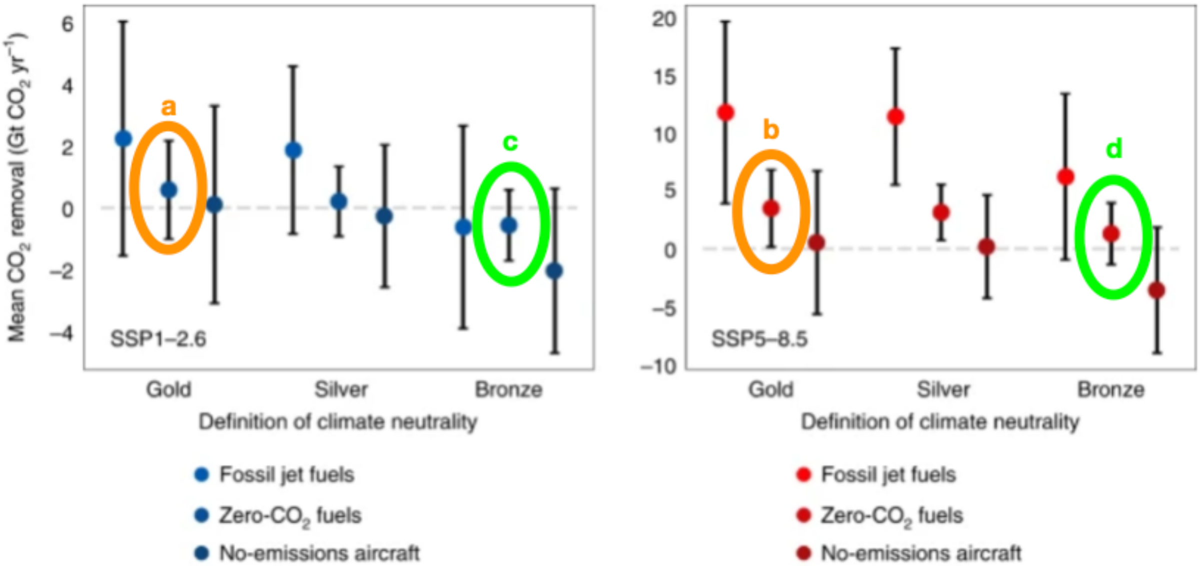

Figure 2: CO_2 removal estimates under different assumptions of aviation volume (the left-hand versus right-hand graphs), fuel use, and baseline for climate neutrality. Note that the vertical scales differ on the two graphs. Source: Brazzola et al. (2022)

To capture the cost difference associated with behavioural change or its absence, we can compare scenario results from the left-hand and right-hand graphs. For example, if we assume the compete use of CO_2-neutral crop in fuels, and take the most restrictive Gold baseline for climate neutrality, we can compare the CDR requirements labels (a) with those labelled (b). The central estimate for (a) depicts roughly 0.5 $GtCO_2$ removal per year, whereas for (b) it is roughly 3 $GtCO_2$, a difference of 2.5 $GtCO_2$ removal per year. Likewise points (c) and (d) represent results under the Bronze baseline, and in this case their difference is roughly 1.5 $GtCO_2$. Thus, depending on the baseline, we would require 1.5 – 2.5 $GtCO_2$ removal per year. Assuming a cost of $200 per ton of CDR, that translates into $300 – 500 billion per year. Global aviation revenues are currently about $900 billion, and in the no-behavioural-change scenario would rise to roughly $3 trillion. Hence the additional cost of CDR to achieve climate neutrality would add roughly 10 – 15% to the price of flying.

This additional cost to flying comes on top of the cost of switching to carbon neutral fuels. The future costs of these fuels are highly uncertain; estimate range from their achieving cost parity with fossil aviation fuels, to them remaining at least 200% more expensive. Work on this is underway, including in our own group. Our results here suggest that if such fuels do achieve cost parity with fossil fuels, then the total costs of achieving climate-neutral aviation are relatively small and affordable. If the costs of carbon neutral fuels remains high, then it will be these costs that will make climate neutral aviation rather unaffordable.

3 Effects of Swiss energy independence

The second major piece of work in this project has been to examine the consequences of choices with respect to Swiss energy independence. To a large extent, we focus on the electric power system, rather than fuels, as electricity is where perceptions of the link between energy independence and energy security in Switzerland are stronger. Past work undertaken in our group suggests a strong public perception that security is enhanced when Swiss reliance on electricity imports is reduced, contrasting with experts' perception that security is enhanced through international cooperation.[3] The issue is of high political importance. The current Swiss climate strategy, for example, contains the goal of Switzerland, by 2050, producing as much electricity as it uses, similar to today.[4] Between now and 2050, however, the strategy passes through periods – following the shut-down of nuclear reactors – of substantial net imports. These have been criticised by political parties as compromising Swiss security. Indeed this could be an issue, should the utilization of transmission capacity be reduced, as will happen if Switzerland fails to negotiate membership in the European Energy Union.[5]

We have divided our work between two modelling frameworks and teams. The first of these is the Calliope model, more information on which can be accessed at this link. The original developer of the Calliope modelling tool is Stefan Pfenninger, who at the beginning of this project was a member of the Climate Policy Lab at ETH. Others contributing to the development of Calliope, and partly funded by this project, were Tim Tröndle and Bryn Pickering, also in the Climate Policy Lab. The Calliope framework excels in terms of allowing energy modellers to incorporate high-resolution weather and climate data. This is especially relevant in predicting the output of an energy system with high reliance on wind and solar resources, both of which produce electricity at levels determined by the weather. We expect our electricity system to supply power at an amount that perfectly matches demand. It is also the case that storing electricity is difficult and expensive compared to storing the fossil fuels – coal and natural gas – traditionally burned to produce electricity. Hence, Calliope produces valuable results because it can discover the geographic distribution of solar and wind capacities that will satisfy consumer demand at all times, with as little reliance on storage as possible. Part of the work that this project funded was gathering and processing the data needed to calculate cost-effective deployment levels of wind and solar power throughout European countries, under various assumptions. These are then relevant for understanding the optimal deployment of wind and solar within Switzerland.

The second modelling framework is Nexus-E, more information on which can be accessed at this link. The Nexus-E model development has been a project of the ETH Energy Science Center, funded from numerous sources, including this project. The members of the Nexus-E team working primarily on this project have been Jared Garrison and Marius Schwarz. Nexus-E is, at its heart, a model of the Swiss power market. It allows the modeler to identify

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[3] Blumer et al. (2015) The precarious consensus on the importance of energy security: contrasting views of Swiss energy users and experts. *Renewable and Sustainable Energy Reviews* 52: 927 – 212.

[4] https://www.bafu.admin.ch/bafu/de/home/themen/klima/fachinformationen/emissionsverminderung/verminderungsziele/ziel-2050/klimastrategie-2050.html

[5] https://www.elcom.admin.ch/dam/elcom/en/dokumente/2021/kurzberichtnetzseitigemassnahmen.pdf.download.pdf/Kurzbericht%20Netzseitige%20Massnahmen%20für%20die%20Sicherstellung%20der%20kurz-%20und%20mittelfristigen%20Versorgungssicherheit%20und%20der%20Netzst

portfolios of energy supply options that result in the lowest total costs to consumers. As with Calliope, it takes as an input weather and climate data, although unlike Calliope these are limited to Switzerland, rather than extending to all of Europe. Given a portfolio of power production outside of Switzerland, however, it can calculate electricity trade between Switzerland and neighbouring countries, the market prices of electricity following current market design rules, and the utilization of transmission lines. The latter allows us to specifically focus in on the effects of a reduction in transmission line access caused by pending EU rules.

One shortfall of both modelling frameworks is that neither includes the option of solar PV panels mounted in high altitude regions, and oriented to maximize winter power production. This is a recent development in Swiss energy policy, post-dating the analysis that we present here.

3.1 Calliope modelling results

The initial work within the Calliope modelling team, partly funded by this project, was to program a model with European-wide data, needed to identify alternative pathways towards a completely decarbonized power system within Europe. Given the high costs of nuclear power, and the relative absence of new developments in Europe, we have assumed that renewable sources – primarily solar and wind – will constitute the entirety of new capacity additions.[6] The development of the Euro-Calliope model led to several published papers, examining different sets of issues, and both relevant for the decarbonization of Switzerland.

The first piece of work partly funded by this project examined the diversity of options for European power sector development. The full paper can be read at this link. In this case, we used the Calliope model not to choose the cost optimal option for Europe, as one typically does with energy system models, but rather to identify the full range of options for which the total costs are only slightly higher, and thus likely to be politically acceptable. For this analysis, we considered all options with costs no more than 10% higher than the cost optimal solution. In theory, there is an infinite number of such options available. We used Calliope to generate a set of 441 different options that are somewhat distinct from each other. We call these options SPORES, standing for spatially-explicit practically optimal results. Every SPORE is technically feasible, in that it supplies enough energy to satisfy consumer demand at all times. The SPORES reflect different choices and trade-offs across a wide range of issues. For example, Figure 3 shows a set of two SPORES that represent polar opposites in

[6] It is clear that if we were to have included the option for nuclear power, at its current investment costs, the model would have returned the result that no new plants would be built. This is partly due to its high costs. It is also due to its lack of flexibility throughout the year; in general, a portfolio of solar and wind, which are negatively correlated in terms of their output throughout the year, outperforms a portfolio of either solar and nuclear or wind and nuclear. If future nuclear power plant designs were to come to market that were much less expensive, and sufficiently so as to make their intermittent operation economically viable, then it would be important to include them in the modelling framework.

terms of the total energy use, which is influenced the amount of energy lost to storage and to curtailed capacity, i.e. simply not using solar or wind power when it is generated.

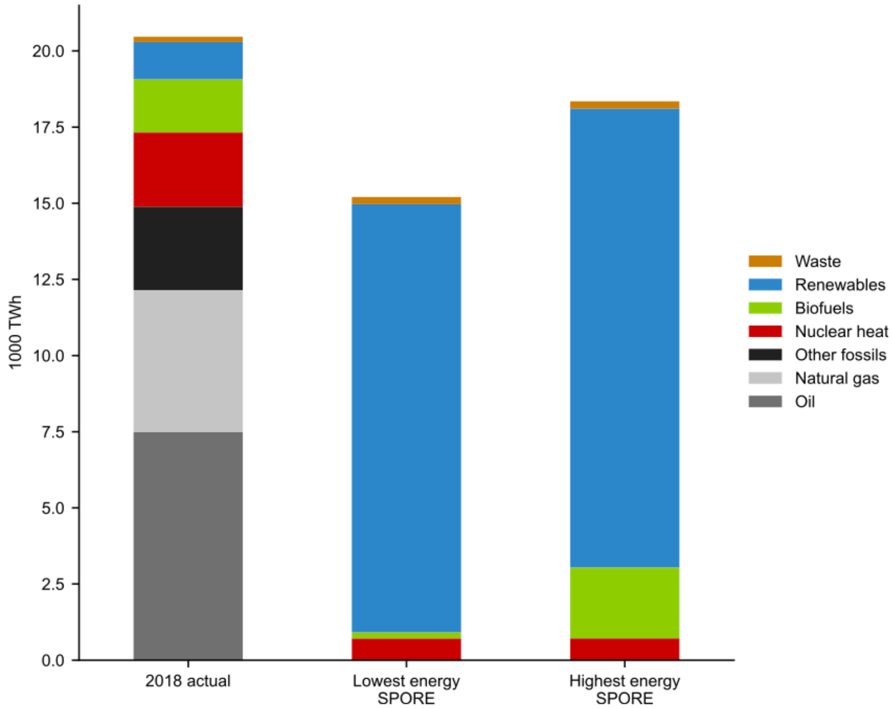

Figure 3: Alternative SPORES, compared to the current energy situation.
Source: Pickering et al. (2022)

The next piece of work, which can be read at this link, focused on the added costs of constraining power systems to operate the national or regional scale (the latter being the administrative unit below national, in the case of Switzerland this is cantonal), rather than having one unified system operating at the European scale. The first way of constraining systems is to require that each geographic unit to be self-sufficient over the course of an average year, producing as much power from renewable sources as it consumes. This would roughly match the current situation for Switzerland at the national level, where imports roughly equal exports. The second way of constraining systems is to require that they are self-sufficient at every moment, i.e. completely autarchic, with no transmission to neighbouring countries or regions. Calliope is able to compute the cost optimal energy mixes assuming different combinations of these constraints.

Figure 4 illustrates average results for the European geographic region encompassing the EU, Switzerland, the UK, and Norway. The least expensive option, averaged across Europe, is that in which both supply (i.e., annual self-sufficiency) and balancing (i.e., self-sufficiency at every moment) operate at the continental scale. This then becomes the baseline for comparing all other options. By contrast, if the supply scale becomes national but the balancing scale remains continental (as is currently the case for Switzerland), then the average costs across all countries rise 107% of the baseline. Moving from this case to one in which both supply and balancing operate at the national scale raises costs much more, up to 140% of the baseline costs. To understand the logic, this scenario would require the installation of generating capacities in places where they are not at all cost-effective, in order to maintain the adequacy of power supply, in all places and at all times. Moving from the national scale to the regional scale implies an additional cost penalty.

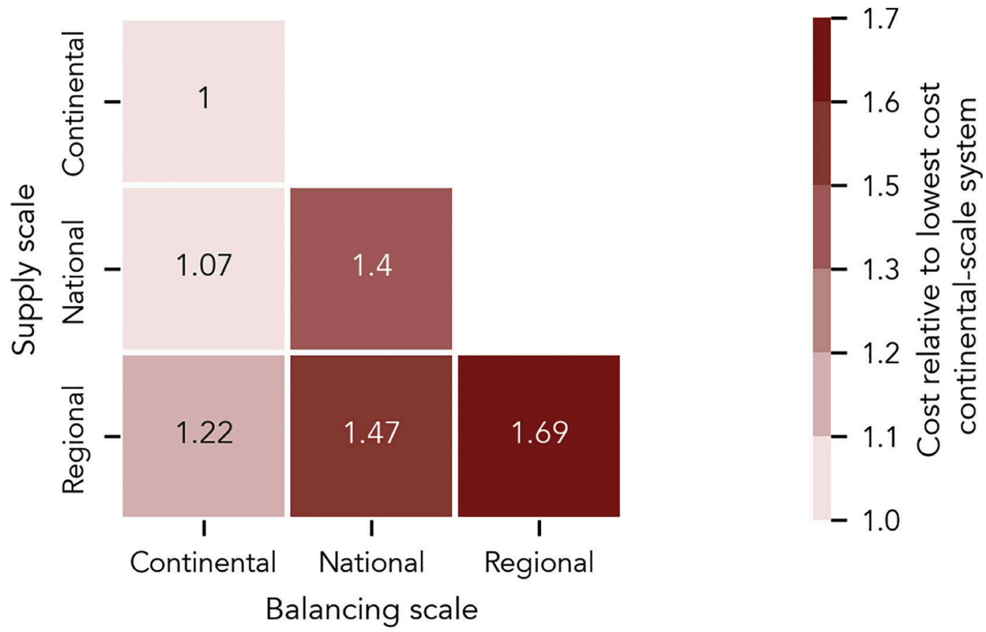

Figure 4: Relative costs of power systems throughout Europe being constrained to be self-sufficient at the national or regional scales. Source: Tröndle et al. (2020)

The results seen in Figure 4 are averages across Europe as a whole. In fact, Switzerland lies close to this European average, in both respects. To maintain Swiss self-sufficiency averaged over a year, i.e. continuing to have balancing trade, implies a small cost penalty on Swiss power consumers, less than 10% additional costs. Were Switzerland to move to complete autarchy, the cost penalty would be higher, roughly 40%.

Neither cost penalty would cripple the Swiss economy. Indeed, as we describe later, even the second option would likely be associated with an overall decline in Swiss energy costs from today, simply because an electrified energy system will be so much more efficient, and hence less expensive, than our current one relying on fossil fuels. However, there are marked differences between the domestic generation requirements under the three scenarios of full integration with Europe, self-sufficiency in terms of annual power production, and full autarchy. These differences in generation requirements could have important implications for their political feasibility.

Figure 5 shows the volumes of electricity consumed and produced under least-cost scenarios for 2040, on an annual basis, given alternative assumptions about Swiss self-sufficiency. Figure 6 shows monthly detail for two of the supply scenarios. The left-hand bar in Figure 5 shows power demand, assuming the complete switch of the vehicle fleet to electric drive trains, and the switch of heating systems primarily to heat pumps. The category “other” for demand corresponds to all current uses of electricity, such as lighting and cooling. Note that the demand shown in Figure 6 omits this demand, but only focuses on new demand types.

The *least-cost* supply scenario in both figures has no self-sufficiency constraints imposed, and indeed results in significant net imports of electricity, roughly 15% of total domestic consumption, as seen most clearly in Figure 5. Most of that imported energy is in winter months, as Figure 6 shows; it primarily derives from wind turbines in northern Europe and in the North Sea, which have their highest output in winter months. The *import = export* supply scenario imposes the constraint of annual self-sufficiency. As Figure 5 shows, it requires a substantially great solar PV capacity to be constructed in Switzerland. As Figure 6 shows, the primary difference is not the elimination of imports in winter months – although these are somewhat reduced due to the additional solar PV capacity – but rather an increase in exports during summer months. Finally, the autarchy scenario shown in Figure 5 has neither imports nor exports; the winter demand covered in second scenario with imports is now covered by a combination of energy storage and domestic wind production. It is noteworthy that storage results in significant losses of energy, which is why, in the autarchy scenario, annual energy supply exceeds annual energy demand.

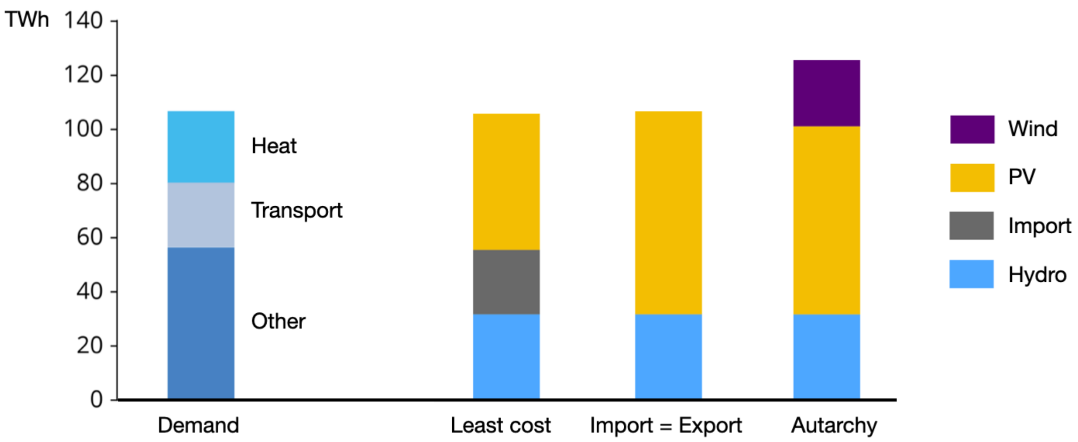

Figure 5: Power generation requirements to meet demand
under alternative energy independence assumptions

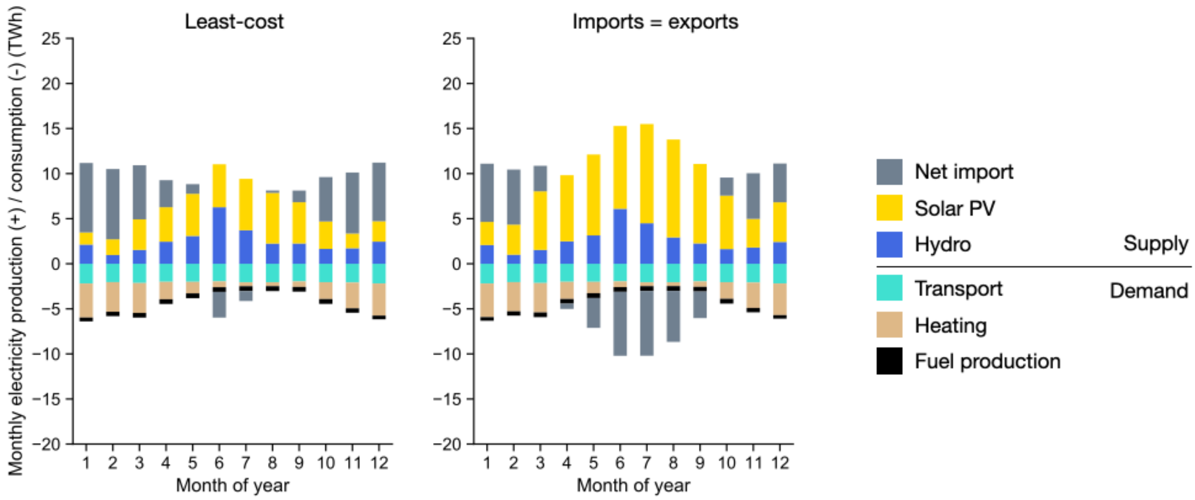

Figure 6: Monthly power sources of power supply,
as well as monthly demand from new areas.

It is worth comparing the solar and wind production levels seen in Figure 5 with current estimates for Swiss supply potentials. In the least-cost scenario, the Calliope model shows an annual solar production of roughly 45 TWh. This is higher than the 34 TWh in the current Swiss Climate Strategy published by the Swiss Federal Office of the Environment (FOEN). The primary reason for the difference is the assumption by the FOEN that road vehicle traffic will decline significantly by 2050; we see no evidence of this happen, given that Swiss road traffic has been increasing for the last 20 years, and no policies are currently being discussed that would change this. The FOEN study also assumes a greater increase in the efficiency of electrical appliances, and a marked reduction in heating demand. Again, our own numbers reflect current European trends in these areas. If 45 TWh is in fact required, then it is relevant that this roughly corresponds to the current estimate of the maximum energy production that all appropriately facing rooftops in Switzerland could provide.[7] Achieving this production level, if solar PV is coming only from rooftops, would almost certainly require a legal requirement to install PV on the full area of all appropriately facing roofs, new and existing. Moving to the annual self-sufficiency scenario, this requires an annual production of roughly 70 TWh. This greatly exceeds the production potential from the Swiss building sector, even if suboptimal roofs are covered in solar panels, and would hence require ground-mounted units. It is noteworthy that Switzerland is an outlier in Europe for its absence of ground mounted solar; across the EU, roughly 50% of the solar power currently produced derives from large – typically ground mounted – systems, rather than smaller rooftop systems on residential and commercial buildings.[8] The difference between the 45 TWh rooftop potential and the 70 TWh requirement is a shortfall of 25 TWh needing to be supplied by ground-mounted systems. Currently there is a proposal for a 2 TWh project in the community of Grengiols. To be self-sufficient, then, Switzerland would need at least 12 projects of this magnitude, in addition to a solar roof mandate. Finally, the autarchy scenario shows an annual wind power production of roughly 25 TWh. This is quite close to the estimate of the maximum wind power potential in the country, which is 29.5 TWh.[9] This would require as many as 6'000 new wind turbines; Switzerland currently has fewer than 50. It would be a substantial challenge, and almost certainly require a major change to the current permitting laws.

To summarize the Calliope modelling results, it is clear that there are multiple pathways forward for both Europe as a whole and Switzerland in particular to achieve a completely decarbonized energy system. In particular, we have focused on the implications of choices with respect to self-sufficiency of electric power production. The least-cost option for increasing electricity production to match new sources of demand would involve a large increase in PV production, at the scale of every available rooftop, combined with a modest level of net electricity imports. Achieving the current FOEN goal of annual self-sufficiency with respect to electricity would impose a small additional cost burden, less than 10% relative to the least-cost scenario. It would, however, require legislative changes allowing for large-

[7] https://www.zhaw.ch/storage/lsfm/institute-zentren/iunr/erneuerbare-energien/dokumente/solarenergie/schweizer-solarstrompotenzial-auf-daechern/photovoltaik-dachflaechenpotential-der-schweiz.pdf
[8] bit.ly/358hQHy
[9] https://www.admin.ch/gov/de/start/dokumentation/medienmitteilungen.msg-id-90116.html

scale development of ground-mounted PV systems. Finally, achieving a goal of complete electricity autarchy would require not only these steps, but also the development of close to the full Swiss wind capacity potential, representing many thousand wind turbines. This would almost certainly require a major change to the rules for permitting.

3.2 Nexus-E modelling results

While the Calliope models allows for the construction of European-wide electricity supply scenarios, on an hourly basis, the Nexus-E model provides a greater set of insights in the Swiss electricity market. We have taken the Calliope results for Europe as an input into the Nexus-E model, and then used these to calculate optimal Swiss renewable deployment, in order to minimize Swiss energy costs taking into account market prices. Because the Nexus-E model tracks market transactions, it can explicitly model the impacts of constraints on electricity transmission: we can move beyond the dichotomy between annual self-sufficiency and complete autarchy by imposing the finer grained constraint of a 70% reduction in net transfer capacity across the Swiss border, which is what the EU rules set to enter into force in 2025 would impose. Finally, with Nexus-E, we can calculate costs to Swiss consumers, taking into account the average costs of power produced in Switzerland, as well as the market prices for electricity imports and exports.

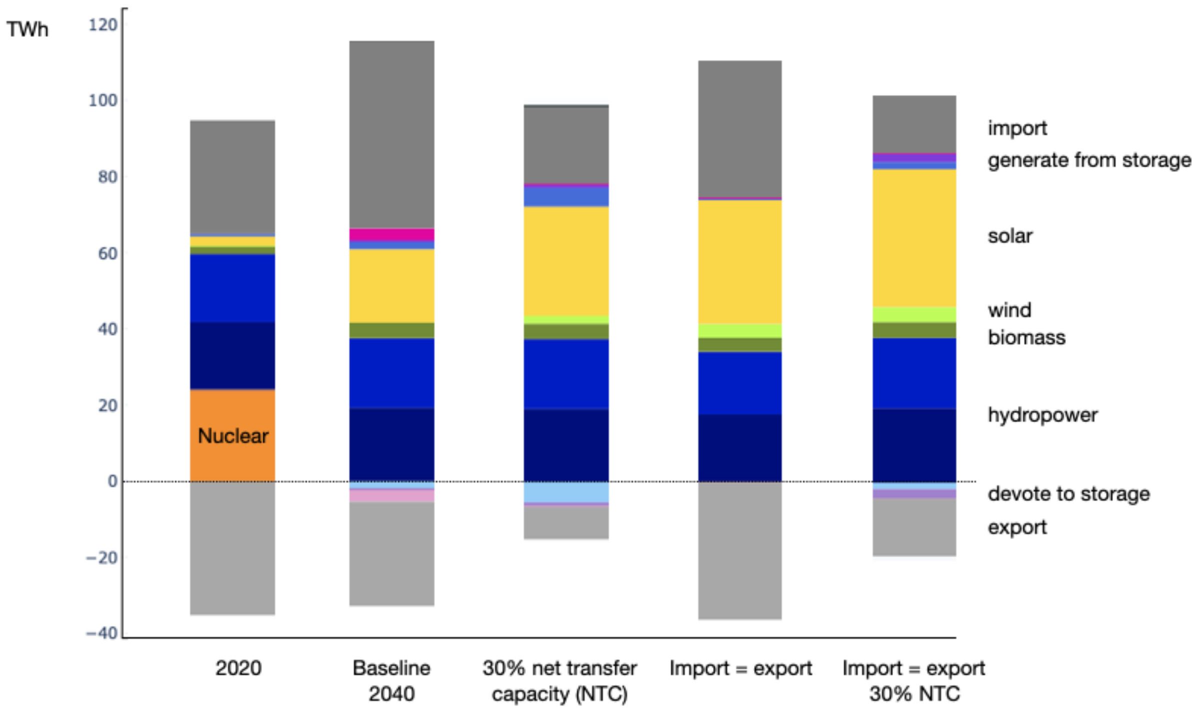

Figure 7: Electricity supply results from Nexus-E under alternative independence and transmission constraints.

Figure 7 shows the least-cost supply options for 2040 under alternative assumptions about Swiss self-sufficiency and net transfer capacity (NTC) availability. The baseline scenario allows for full utilization of current NTC, as well as allowing for net imports. It is important to note that it is based on a demand profile somewhat different than that used for the Calliope modelling, with less electrification for heating and mobility; hence, overall demand is assumed to be roughly 85 TWh annually in the Nexus-E model, compared to the 105 TWh in the Calliope model. This then gets reflected in the lower utilization of solar PV in the baseline scenario. In both cases, nearly all supply beyond that of hydropower is satisfied by solar PV, the Nexus-E results show 20 TWh per year being required, augmented by 5 TWh of biomass-based generation, compared to the 45 TWh estimated by Calliope. In the import = export scenario, the solar PV requirement rises to slightly more than 30 TWh, and the model also suggest some wind power being built in Switzerland. It is noteworthy that these results are quite close to the FOEN scenarios in terms of both solar and wind production, under a similar demand profile as well as the target for imports and exports to match. The scenario for 30% NTC (or, a 70% reduction in NTC), also sees 30 TWh of solar power, as well as greater use of storage. Finally, the scenario combining an import = export constraint as well as the 30% NTC differs in terms of requiring slightly more wind and solar. It is noteworthy that it departs substantially from the Calliope results suggesting the need for 70 TWh of solar and 25 TWh of wind production in the case of complete autarchy. Partly this is on account of the reduced demand assumption in the Nexus-E model, but it also can be traced to the significant difference between a major reduction in NTC and its complete elimination.

What can one learn from the differences between the two sets of results, those presented in Figure 5 and Figure 7? First, the amount of solar development hinges greatly on the extent of new power demand. Second, taking into account market prices, and not just overall systems costs, favours the development of a limited amount of wind power in Switzerland. Third, there is a marked difference between a 70% reduction in NTC and complete autarchy. With 30% of NTC remaining, Switzerland can avoid the need for the large amounts of wind power development that would be required under a situation of complete autarchy.

Figure 8 provides a closer view into the changing costs facing consumers. The left-hand side compares volumes of electricity produced domestically, as well as imports and exports, in 2020 with this in the baseline scenario for 2040. As can be seen domestic production remains quite similar, essentially with solar and biomass replacing the loss of nuclear, and net imports covering the rise in overall demand. The right-hand side examines the financial side, in terms of the money spent for domestic production and imports, as well as the revenues from exports. What we see is that the solar and biomass added to the system, while similar in overall energy magnitude to the nuclear that is lost, come at a much lower cost. These cost differences exist not just in Switzerland: on an energy basis, electricity imports would rise by roughly 50% between 2020 and 2040, and yet the cost of those imports would stay roughly constant. Similarly, the energy volume of exports would decline only slightly, but the revenues from those exports would decline by 50%.

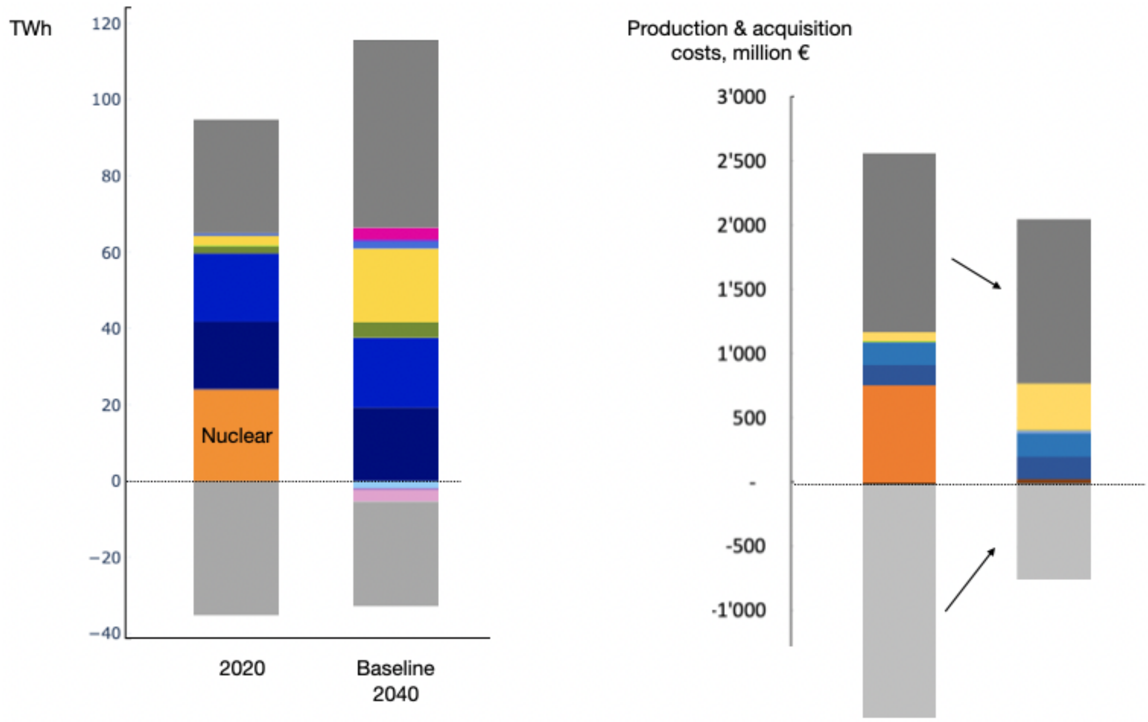

Figure 8: Comparing energy quantities with costs in the 2020 and 2040 baseline scenarios

Comparing the net cost of electricity seen in Figure 8 – domestic production plus imports minus exports – we see an increase from 2020 to 2040 of roughly CHF 500 million. We have not done a formal analysis, but a back of the envelope calculation suggests a major net benefit to the Swiss economy. While the cost of electricity will have risen by CHF 500 million, electricity will have replaced roughly 60% of the fossil fuels currently imported, which comprise 10 million tons of refined oil products and 120 thousand terajoules of gas.[10] Given pre-Ukraine war market prices, current fossil energy imports represent an expenditure of roughly CHF 7 billion annually.[11] This would thus decline by 60%, a savings of CHF 4.2 billion annually. Of the CHF 7 billion currently spent for fossil fuels, roughly 20%, or CHF 1.4 billion, is for fuels used for aviation and high temperature industrial heating applications. These would not be electrified, but rather replaced with carbon-neutral synthetic fuels. If one assumes that by 2040 these fuels cost twice those of current fossil fuels, this would represent an additional outlay of CHF 1.4 billion. The net savings exceeds CHF 2.3 billion per year, or CHF 230 per person assuming a Swiss population of 10 million in 2040. Even given a 40% cost penalty on electricity, in the case of Swiss electricity autarchy, the net benefits would exceed CHF 2 billion annually, or CHF 200 per capita. Obviously these calculations are exceedingly crude. They do, however, provide an indication that the switch to carbon neutrality, if not climate neutrality, could create an overall economic benefit. Qualitatively, these are similar to recent findings in the peer-reviewed literature examining the global

[10] https://www.bfs.admin.ch/bfs/de/home/statistiken/energie.html
[11] As market prices, we assume CHF 600 per ton of refined oil products, and CHF 9,500 per Terajoule of natural gas.

economy.[12] That study, from a team at Oxford University, found energy costs to decline by 20% by 2040 in a decarbonization scenario compared to business as usual. That is similar in magnitude to the effect for Switzerland that we find here.

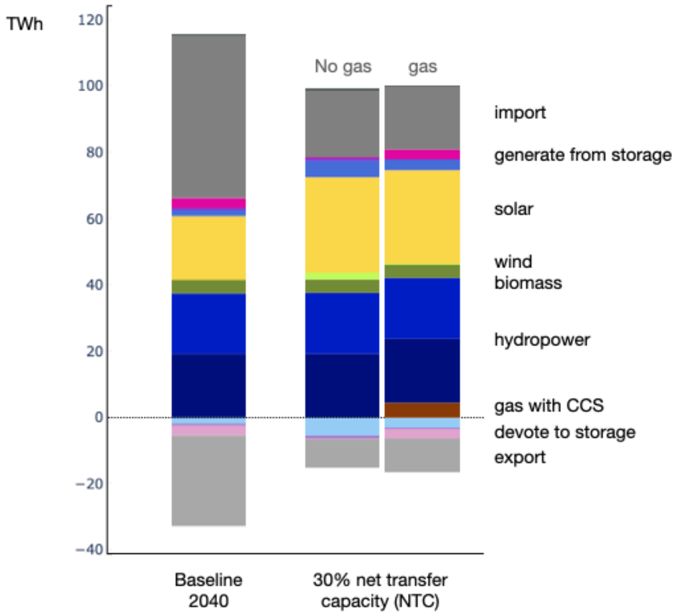

Figure 9: Gas utilization in the 30% NTC scenario

The final piece of analysis that we have conducted with the Nexus-E model is to examine the implications of utilizing natural gas for emergency peak power production. This reflects a recent decision of the Bundesrat, as a stopgap measure to cover possible winter shortfalls in electricity in the case of a 70% reduction in NTC. Figure 9 shows these results. In the baseline scenario for 2040, allowing the possibility of electricity production from natural gas (satisfying a carbon constraint by stipulating the use of carbon capture and storage, CCS) does not result in any change: utilizing gas would result in higher overall system costs, and so allowing it in the model has no effect. However, in the scenario where NTC is reduced by 70%, the model does select natural gas to supply about 4 TWh of power production, if it is allowed to do so. It is noteworthy that this use of gas would generate about 1.7 $MtCO_2$, needing to be shipped to permanent underground storage facilities, likely by pipeline. This represents a significant increase on the 9.5 $MtCO_2$ needing to be shipped for permanent storage envisioned in the Swiss Climate Strategy of the FOEN, but is not a game changer. The main impact of adding natural gas to the system would be in terms of reducing the need for wind power development. Given current challenges associated with siting wind projects in Switzerland, this could be a benefit.

In all, the results from the Nexus-E modelling experiments agree qualitatively with those from the Calliope model, once one harmonizes the assumptions concerning demand. The Nexus-E results also agree quite closely with the Swiss Climate Strategy, arrived at through a larger

[12] Way et al. (2022). Empirically grounded technology cost forecasts and the energy transition. *Joule* 6(9), 2057 – 2082.

modelling study financed by the FOEN. Our results, however, provide significant insights that go beyond the FOEN scenarios. We show that the costs of constraining NTC with our neighbours would be substantial, but not prohibitive. The largest impact would be not economic, but rather related to feasibility, as the NTC constraint would require additional wind power, or natural gas power, to be developed. Our results suggest, in qualitative agreement with other studies, that decarbonization is likely to offer overall economic benefits, rather than imposing costs.

4 Conclusion

The background to this project was that a broad understanding had emerged that the transition to a climate neutral economy by 2050 is possible, bolstered by numerous analyses, including the FOEN Climate Strategy in the case of Switzerland. Our questions were whether this would be influenced by particular behavioural changes, or their absence, as well as decisions to make Switzerland more self-sufficient with respect to energy production than it is today.

On the first issue, behavioural change, our findings suggest that the reduction in two behaviour patterns leading to significant non-CO_2 GHGs could make the costs, and political feasibility, of achieving climate neutrality substantially lower. This is especially the case with respect to meat consumption, and especially in countries where meat prices are currently relatively low.

On the second issue, our findings suggest that efforts to achieve self-sufficiency on an annual basis with respect to the future dominant energy carrier – electricity – are likely to require policy changes enabling substantially more solar energy development than is currently feasible in Switzerland, especially if the electrification of heating and transport proceeds at an aggressive pace. Reductions foreseen in net transfer capacity – the utilization of transmission lines with neighbouring countries – will not have a major additional effect. A goal of autarchy with respect to electricity production would require substantial additional policy changes, such as those that would enable the construction of many thousand wind turbines within Switzerland at a pace far quicker than has been possible in the past. Even under the more challenging conditions, however, decarbonization of the energy system is likely to bring overall cost savings relative to today.

Annex A: List of published peer-review journal articles funded in whole or in part through this project

Brazzola et al. (2021). Offsetting unabated agricultural emissions with CO2removal to achieve ambitious climate targets. *PloS ONE* 16(3 March),e0247887. https://doi.org/10.1371/journal.pone.0247887

Brazzola et al. (2022). Definitions and implications of climate-neutral aviation. *Nature Climate Change* 12(8): 761 – 767. https://www.nature.com/articles/s41558-022-01404-7

Craig et al. (2022). Overcoming the disconnect between energy system and climate modelling. *Joule* 6: 1405 – 1417. https://doi.org/10.1016/j.joule.2022.05.010

Lombardi et al. (2020). Policy Decision Support for Renewables Deployment through Spatially Explicit Practically Optimal Alternatives. *Joule* 4: 2185 – 2207. https://doi.org/10.1016/j.joule.2020.08.002

Pickering et al. (2022). Diversity of options to eliminate fossil fuels and reach carbon neutrality across the entire European energy system. *Joule* 6: 1253 – 1276. https://doi.org/10.1016/j.joule.2022.05.009

Tröndle et al. (2020). Trade-Offs between Geographic Scale, Cost, and Infrastructure Requirements for Fully Renewable Electricity in Europe. *Joule* 4: 1929 – 1948. https://doi.org/10.1016/j.joule.2020.07.018

Annex B: Presentations/discussions of the Principal Investigator with Swiss policy-makers, incorporating results from this work

August 2021, Bern: Private presentation to Bundesrätin Simonetta Sommaruga on strategies for the Swiss CO_2 law.

September 2021, Zürich: Appearance on the SRF show ARENA, discussing the Swiss CO_2 law with representatives from the SVP, FDP, SP, and GP.

April 2022, Bern: Presentation to members of the Nationalrat and Ständerat on Swiss climate policy, as part of an event jointly sponsored by the Swiss Academy of Sciences and the Swiss Parliament.

August 2022, Magglingen: Presentation to senior managers in the Department of Environment, Transportation, Spatial Planning, Energy and Communication (UVEK).

September 2022, Bern: Presentation to party leaders of the GP, SP, GLP, EVP, and FDP as part of the Climate Dialog of the Swiss Academy of Sciences.