Quantifying carbon flows in Switzerland: top-down meets bottom-up modelling

Andreas Froemelt 1,2, Arne Geschke 3 and Thomas Wiedmann 1

1 Sustainability Assessment Program, School of Civil and Environmental Engineering, UNSW, Sydney, NSW, Australia
2 Current address: Ecological Systems Design, Institute of Environmental Engineering, ETH Zurich, Switzerland
3 ISA, School of Physics, The University of Sydney, Sydney, NSW, Australia

E-mail: froemelt@ifu.baug.ethz.ch

Abstract

Modelling frameworks that aim to support policymakers in deriving effective measures to reduce environmental impacts should provide both: quantitative information on locally occurring consumption patterns and production systems as well as assessment of policy scenario outcomes. Regionalised models that can deliver on these aims are emerging, but are currently limited in resolution or have other restrictions. An advanced model can be achieved by exploiting the advantages and overcoming the limitations of top-down and bottom-up approaches. In this article, we describe a highly detailed, spatially-resolved modelling framework that quantifies local activities and simultaneously analyses system-wide environmental and economic effects of planned interventions. We combined an existing, highly detailed bottom-up model for Switzerland (focusing on individual households) with a macro-economic top-down approach by developing a new Swiss sub-national, multi-region input-output model. We conducted two case studies to demonstrate its abilities and to highlight its usefulness. First, production-based greenhouse gas emissions and consumption-based carbon footprints were computed for all Swiss cantons and regional differences, interdependencies as well as embodied carbon flows among regions were investigated. We find that rural cantons have higher production-based emissions per gross domestic product than more urban cantons because of different economic structures. In contrast, certain ‘city-cantons’ entail highest consumption carbon footprints per inhabitant due to high per-capita gross capital formation. Furthermore, this case study discusses the importance of providing regionalised information on effects of measures along the economic value chains. Second, a detailed scenario assuming a realistic lifestyle change for an actual household and a thorough physical retrofit of its home was set up. Regionalised environmental and economic consequences along the supply chains were evaluated. This case study exemplifies how the modelling framework can be used to inform policymakers about expected benefits and downsides of detailed scenarios and emphasises the importance of considering rebound effects.

1. Introduction

Steffen et al [1] as well as Hoegh-Guldberg et al [2] impressively reveal that environmental impacts of current human activities exceed the carrying capacity of the Earth system, posing a severe risk for nature and mankind. A change in today’s consumption patterns and production systems is thus imperative [2, 3]. Thereby, policymakers can assume a key role by devising targeted policies to create conditions incentivising sustainable consumption and production [3–6]. Given the complexity of economy and human behaviour, policymakers are in need of tailored, highly resolved information for developing effective environmental strategies [7–11]. Complicating the situation even more, the responsibility for implementing certain policy measures may vary across different levels of authorities [12, 13]. In this regard, regional and local initiatives have drawn a lot of attention lately and are considered...
essential for the abatement of adverse environmental impacts [8, 11, 12, 14–16]. This calls for vertical and horizontal collaborations among public agencies and hence for regionalised data as a planning base [7–9, 11, 12, 15, 17, 18].

Frameworks that aim to effectively support policymakers should offer two key features: (a) provision of quantitative information on locally prevailing consumption patterns and production systems [8, 9, 11, 12, 15, 16]; (b) assessment of system-wide implications of planned measures, desirably from an environmental, social and economic point of view [16].

There are basically two possibilities to establish such frameworks: top-down and bottom-up models. Top-down approaches are more widespread and are often based on input-output modelling [11, 19–21]. Being simplified, but powerful models of economy, they usually start at a national or even global level, and then attempt to dive into an ever-increasing spatial detail via different techniques (e.g. [22–26]) or by incorporating micro-data (e.g. [27–29]). An interesting subgroup is formed by sub-national multi-region input-output models (MRIO\(^4\)) that are able to provide important information especially in cases of heterogeneous economic structures within a country [26, 30]. Despite the power and usefulness demonstrated for top-down models (e.g. [15]), they have not reached the level of individual entities yet (households, buildings, enterprises) [18]. Consequently, they have limited abilities to capture the variability of environmental impacts induced by specific actors in a certain area, which would be particularly important for designing targeted policy campaigns [5, 31, 32]. Similarly, they also show some limitations to compute highly detailed policy scenarios [33], such as the refurbishment of specific parts of actual buildings (e.g. insulation of walls or windows) or a lifestyle change of a subset of local households.

Bottom-up approaches on their part begin with modelling and parameterising individual units and then attempt to upscale by applying the model to actual entities in a certain area [34]. Existing models usually focus on specific domains such as building stocks (e.g. [35–38]) or simulation of mobility behaviour (e.g. [37]). In Froemelt et al [39], we presented a comprehensive framework that predicts consumption profiles, transport patterns and building energy demand for each individual household in a certain region. While this model is able to reproduce the variability of household footprints, comes with an unprecedented high detail, offers options for in-depth policy scenarios and provides results on any desired spatial scale, it focuses on households only and its hybrid life cycle assessment is not able to track economic flows between regions and industry sectors in a country.

Given the complementary benefits of both realms, the goal of this paper is to present a new modelling platform that emerges from the combination of top-down and bottom-up models. Since the feasibility and usefulness of the bottom-up model [39] was demonstrated by its implementation for Switzerland, we will develop a new top-down Swiss sub-national MRIO and simultaneously link the two models.

The combined model complies with the two abovementioned requirements for effective policy-making support [16]. It allows for deriving targeted measures by quantifying the variability of environmental impacts in a certain area, for setting up detailed applications of sets of policy interventions, and for understanding system-wide economic and environmental effects of planned measures. By identifying where and at which scale impacts may take place and thus indicating which problems can be controlled within a certain jurisdiction, it will help to involve important stakeholders, be it along the supply chains or at different governmental levels [12, 32].

We present the combined model in two concrete case studies. First, we quantify carbon flows within Switzerland in order to demonstrate how the model can reveal hotspots and interrelationships among sub-regions. Second, the implications of a realistic lifestyle change of a particular household including the effects of insulating its home are simulated to provide evidence on how the model could be used to elaborate and assess detailed scenarios.

2. Methods

The emphasis of this article lies on the combination of bottom-up and top-down approaches to support environmental decision-making in Switzerland. However, while a bottom-up model already exists [39], regionalised top-down approaches are lacking for Switzerland. Large parts of this section focus thus on the development of a MRIO for Switzerland in the Industrial Ecology Virtual Laboratory (IELab) framework [26].

2.1. Bottom-up model

In their comprehensive bottom-up modelling framework, Froemelt et al [39] used machine learning techniques to combine three highly resolved and regionalised models to predict the consumption behaviour including associated demands and environmental impacts for each individual household in Switzerland. The three interlinked models are: (a) a building energy model that is based on physical principles and that estimates heat and hot water demand for each residential building in Switzerland using

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\(^4\) Please note that an overview of all abbreviations used in this article is provided in appendix A.
extensive spatio-temporal data [35, 38]; (b) an agent-based transport simulation [40, 41]; (c) a data-driven consumption model that employs data mining techniques to detect typical household expenditure patterns ([42]; and similarly used in [43]). The resulting regionalised bottom-up model provides a wealth of detail in socio-economic, physical and monetary aspects for all Swiss households (about 400 categories for each actual household) and their residential homes [39].

2.2. Industrial Ecology Virtual Laboratory (IELab)

A highly suitable platform to create a disaggregated and regionalised top-down model is the IELab [26]. The IELab is a collaborative research platform that enables its users to build MRIO tables for customised regions and sectors. It provides a high flexibility for modellers and yet a set of distinct tools to efficiently establish input-output-models regionalised at sub-national level [26, 30]. One of the core tasks of IELab is the reconciliation of so-called base tables by means of an optimisation engine working in a cloud-computing environment [30, 44]. These base tables are aggregated derivatives of a high-resolution root classification and are constructed based on an initial estimate that is subsequently subjected to several constraints during optimisation. The root classification itself (definition of sub-regions and industrial sectors) is usually too specified and a corresponding ‘root-table’ would exceed memory capabilities of today’s computers [25, 26]. However, it facilitates a consistent and efficient way for constructing sectorial and regional aggregated base tables.

The IELab has particularly been employed for a multitude of research articles based on the Australian implementation of IELab [7, 25, 45–47] as well as on the worldwide MRIO EORA [17, 48–50]. Further IELab-impelntations for a few other countries exist [51, 52].

2.3. SwissLab: IELab-implementation for Switzerland

The conceptual framework of the IELab-implementation for Switzerland (SwissLab) is outlined in figure 1. The root classification is disclosed in the supporting information (SI) (available online at http://stacks.iop.org/ERL/16/014018/mmedia) and encompasses 794 sectors according to level 5 of the Swiss classification of economic activities (NOGA [53]) and 2352 regions that accord to all Swiss municipalities as of 2014 [54]. Note that level 4 of NOGA equals the European classification NACE [55]. According to the latest available Swiss input-output table (SIOT), the reference year was set to 2014 [56]. However, IELab together with corresponding constraints allows for computing time series (see SI for available years of the databases).

In order to build an initial estimate, which is needed as a starting point for the subsequent reconciliation process, we proceeded similar as in [25] and used full-time equivalents (FTE) together with so-called non-survey methods [25, 66, 67] to disaggregate the official SIOT [56]. The STATENT-database [57] maintained by the Swiss Federal Statistical Office (FSO) provides detailed information about each economic local unit in Switzerland allowing thus the retrieval of FTE in root detail regarding both sectors and regions.

An important task when working with IELab is the definition of constraints. The optimisation algorithm in the reconciliation step needs these constraints to ensure the construction of meaningful and accurate base tables [25, 26, 30, 44]. The basis for all input-output analyses and hence essential for any such model is a balancing constraint that warrants inputs to economy equals its outputs [11, 19, 68]. Furthermore and apart from the obvious constraint based on [56, 59–61] to ensure the reproduction of the official SIOTs, we integrated constraints relying on economic data for different (aggregated) sectors on a cantonal level [62–65]. Finally and as a first interface to the bottom-up model, we used the predicted expenditure data from Froemelt et al [39] to constrain regionalised household final demand (cf figure 1).

While above steps enable the construction of base tables, environmental assessments based on input-output models are only possible if so-called satellite-accounts are introduced [11, 20]. This means that direct environmental impacts of the different economic sectors need to be added to the table. These satellites then allow for coupling with financial flows between sectors and regions and thus for computing upstream impacts [19]. Currently, Swiss official direct air emission accounts [58] covering ten gases and two particular matter categories are integrated in the SwissLab (see figure 1). Focusing on greenhouse gas emissions (GHG), this enables assessing the consumption-based perspective of carbon responsibility, meaning that the emissions are accounted towards the final beneficiary of the supply chain rather than the direct emitter. The implementation of five different GHG categories (CO₂ [fossil and biomass], N₂O, CH₄, and HFC/PFC/SF₆) in SwissLab offers the possibility to provide policymakers with valuable information beyond total carbon footprints. For example, the varying effects of long-lived and short-lived GHG could be considered to derive and prioritise different GHG mitigation policies [69]. As shown in figure 1, we also added FTE from the STATENT-database [57] as satellites to be able to perform social assessments. Note that satellites are similarly treated as other components of the input-output table to produce an initial estimate and that constraints also needed to
be defined for them to ultimately construct a base table.

Refer to the SI for more details on underlying databases and how they were implemented into SwissLab.

2.4. Direct household emissions and emissions abroad

Direct emissions from households and emissions caused outside Switzerland cannot be assessed via input-output analysis of SwissLab-base-tables and are thus covered differently.

To be consistent with other data in the SwissLab, we extracted direct household emissions in the domains of housing and transport from [58] and prorated this official statistics to all Swiss households based on the respective emissions predicted by Froemelt et al’s bottom-up model [39]. Having emission estimates for each geo-referenced household at hand allows for aggregating easily to base-table-regions.

SwissLab is basically constraint by the Swiss borders. To estimate emissions outside Switzerland, but caused by Swiss activities, GHG-multipliers were computed with the global EORA-model that includes Switzerland as a separate region [48, 49]. These multipliers were then converted to total emissions per actual aggregated NOGA-sector. This allowed for including the EORA-based estimates into SwissLab similar to satellite-accounts. The advantage of this kind of integration lies in the automated scaling of the international emissions along the regions- and sectors-configurations of a user-specified base table. However note that the EORA-factors already adopt a life cycle perspective and should thus be applied directly to a final demand vector instead of being multiplied by the Leontief-Inverse [19] when used in environmental assessments (see also section 2.5).

2.5. Carbon flows analysis

As a first case study, we investigate carbon flows between the 26 cantons in Switzerland. For this purpose, a base table was constructed with 272 sectors (NOGA-level 3 [53]) and using the cantons as regions. The evaluation of the resulting base table with the official SIOT was based on mean absolute distance and arithmetic mean of relative differences [25] (see SI). The SI also presents a comparison of the base table with the bottom-up results from Froemelt et al [39] and a juxtaposition with existing, but not regionalised, Swiss carbon footprint studies [70, 71]. Considering all evaluation efforts, especially the mean relative deviation on SIOT-aggregated sectors of only 16%, indicate that SwissLab was able to
compute a reasonable base table for the subsequent computations.

We computed carbon footprints for each canton by distinguishing six components (see table 1) that allow for adding up to the well-known consumption-based footprints (global life cycle GHG induced by the final demand of a canton) and production-based emissions respectively (direct emissions released within the geographic boundaries of a canton plus international aviation and shipping) [6, 13, 33, 72–75]. Both accounting perspectives are highly complementary and provide important insights for policymakers from different angles [6, 33, 73, 76–78]. For the current study, we considered all GHG available from the official Swiss air emission accounts [58] (CO₂ [fossil and biomass], N₂O, CH₄, and HFC/PFC/SF₆).

As indicated above, emissions caused abroad (ROWim) could be determined by multiplying the EORA-factors with the canton’s final demand, while direct household emissions (HHdir) were aggregated on cantonal level based on the estimates for individual households. Emissions within a canton induced by final demand outside Switzerland (ROWex) were computed as the difference between direct emission statistics [58] and emissions caused by Swiss cantons (including the canton under consideration; NEx + CEm). Note that this means that re-exports from outside Switzerland are not considered.

Three components relate to carbon flows within Switzerland: national imports (NIm), national exports (NEx) and cantonal emissions (CEm). These carbon flows were computed by iteratively setting the satellite-accounts to zero for all cantons except for one. By using standard input-output analysis approaches [19], this allowed for computing the emissions released in a certain region by taking flows through intermediate industries into account. In other words: independent of where something is bought, this approach enables to track emissions back to the final demand (e.g. if a Zurich household buys vegetables in Berne, but the vegetables were grown in the canton of Thurgau, the caused emissions in Thurgau would be allocated to Zurich’s national imports).

2.6. Lifestyle-change scenario: once upon a future time

In a second case study, we focus on an individual household to exemplify the interplay of the top-down and bottom-up approaches within the combined framework presented in this article.

We consider the household with the largest carbon footprint within the city of Zurich. The household’s impacts could be computed by means of its expenditure behaviour predicted by the bottom-up model [39] and the base table generated in section 2.5. We now assume that the household decides for a drastic change of its lifestyle towards a more sustainable one. Based on the consumption patterns found in [42] and the lifestyle-allocation-probabilities for individual households in [39], we were able to re-assign an actually observed low-carbon lifestyle which is realistic for this household type. We accounted for the fact that the household stays in its current home.

Finally, we presumed that the household would invest the freed up money (the new lifestyle comes with substantially lower expenditures) into retrofitting its house, which is among the most promising GHG mitigation options according to [79]. The household’s final demand vector was adjusted accordingly and the new heating demand could be estimated with the physically-based building energy sub-model [35, 39] (assumption that the roof, walls, floor and windows are upgraded to high state-of-the-art insulation). The environmental assessment followed basically section 2.5. Additionally, we also considered FTE and value added to obtain simplified estimates of social and economic impacts (similar to [25, 46]).

3. Results and discussion

3.1. Carbon flows analysis

In the first case study, we quantified the carbon flows in and among cantons as well as across the national borders. Figure 2 presents the carbon footprints differentiated according to table 1. The absolute values in figure 2(a) reveal the predominance of Zurich and Berne reflecting their importance for economy and their population size (Zurich and Berne together produce 33.3% of the national gross domestic product (GDP) and are home to 29.8% of the Swiss population [63, 80]). The carbon flows matrix in the SI also confirms Zurich and Berne as the most important sources and destinations. The tail of figure 2(a) mainly consists of cantons with low population and low GDP (see also the size and colour of markers in the scatter plots of figure 3). Not surprisingly, these results suggest that higher emissions are caused in areas with high densities of population and economic activities.

To provide more insights, figure 2(b) ranks cantons according to production-based emissions per GDP and figure 2(c) to consumption-based footprints per capita. In both sub-figures it becomes evident that the consumption perspective always exceeds production-based emissions supporting the findings of other studies that Switzerland is a net-importer of GHG [70, 81–83]. As can be seen in figures 2(b) and 3(b), the rural cantons of Uri, Appenzell-Innerrhoden and Jura are spearheading the production-based emissions per GDP. This can be
explained mostly by their economic structure. Relating the official emissions data [58] to the sector statistics on gross value added (GVA) [63] suggests that agriculture and the provision of utilities (e.g. energy) exhibit high emissions per GVA, while this is low for financial services. All these three cantons produce high shares of their GDP in agriculture and/or in utility provision and have a rather high FTE-percentage in these sectors, whereas GDP- and FTE-shares are rather low for financial services (see SI [57, 63]). As can be deduced from figure 3(a), this also results in a similar composition of their footprints.

The lowest production-based emissions per GDP can be found in Zug, Geneva and Basel-Stadt. These three cantons show the highest GDP per capita in Switzerland [63]. Furthermore, these cantons are special because they mainly consist of their core city with comparably little hinterland within the cantonal
boundaries. Since these are the only cantons in which more than 90% of the population lives in so-called core municipalities of urban agglomerations [80, 84] and also the only ones with no municipalities that are classified as rural by the Federal Office for Spatial Development [84], we will summarise them henceforth as 'city-cantons'. In all of these three cantons, agriculture and utility provision provide minor contributions to the cantons’ GDPs, while financial services represents a major sector in terms of GVA and FTE (the latter’s share is also high for services in general) [57, 63].

Switching from the production-oriented perspective in figure 2(b) to consumption-based carbon footprints in figure 2(c) the order of the rankings substantially changes, with the mentioned ‘city-cantons’ as an interesting case. While Basel-Stadt and Zug show highest consumption footprints per capita, Geneva ranked lowest. Since consumption-based footprints directly depend on final demand, its composition as well as total impact multipliers (life cycle GHG per final demand) have to be studied to explain the differences. In order to ease the traceability of reasons, we aggregated the 7072 intensity-factors (26 regions × 272 sectors) at the sector levels of [63] in the SI. There, it becomes clear that demand for agricultural products, manufacturing and construction and utilities entail large life cycle GHG, especially compared to financial services. Thereby, demand for manufacturing and construction particularly increase imported emissions (ROWim), whereas demand for agriculture causes a relative increase in national emissions (NEx + CEm) by trend. Analysing the final demand categories on a national level (see SI) reveals that gross fixed capital formation (GCF) in machinery and buildings show generally high investments in manufacturing and construction, while total household consumption not only demands for utility provision and manufacturing and construction, but also for agriculture.

Applying these insights to the three ‘city-cantons’ does not explain the differences in the first place since all three have similar portions of the final demand categories and show comparable compositions of their footprints (see figure 3(a)). The rather high share in imported emissions (ROWim) for all three cantons can be traced back to the high demand for the manufacturing and construction sectors induced by the comparably high contributions of the GCF-categories to the total final demand. The relative low percentage of household consumption in final demand also explains the seeming contradiction to the study of Froemelt et al [39] who found lower consumption-based footprints for urban municipalities compared to rural areas by trend. However, they only considered household consumption [39]. Concentrating on households only, the SwissLab-table and Froemelt et al’s footprints are rather close (e.g. for Basel: 9.1 tCO₂-eq vs. 9.0 tCO₂-eq per person per year).

While the relative structure of final demand provides interesting information, the low per-capita consumption-based footprint of Geneva has to be explained by absolute figures (cf SI). Compared to Basel-Stadt and Zug, Geneva has a lower total per-capita final demand. Especially the per-capita consumption of households is lower resulting in a weaker demand for agriculture, utility provision and manufacturing and construction. In addition to that, Geneva features the lowest direct household emissions in Switzerland.

Even though it is of high importance to understand the differences in the footprint compositions of the cantons—especially if it comes to finding hotspot-sectors or to pinpointing specific problems in a region—the quantification of carbon flows is also important to assess where interventions would be needed, which stakeholders along the supply chains should be involved for a certain emission reduction goal and which emissions can be tackled.

| Carbon footprint components | Abbreviation | Description |
|-----------------------------|--------------|-------------|
| Global emissions            | ROWim        | Emissions released outside Switzerland by the canton's final demand |
| National imports            | NIm          | Emissions released inside Switzerland but outside the considered canton by the canton's final demand |
| Cantonal emissions          | CEm          | Emissions released within the canton by its own final demand |
| Household emissions         | HHdir        | Direct emissions released by the households living in the canton |
| National exports            | NEx          | Emissions released within the canton but caused by the final demand of other cantons |
| Global exports              | ROWex        | Emissions released within the canton but induced by final demand outside Switzerland |

Note: Production-based emissions = CEm + HHdir + NEx + ROWex. Consumption-based carbon footprint = ROWim + NIm + CEm + HHdir.
within a certain jurisdiction \cite{12}. For the latter purpose, figure 3(c) plots carbon ‘self-sufficiency’. This means, we compute the ratio of the production-based emissions induced by the local final demand (CEm + HHdir; see table 1) and the total production-based or the consumption-based footprint respectively.

In figure 3(c), three groups can be distinguished: large cantons with high carbon self-sufficiency, cantons in-between and again the three ‘city-cantons’ with low shares of own emissions in their total footprints. A positive correlation of self-sufficiency in production- and consumption-based terms is observed by trend.
According to these findings, bigger cantons with more hinterland are apparently better able to satisfy their own demand and thus less dependent on other cantons, while no clear relationship to GDP emerges in the overall picture. Among the ‘in-between-cantons’, however, smaller cantons with rather low GDP segregate and show medium self-sufficiency for their consumption-based footprint and simultaneously a low self-sufficiency-rate in a production-based view. Again, the positioning of the ‘city-cantons’ in figure 3(c) can be explained by their final demand in addition to the comparatively low direct household emissions: the high share of GCF increases the import and export footprint components, while the low contribution of households relatively decreases demand for agriculture and hence the share of cantonal emissions. These trends reduce these cantons’ carbon self-sufficiency in both perspectives.

However, a region does not necessarily need to increase its carbon self-sufficiency. As can be seen in figures 2 and 3, a high carbon self-sufficiency does not automatically imply a lower carbon footprint. A regional specialisation and thus a higher dependence on other regions might even be beneficial in an overall perspective [14, 85, 86]. Yet, for cantonal authorities it is important to know how much of their footprints can be tackled directly within their boundaries and to become aware of the fact that their environmental measures will affect other regions or need assistance from them [13]. To achieve certain reduction targets, the ‘city-cantons’, for example, might need to involve more policymakers from other regions in Switzerland than the cantonal authorities of Zurich or Berne. Furthermore, it is also important to realise if and where international agreements are needed in case carbon flows cross the national borders.

3.2. Lifestyle-change scenario

The quantification of carbon flows can thus help to better inform policymakers, especially when planning and preparing environmental policy instruments. The presented combination of bottom-up and top-down models goes beyond that and is able to track system-wide effects of employed specific measures.

For the Zurich household under consideration, figure 4 shows a drastic reduction of GHG as a result of adopting a new lifestyle. However, figure 4 also shows negative impacts on FTE and value added. Direct GHG emissions of the household were solely reduced by an adjusted mobility behaviour in this first step. Assuming that the household re-invests its liberated money into refurbishing its home in a next step, further massively lowers its direct GHG thanks to a decrease in heating demand6. The re-investment still leads to a substantial overall reduction of the household’s carbon footprint. However, the reduction gains within Switzerland are compensated by an increase in global emissions. This is a result of prorating the saved money along

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6 NB: the annual per-capita reduction of 1.6 tCO₂-eq due to refurbishment is above the average mitigation potential of 0.9 tCO₂-eq for this mitigation option in the meta-study of [79], but within the range of their reviewed studies.
Figure 5. Regionalised effects of the two steps in the lifestyle-change scenario for the individual Zurich household under consideration: First, adopting a new lifestyle is assumed (lifestyle-change); second, the saved money is invested to retrofit the household’s home (re-investment). The first row of maps depicts absolute values of greenhouse gas emissions (GHG) in (a) and percentage change in the cantons for the two steps in (b) and (c); the second row of maps illustrates induced absolute value added (VA) in (d), while (e) and (f) show the percentage change in the two scenario steps; similarly, the third row displays induced absolute values of full-time equivalents (FTE) in all cantons in (g) and percentage changes in (h) and (i). Note that in all maps only indirectly induced impacts via the SwissLab-base-table are considered, while direct household effects and global impacts are not taken into account in this figure. Shapefiles of the cantonal boundaries are provided by [54].

Figures 5 shows the regionalised impacts of the scenario. While GHG decrease everywhere, value added and FTE increase in many parts of Switzerland, but especially in the inner part of Switzerland, for instance in the canton of Uri. How much a canton gains or loses in value added and FTE terms depends on two counteracting forces: The new lifestyle generally initialises a lower demand for all economic sectors, while the re-investment in the building sector favours cantons with higher GDP and FTE-shares in manufacturing and construction and indirectly also cantons with a focus on the provision of utilities; the latter being the case for Uri. Furthermore, it is important to realise that figure 5 depicts relative changes. A large relative change might be based on a small absolute value.
One could argue that the saved money might even be enough to replace the current oil boiler with a ground-source heat pump in addition to installing photovoltaic panels on the roof or buying a battery electric vehicle. These measures would further decrease long-term direct household emissions but increase one-time indirect effects. In any case, the big question is how the household will spend the liberated money in the following year, after having technically optimised its home.

The case of the Zurich household demonstrates the insightful combination of a bottom-up model that enables computing the detailed changes of final consumption and a top-down approach that allows for tracking system-wide effects. However, this scenario also emphasises the importance of rebound effects, whereby savings in one area might lead to backfiring in other domains [20, 87, 88]. Last but not least, if other households would follow the case study household, further considerations are needed such as the development of prices or the long-term change in economic structure.

3.3. Limitations
Just as every model, the presented combination of top-down and bottom-up approaches is subject to many assumptions leading to uncertainties in the results and limitations of their applicability. Most of these uncertainties have already been discussed in earlier publications of the models used for this study (e.g. [25, 26, 30, 35, 38, 39, 47]). Particularly, we would like to point out the limitations of using a purely monetary input-output framework and its implicit assumption of linearity and economic allocation [11]. Both are inherent to many input-output studies and are simplifications of reality that potentially affect the overall results [19, 33, 89, 90].

Furthermore, assumptions are needed to estimate sub-national multi-region input-output tables via non-survey methods. While the research on non-survey methods is advanced, the possibilities of evaluating these estimates are limited due to a lack of sub-national data on interregional trade [25, 26, 47, 66]. We envisage evaluating the different non-survey methods for the case of Switzerland and establishing an uncertainty framework based on our findings in future research. That said, SwissLab and the bottom-up household consumption model both allow to integrate further data if better information is available, for instance, at a local level.

Pertaining to the two presented case studies, the highly simplified assumptions for the lifestyle-change scenario needs to be pointed out once more. Moreover, it shall be mentioned that re-exports from outside Switzerland were not considered in both case studies. Improving the nesting of SwissLab into a global input-output model and thus replacing the currently implemented simplified link to EORA is another important future research work; especially because the comparison of the case-study-base-table with existing Swiss carbon footprint studies in the SI suggests that embodied emissions in imports and exports might currently be underestimated by SwissLab and need further investigations.

Finally, for a holistic environmental assessment of scenarios, also other environmental indicators than GHG should be included in upcoming studies.

4. Conclusions and outlook
In order to support the design and prioritisation of targeted policy interventions, we combined top-down and bottom-up models to create a new model platform. This new framework is a response to the calls of [16, 18, 91] for highly resolved modelling approaches and it is able to assess environmental footprints of locally occurring consumption patterns and production systems. The two modelling approaches were connected at several interfaces. On the one hand, the bottom-up characteristics allow the model platform to compute highly detailed scenarios at the level of individual households. On the other hand, the top-down part enables for simultaneously assessing system-wide direct and indirect economic and environmental impacts of planned actions by tracking economic flows between regions and industries. Thereby, it can also identify potential stakeholders along the supply chains. The presented framework profits thus from the advantages of both modelling domains. The abilities of this combined overall model were demonstrated in the scope of two case studies.

The first case study revealed interesting regional differences in Switzerland and a high interdependency of certain cantons with other regions. This analysis showed the production perspective complementing the bottom-up consumption model, the explicit modelling of carbon flows in Switzerland, and provided potentially important information for planning measures along the supply chains and about controlling emissions within the Swiss borders.

Likewise, the household case study demonstrated the economy-wide effects of detailed targeted measures and confirmed the importance of considering indirectly induced impacts in a life cycle assessment manner (as pointed out by, e.g. [77, 78]). In addition, it showed the strength of the bottom-up model part that comes with detailed consumption profiles for individual households and allows for setting up in-depth scenarios including the estimation of new heating demands after physical refurbishment of a home.

The latter case study also revealed the importance of rebound effects that can considerably constrain the achievement of real GHG reductions in
lifestyle-change scenarios [87]. To better account for such implications, we will attempt to push the current framework towards computable general equilibrium models (CGE), which proved to be beneficial [92, 93] in this regard and require an input-output model as a preliminary step. However, the computation of structural change over time or the consequences of economic shocks as induced by, e.g. pandemic global disease outbreaks could be analysed already in the current modelling framework.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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Appendix A. General abbreviations

All abbreviations used in the present article are listed and defined in table 2.

| Abbreviation | Full description |
|--------------|------------------|
| AEA          | Swiss air emission accounts [58] |
| BU           | Bottom-up |
| CEm          | Cantonal emissions: emissions released within a canton by its own final demand |
| CGE          | Computable general equilibrium model |
| EORA         | A worldwide (global) multi-region input-output model [48, 49] |
| FSO          | Swiss Federal Statistical Office |
| FTE          | Full-time equivalents |
| GCF          | Gross fixed capital formation |
| GDP          | Gross domestic product |
| GHG          | Greenhouse gases |
| GV           | Gross value added |
| HHdir        | Household emissions: direct emissions released by the households living in a certain canton |
| IE Lab       | Industrial Ecology Virtual Laboratory [26, 30] |
| MRIO         | Multi-region input-output model |
| NACE         | (French: Nomenclature statistique des activités économiques dans la Communauté européenne) European classification of economic activities [55] |
| NEx          | National exports: emissions released within a canton but caused by the final demand of other cantons |
| NIm          | National imports: emissions released inside Switzerland but outside the considered canton by the canton's final demand |
| NOGA         | (French: Nomenclature générale des activités économiques) Swiss classification of economic activities [53] |
| Reg. PS      | Regional primary sectors |
| ROWex        | Global exports: emissions released within a canton but induced by final demand outside Switzerland |
| ROWim        | Global emissions: emissions released outside Switzerland by a canton's final demand |
| SI           | Supporting information |
| SIOT         | Swiss national input-output table [56, 59–61] |
| STATENT      | (German: Statistik der Unternehmensstruktur) Swiss database providing information about all economic local units in Switzerland [57] |
| VA           | Value added |
Appendix B. Abbreviations and locations of cantons

Table 3 provides an overview of names and abbreviations of all 26 Swiss cantons, while figure 6 maps the cantons' locations.

Table 3. Overview of names and abbreviations of the Swiss cantons.

| Name                  | Abbreviations |
|-----------------------|---------------|
| Aargau                | AG            |
| Appenzell Inner Rhoden| AI            |
| Appenzell Ausser Rhoden| AR          |
| Berne                 | BE            |
| Basel-Land            | BL            |
| Basel-Stadt           | BS            |
| Fribourg              | FR            |
| Geneva                | GE            |
| Glarus                | GL            |
| Grisons               | GR            |
| Jura                  | JU            |
| Lucerne               | LU            |
| Neuchâtel             | NE            |
| Nidwalden             | NW            |
| Obwalden              | OW            |
| St Gallen             | SG            |
| Schaffhausen          | SH            |
| Solothurn             | SO            |
| Schwyz                | SZ            |
| Thurgau               | TG            |
| Ticino                | TI            |
| Uri                   | UR            |
| Vaud                  | VD            |
| Valais                | VS            |
| Zug                   | ZG            |
| Zurich                | ZH            |

Figure 6. Locations of cantons. See table 3 for the abbreviations. Shapefiles of the cantonal boundaries are provided by [54].
ORCID iDs

Andreas Froemelt  
https://orcid.org/0000-0001-9388-7816

Arne Gescheke  
https://orcid.org/0000-0001-9193-5829

Thomas Wiedmann  
https://orcid.org/0000-0002-6395-8887

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