Decoupling energy use and economic growth: counter evidence from embodied energy in Swiss trade

Vincent Moreau[a], François Vuille[b*]

[a] Ecole Polytechnique Federale de Lausanne, College of Humanities, CM 2 267, Station 10, 1015 Lausanne, Switzerland. vincent.moreau@epfl.ch

[b] Ecole Polytechnique Federale de Lausanne, Energy Center, BAC 104, Station 5, 1015 Lausanne, Switzerland. *corresponding author, f.vuille@epfl.ch, +41 21 693 2487

Abstract: Many efforts have been made to decouple economic growth and energy use to reduce energy related environmental impacts. Switzerland exhibits a decrease in energy intensity, which can be interpreted as successful decoupling. In this article, we analyze whether this apparent decoupling is due to the structural effects of deindustrialization and tertiarization, which shift domestic energy use abroad and re imports it as embodied energy in products.

The contributions of three drivers of energy use, scale as a result of population and economic growth, structural changes, and energy efficiency measures, are estimated at the level of economic activities. Index decomposition analysis shows that structural changes play an important role, in particular for manufacturing. Using a hybrid input output approach, we quantify the embodied energy in Swiss trade from 2001 to 2013.

The results show that the share of energy embodied in imports reaches 60% of total energy consumption in 2013. Shifting energy intensive activities abroad brightens the picture domestically but increases overall energy consumption. We compare the energy intensity of activities with and without embodied energy and show that the growth in total energy use slightly exceeds economic growth, in other words decoupling is more virtual than actual.

Keywords: Decoupling; Embodied energy in trade; Hybrid input output analysis; Multi regional input output tables; Index decomposition analysis; Switzerland

Highlights:

- Accounting for indirect, embodied, energy in trade, the energy intensity of economic activities in Switzerland has increased from 2001 to 2011.
- The growing share of embodied energy in total energy use results from structural changes in economic sectors despite energy efficiency.
- Disaggregation at the level of economic sectors provides insights into how comprehensive energy policy should account for production, consumption and trade related aspects.

1. Introduction

Economic development is directly proportional to the level of energy use as shown by long term empirical evidence (Warr et al., 2010). Given the impact of the energy sector on climate change, efforts have been made to decouple economic growth from final energy consumption. In Switzerland for instance, from 2001 to 2013, gross domestic product (GDP) increased by almost 23 %

while final energy consumption increased by only 3 %. This trend appears even stronger on a per capita basis, while population grew by 12 % and GDP per capita rose by 9.5 % over the same period of time, final energy consumption per capita declined by 8 % (SFSO, 2015). Hence the ratio of final energy consumption to GDP, or energy intensity, exhibited a downward trend as shown in Figure 1[1]. This has been considered successful decoupling of GDP and final energy consumption (SFOE, 2014).

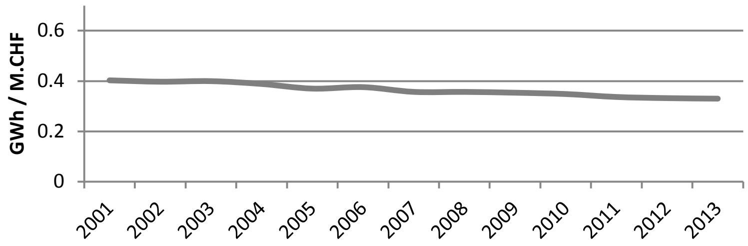

Figure 1 : Energy intensity of economic activities in Switzerland (adapted from SFOE, 2014)

Several factors may explain a decreasing energy input per unit of GDP. Energy efficiency measures are expected to be the main factor in reducing energy intensity and are a clear indicator of successful decoupling, provided rebound effects remain low (Chitnis et al., 2013). However, other factors may also result in lower energy intensity, though they cannot be considered as actual decoupling. For instance structural changes in the economy may lead to a lower energy consumption per unit of GDP: deindustrialization (i.e. the export of energy intensive industries abroad) on one hand, and tertiarization (i.e. the growing share of the service sector) on the other, tend to yield higher value added per unit of final energy consumption. In this article, we first attempt to understand which of these different effects may explain the observed decrease in energy intensity in Switzerland.

At constant consumption levels, deindustrialization induces an increase in imports of semi-finished and finished products to compensate for lost domestic production of those same products. From a consumption perspective, the energy used abroad to manufacture these products is imported in the form of embodied energy. In other words, the decrease in final energy consumption associated with deindustrialization is (partly) offset by the energy embodied in imports.

Hence the overarching question is to understand the respective contributions of energy efficiency efforts, structural changes in the economy and trade to the observed decline in energy intensity. We then estimate energy intensity accounting for the energy embodied in products (goods and services), imported and exported. The main objective is to show whether final energy consumption and GDP are actually or virtually decoupling by transferring consumption abroad. Virtual decoupling can be distinguished from relative decoupling as it results solely from lower domestic energy consumption rather than higher GDP.

[1] In this article, final energy consumption corresponds to the energy used by economic activities to supply final demand and includes the energy sector (e.g. transformation losses in nuclear power plants, refineries and pumped hydro storage) but excludes non-energy use of fossil fuels (e.g. lubricants and bitumen) which make a significant difference for the chemical and construction sectors.

To do so, we attempt to disaggregate the different effects underlying energy use, namely population and economic growth, energy efficiency and structural changes in economic activities, in order to understand their contribution towards decoupling, if any. Based on its consumption, Switzerland provides a case in point as it holds a sizable trade deficit in physical terms, such that the embodied energy in trade is likely to be significant (see figure 2). In other words the imports together with their embodied energy represent a large share of total output in both monetary and energy terms. Moreover, domestic industrial activities are relatively efficient, making products manufactured in Switzerland less energy intensive than their foreign counterpart.

In this article, we explain the reasons why Switzerland has apparently managed to decouple energy use from economic growth, and show how accounting for energy embedded in trade changes the overall picture. We first estimate the total energy balance of economic activities in Switzerland, including energy embodied in imports and exports. Second, we decompose the effects of scale, energy efficiency and structural changes in the economy to evaluate which contributes the most to energy consumption and actual or virtual decoupling. Third, comparisons across data sources have the dual purpose of validating the results and examining methodological approaches suitable for application to other nations. Since 2002, trade statistics include electricity which is exchanged almost exclusively with neighbouring countries, and make embodied energy highly relevant to comprehensive energy policies. Section 2 of this article provides some background information while section 3 explains the methodological approach. In section 4, we discuss the results and a conclusion ends the article.

2. Background

Energy policies in Europe and elsewhere place high expectations on efficiency measures to reduce final energy consumption (e.g. European Commission, 2011; Swiss Confederation, 2013). Figure 1 shows the decline in energy intensity in Switzerland at a relatively constant rate of 0.5 % per year since 2001. Figure 2 shows the monetary (10^3 million CHF) and physical (gigatons) trade balances for Switzerland over the past 20 years. Around the turn of the century, the trends clearly started to change in both monetary and physical terms. Between 2001 and 2013, the trade surplus in monetary terms increased 14 fold (+ 22’000 million CHF) while the trade deficit in physical terms increased by 14 % (+ 4.4 Gigatons), a sign that the economy continues to import more semi-finished and finished products (Swiss Customs Administration, n.d.). Countries across Europe exhibit similar “deindustrializing” profiles, increasingly relying on imports and exports as domestic manufacturing declines and income rises (Schaffartzik et al., 2014).

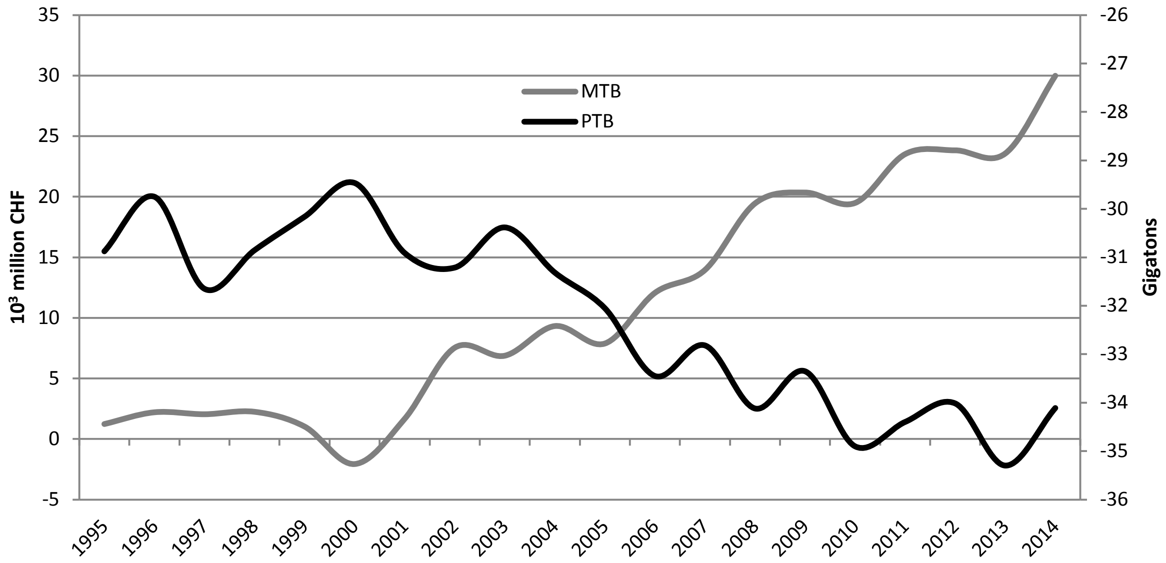

Figure 2 : Trade balances for Switzerland in monetary (MTB, left axis) and physical (PTB, right axis) terms (Swiss Customs Administration)[2]

The energy and material flows necessary to produce the imports, so called indirect or hidden flows, are generally quantified using one of two approaches. From the bottom up, trade statistics at the product (goods and services) level are linked to the corresponding life cycle inventories and impact assessment (LCA). The more common top down methodological approach uses input output tables (IOTs) which quantify monetary exchanges among economic sectors in order to satisfy final demand from consumers. Satellite accounts typically provide coefficients for production factors such as resource use, including labor and energy. This article focuses on energy balance which has received less attention compared to environmental impacts such as carbon footprints.

One of the first attempts to quantify the energy embodied in products was based on an extended version of input output tables for the US (Bullard and Herendeen, 1975). Hybrid approaches based on LCAs tend to evaluate the impacts embodied in products rather than energy alone. Jungbluth et al. (2011) showed that 60 % of the environmental impacts of consumption in Switzerland occurred abroad, 40 % of which as a consequence of food purchases using hybrid input output analysis. This methodological approach was reused to derive time series for the environmental impacts of final demand, concluding that foreign impacts accounted for almost 75 % of the total in 2011 (Frischknecht et al., 2014). Although less than a handful of studies have estimated the impacts of Swiss consumption abroad, none have disaggregated direct and indirect energy use at the level of economic sectors with differing intensities for imports and exports. Input output analysis has increasingly been used to estimate trade related emissions thanks to the availability of environmentally extended input output tables (EE IOTs) (e.g. Baiocchi and Minx, 2010; Peters et al., 2011). Since Wiedemann et al. (2007) conducted a thorough review of input output analysis to estimate the environmental terms of trade, multi-regional input output tables (MR IOTs) also became widely available (Dietzenbacher et al., 2013; Tukker et al., 2013; Tukker and Dietzenbacher, 2013).

[2] The physical trade balance (PTB) is defined as the difference between the weight of imports and exports, as opposed to monetary trade balance (MTB) which is the difference between the value of exports and imports. This illustrates the fact that monetary and material flows generally move in opposite directions.

As a result, numerous studies have quantified embedded emissions in trade globally and for major exporters such as China (e.g. Muradian et al. 2002; Munksgaard et al. 2005; Peters et al. 2011; Minx et al. 2011; Xu and Dietzenbacher 2014). The German Federal Statistical Office published the results of an energy and greenhouse gas input output analysis of domestic activities and showed that energy embodied in imports, rose by 17.9 % from 2000 to 2007 (Mayer and Flachmann, 2011). The higher energy content in imports was particularly significant for basic metals as a consequence of outsourcing and relocation of such energy intensive activities abroad. However, several gaps were identified, including a lack of detailed analysis to understand potential shifts in energy intensive activities. Data unavailability, due to high levels of aggregation or confidentiality where the number of actors per economic sector is small, is also a reason why comparatively few studies exist for Switzerland. When comparing bottom up LCA based approaches and EE IOTs to estimate the impacts of trade flows, results differ for key activities, agricultural products and consumer goods in particular (Schuerch et al., 2012). Thus decomposition by economic activity is essential for robust results and effective policies. In this article, we use detailed energy accounts over extended periods of time to show how structural changes have affected total energy balance and intensity.

3. Methodology

3.1. Dual approach

To explain changes in energy intensity in Switzerland, we adopt a dual approach for comparison and validation purposes. First, we identify and quantify the main drivers of energy use drawing upon index decomposition analysis (IDA). IDA is a well-established techniques for such purposes (Su and Ang, 2012). Hoekstra and van den Bergh (2003) showed that IDA is particularly suitable for detailed sectorial analysis in estimating the contribution of each determinant, all else kept equal. From this analysis, we conclude on the respective role that energy efficiency efforts, deindustrialization and tertiarization have played in the decreasing energy intensity of Switzerland.

We then estimate the energy embodied in imports and exports per sector based on a hybrid approach using energy accounts to compile energy intensities and IOTs for trade flows. Similar to domestic energy intensity, changes abroad can result from energy efficiency measures as well as productivity increase.

Finally, we use multi-regional input output tables (MR IOTs) in order to validate the results on the energy embodied in trade (see section 3.3. below). The next section (3.2.) details the methodological approach while section 3.4. provides an overview of the data sources.

3.2. Index Decomposition Analysis

The energy use E per economic activities j depends on a number of factors. We hypothesize that the following three factors are the most meaningful to explain this consumption: scale, structure and intensity as shown in equation (1).

$$E = \sum_j \underbrace{Monetary\ output}_{Scale} \times \underbrace{\frac{Monetary\ output_j}{Monetary\ output}}_{Structure} \times \underbrace{\frac{Energy\ use\ j}{Monetary\ output\ j}}_{Intensity} \quad (1)$$

First, the *scale* factor accounts for the size of the population and the level of economic activity. This is directly measured by the sum of the monetary outputs of all sectors, equivalent to GDP. Second, the *structure* factor accounts for the nature of the economic activity *j* and is measured by the share of domestic output per economic sector over total output, i.e. including imports. This factor is of particular interest here as it provides a proxy for deindustrialization. Third, the *intensity* factor reflects the energy intensity of the different economic activities as a result of energy efficiency measures and it given by the ratio of the energy used per unit of output in each sector j.

We determine the contribution of each of these factors with index decomposition analysis, an especially useful technique for decomposing aggregated variables (Hoekstra and van den Bergh, 2003). Equation (1) can be rewritten as follows:

$$E = \sum_j E_j = \sum_j Q \frac{Q_j}{Q} \frac{E_j}{Q_j} = \sum_j Q S_j I_j \quad (2)$$

where E_j is the energy use per sector *j* in [GWh], Q is the volume of economic activity in [M.CHF2011], S_j is the structure of economic sector *j* in [%] of domestic vs. overall output and I_j is the energy intensity of sector *j* in [GWh/M.CHF2011].

In order to analyze the decrease in the overall energy intensity observed in Figure 1, we are interested in changes of E_j as a function of the changes in scale Q_j, structure S and energy efficiency measures I over time. Such changes in equation (2) can be expressed by the ratios in each of these three multiplicative factors:

$$dE = {}^{E(t)}\!\big/_{E(t_0)} = dQ \cdot dS \cdot dI \quad (3)$$

Several decomposition techniques exist to derive equation (3) from equation (2). A relatively common approach applied here, is the logarithmic mean divisia index or LMDI (Ang, 2005). In general, such estimates vary across nations, economic activities and time scales. As illustrated in Figure 2, significant changes occurred over the decade from 2001 (t_0) to 2011 (t), providing a relevant time frame for our analysis. The energy intensity per economic activity I_j is computed with energy use E_j and monetary output Q_j from energy accounts and the Swiss input output tables as illustrated in equation (4). When decomposing for the three factors, we assume that changes in *intensity* results from energy efficiency measures alone, the other factors capturing growth and structural effects. In equation (3) we are interested not only in domestic energy use but also in the embodied energy in imports and exports.

3.3. Input output analysis of energy embodied in trade

The embodied energy in trade was computed in two ways and compared. First the foreign and domestic energy intensities per economic activity were multiplied by the volumes of imports Q_j^{Imp} and exports Q_j^{Exp} respectively to compute the net energy embodied in trade or energy trade balance, as shown in equation (4a).

$$E^{Trade} = \sum_j E_j^{Trade} = \sum_j \left(I_j^{Imp} Q_j^{Imp} - I_j Q_j^{Exp} \right) \quad (4a)$$

$$E^{Tot} = \sum_j E_j^{Tot} = \sum_j \left(E_j + E_j^{Trade} \right) = \sum_j \left(I_j Q_j + I_j^{Imp} Q_j^{Imp} - I_j Q_j^{Exp} \right) \quad (4b)$$

where the intensity of domestic activities I_j and imports I_j^{Imp} varied according to data availability as explained below in section 3.4. In order to complete the time series, missing data between 2001 and 2011 was estimated by linear regression and extrapolated to 2013.

Total energy balance per economic activity was also computed by adding domestic energy intensity multiplied by output for all sectors, equation (4b). The embodied energy in imports was aggregated across economic activities j to estimate the share of the total energy balance indirectly supplied by imports.

Second, the embodied energy in trade was derived from Exiobase's multiregional input output tables (MR IOTs) available for the years 2000 and 2007 with 129 and 163 sectors respectively, in 43 countries including Switzerland and the rest of the world (Tukker et al. 2013). Given the matrix A of j by j industry transaction coefficients, the total monetary output X of each industry j to supply final demand Y is represented in equation (5):

$$X = (U - A)^{-1} Y \quad (5)$$

where U is the identity matrix and $(U - A)^{-1}$ known as the Leontief inverse. This input output model is easily extended with factor inputs for resources such as energy. The total input of energy E for final demand Y is the following:

$$E = e(U - A)^{-1} Y \quad (6)$$

where the vector e of energy intensities is also available from Exiobase's satellite tables in 2000 and 2007. The energy vector E computed from MR IOTs provides the final demand supplied for by foreign imports and domestic production which are easily disaggregated. Due to the large size of the matrix A (129 activities x 43 regions means more than 5500 rows and columns for 2000 only), as well as of vectors Y and e, all calculations were carried out in Matlab.

3.4. Data sources

Swiss environmentally extended input output tables (EE IOTs) are available for the years 2001, 2005, 2008 and 2011. We used them to estimate the volumes of imports and exports per economic activity for each of these particular years. However the introduction of the European system of national and regional accounts, which Switzerland also applies, reduced the degree of comparability between the 2011 table and previous versions (ESA, 2010). In addition, the IOT for 2011 represents 49 sectors whereas 66 are described in the earlier tables with a higher level of disaggregation for energy intensive activities (Nathani et al., 2013). The energy accounts published by the Swiss Federal Office of Statistics provide time series of both energy and non-energy uses of fuels by sector. This statistic aggregates the data into 14 sectors, such that the IOT data was aggregated to a degree comparable with the first level of the European Statistical classification of products by activity (CPA). At this level, differences between IOTs prior and posterior to the new system of European accounts remain small.

Energy embodied in imports to Switzerland were characterize with energy intensities for the EU (plus Norway) available from Exiobase's MR IOT for 60 sectors for the year 2007 (Tukker et al. 2013). In monetary terms, 80 % of all imports to Switzerland come from Europe, 98 % of which from the EU including 40 % from Germany alone (Swiss Customs Administration, n.d.). While this proportion has remained stable over the time period of interest (2001-2011), a very slight decline of imports from the EU can be observed in favor of China and India. The Americas and Africa are also declining as origins of Swiss imports. Hence, assuming all imports to Switzerland are produced with energy intensities prevalent in the EU provides a close lower bound to embodied energy. Figure 3 compares the energy intensities in Switzerland and the EU for 14 sectors which we used in order to qualify exports and imports respectively. Changes in domestic intensities are represented from 2001 to 2011 while the intensities of imports remain constant due to a lack of comparable data for the EU.

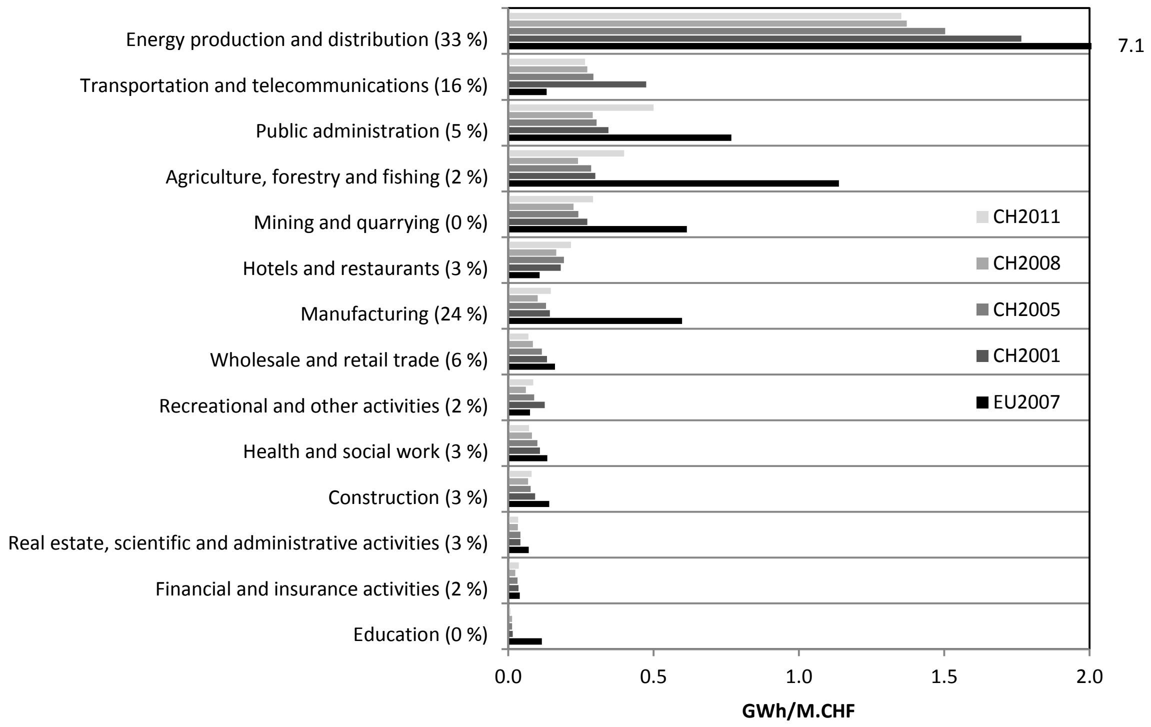

Figure 3: Energy intensity in Switzerland and Europe per economic activity with percentages of domestic energy use in brackets for 2001 (adjusted in constant CHF 2011)

With the exception of the aggregated transportation and telecommunication sector, Figure 3 shows that economic activities in Switzerland are significantly less energy intensive than that in the EU. The absence of heavy industry, such as mining and smelting, explains part of the large differences occurring essentially in energy intensive sectors. At this level of aggregation, products manufactured in Switzerland fare better than imports, overall their energy intensity is lower. However, disaggregating the manufacturing sector would be necessary for drawing up accurate comparisons.

4. Results

The results of decomposition analysis reported in section 4.1. show that structural changes explain why embodied energy continues to rise as demonstrated by the results in section 4.2 and validated in section 4.3.

4.1. Factors explaining the decrease in energy intensity in Switzerland

Decomposition of the three factors influencing energy use (scale, structure and intensity) is shown in Figure 4 as percentage change from 2001 to 2011 for each economic sector. They are sorted by the degree of structural change, with those which experienced the greatest negative changes in domestic output at the top. Several conclusions can be drawn from Figure 4, in particular the polarization of energy demanding sectors at both ends of the scale showing significant changes. The scale or level of activity increases in every sector, especially in manufacturing, energy production and distribution and transportation, commensurable with population growth. Moreover, structural effects have transformed these sectors in opposite ways, with deindustrialization in the manufacturing sector as shown by a – 5 % change. Such changes as moving production and related energy use abroad, are referred to as energy leakage and manufacturing clearly leaks the most.

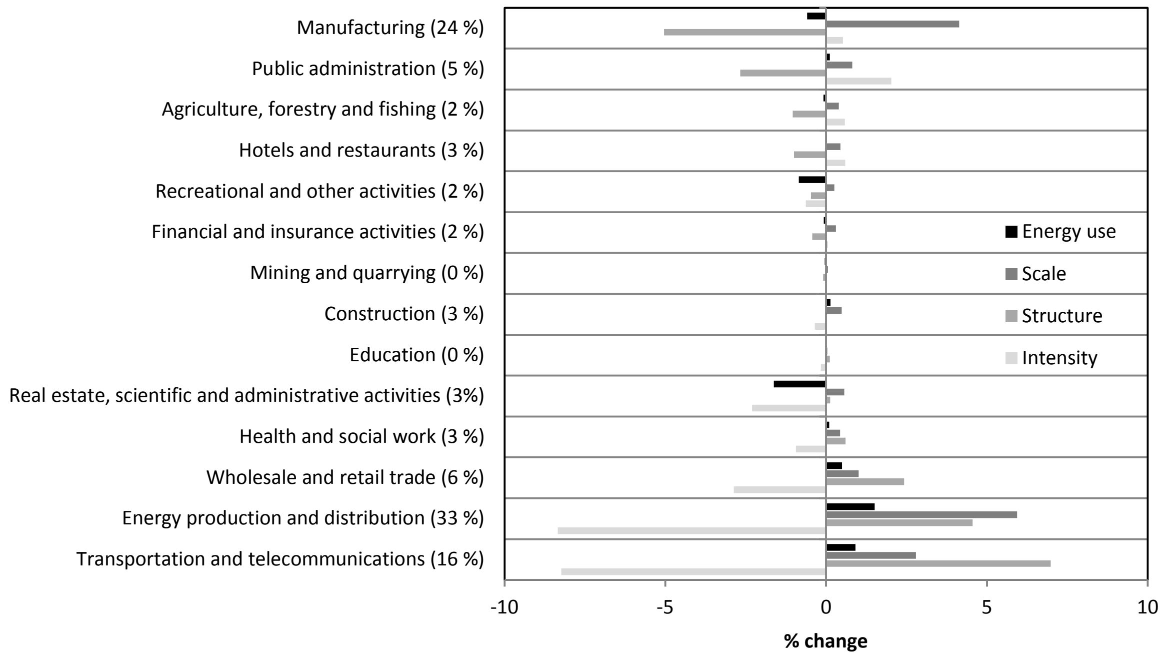

Figure 4: Contributions from scale, structure and efficiency factors to changes in energy use per economic sector in Switzerland between 2001 and 2011 (in brackets the percentage of domestic energy use in 2001)

Part of the energy embodied in imports of finished products is captured by the wholesale and retail trade sector which increases its share of domestic output.

Interpretation of the results in the energy and transportation sectors is less intuitive. Figure 4 also shows that significant changes occurred in these two sectors as a result of structural shifts in demand for services or tertiarization. Disaggregating the transportation and energy sectors would be necessary to understand which activities underwent the greatest changes. However, it appears clearly that the efforts to improve energy intensity in these two sectors (- 8 %) through energy efficiency measures have been largely offset by structural changes and growth resulting in net increase in energy use.

Overall, three conclusions can be drawn from Figure 4:

- Scale and energy efficiency are the two factors contributing most to changes in energy consumption. Scale increases in the three key energy demanding sectors, namely manufacturing, energy and transportation and telecommunications and energy intensity decreases most in the latter two.

- Structural effects tend to offset each other across sectors and in particular among trade oriented sectors (manufacturing, wholesale and retail trade and transportation and telecommunication).
- Overall, energy use changes little for the period from 2001 to 2011 in most sectors, and hence for Switzerland in general. Indeed, the impacts of scale (+ 17 %), which accounts for population and economic growth, structure (+ 4 %) and energy intensity (- 20 %) tend to compensate each other.

4.2. Energy embodied in trade

We aggregated the results of Figure 4 across all economic activities in Switzerland and added the energy embodied in trade in order to visualize the indirect impact of structural changes on energy use. The results shown in Figure 5 start from the domestic energy use in 2001 and end with energy embodied in trade for 2011.

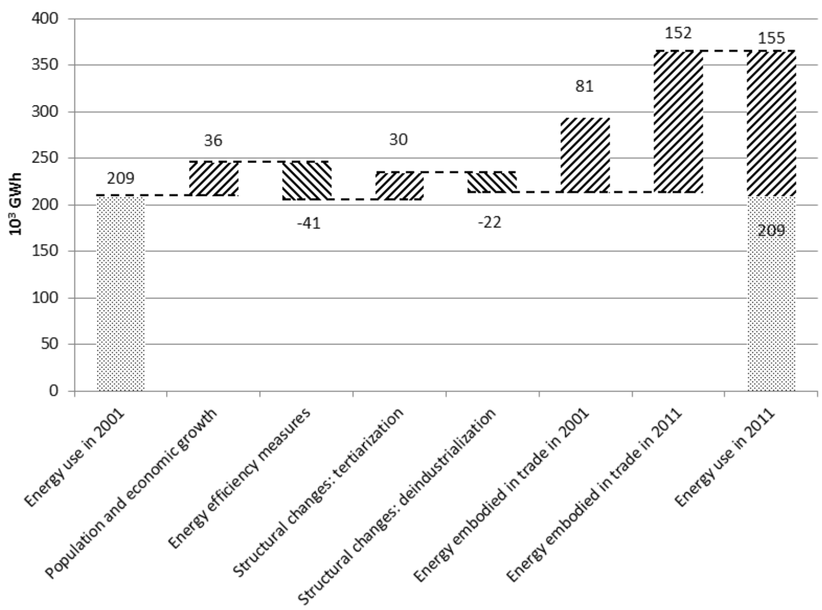

Figure 5: Overall effect from scale, structural changes, efficiency measures and embodied energy on total energy consumption (2001-2011)

Figure 5 shows the contributions of each factor in absolute terms with the effect of structural changes on energy use separated between increase (tertiarization) and decrease (deindustrialization). Interestingly, all contributions are of the same order of magnitude except for energy embodied in trade.

Domestically, structural changes play a slightly smaller role than population and economic growth or energy efficiency measures, but have as an indirect consequence to shift the energy use abroad, as shown by the analysis at the level of economic activities in Figure 4. This delocalization of energy use is represented in Figure 5 by the energy embodied in trade, which is the difference between that in imports and exports. The effect of structural changes on energy embodied in trade is significant as it results in indirect energy consumption growing from 81’000 GWh in 2001 to 152’000 GWh in 2011.

Figure 6 shows that embodied energy in imports rose by 97 % (+ 107’000 GWh) while that embodied in exports rose by 119 % (+ 35’000 GWh) from 2001 to 2011. Thus, the energy trade balance computed from equation (4a) yields an 89 % increase (+ 72’000 GWh) in the energy embodied in trade over the same period of time. In the complete time series of Figure 6, the values of energy embodied in imports and exports were estimated for the years marked with a star. Linear regression for these estimates provided a reasonably high level of confidence (R^2 = 0.93).

The dotted line in Figure 6 shows the total energy balance of economic activities supplying final demand in Switzerland as calculated with equation (4b). From a consumption perspective, the results show that Switzerland increasingly depends on large inputs of energy embodied in imports. Such indirect energy consumption represented 38 % (110’000 GWh) of the total energy balance in 2001 and 60 % (217’000 GWh) in 2011. Estimated values for 2013 show that the share of energy embodied in imports might have reached a plateau. Yet total energy balance rose by 24.5 % from 2001 to 2011 (dotted line). This is more than GDP which grew by 19 % over the same period of time. Therefore, economic activities and energy use (final and embodied) have remained strongly coupled. In other words, based on direct and indirect energy consumption there is no observable decoupling between economic growth and rising energy use.

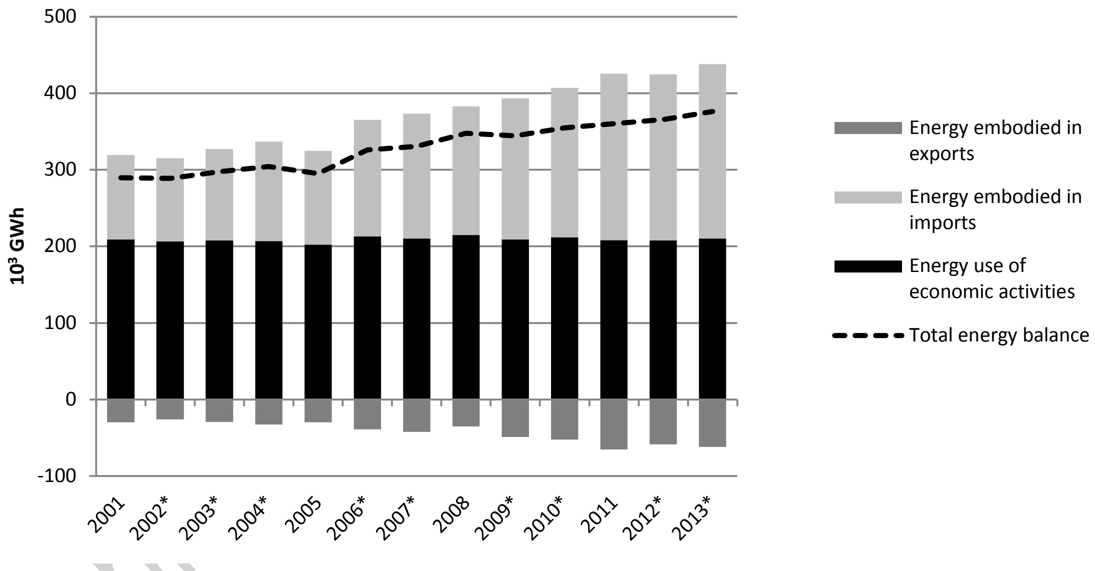

Figure 6: Total energy balance for Switzerland

Interestingly, Figure 6 shows that the economic downturn of 2008 has meant very little changes in energy terms. Structural changes happen over extended periods of time. Thus we used the MR IOTs available for the years 2000 and 2007 in order to validate these results. Compared with the first, hybrid IO approach, the embodied energy in imports and exports derived from MR IOTs resulted in highly different values for 2000 and 2007. As the level of disaggregation increases between the IOT of 2000 and that of 2007, data uncertainty in the case of Switzerland likely increases as well since some sectors have very few actors.

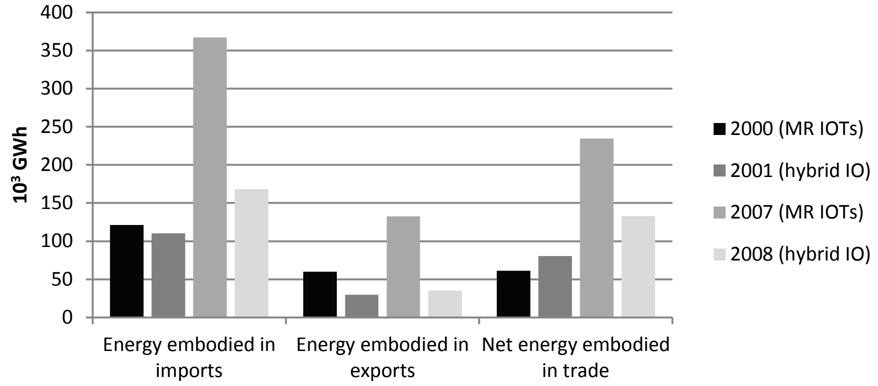

Figure 7: Comparison of energy embodied in trade from both methodological approaches

For the year 2007, the data would imply that the energy embodied in imports is more than 175 % of the energy used in domestic activities. Thus, comparing the hybrid IO approach, based on the energy accounts for Switzerland, with that based solely on MR IOTs partly reflects the limited availability of data for Switzerland. Nevertheless, the results of the latter IO approach provide a lower and upper bound for the net energy embodied in trade or energy trade balance reported above.

4.3. Virtual decoupling

Figure 8 below shows the original curve of Figure 1 for domestic energy intensity in Switzerland, to which we have added the same data series adjusted for embodied energy in trade. As expected from the results above (Figure 6), energy intensity increases slightly when adjusted for embodied energy. This trend in "total energy intensity" differs significantly from that bolstered by domestic activities alone. Overall, economic activities are becoming more energy intensive, not less. On the one hand deindustrialization is shifting energy use abroad, thus improving energy intensity domestically. On the other hand, tertiarization increases value added per unit of energy or resource use. Yet total energy use increased more than GDP. The differences in energy intensities domestically and abroad partly explain the absence of decoupling. For instance the intensity of the manufacturing sector shown in Figure 3 means that economic activities fare better in Switzerland than abroad in energy terms, albeit on a highly aggregated level.

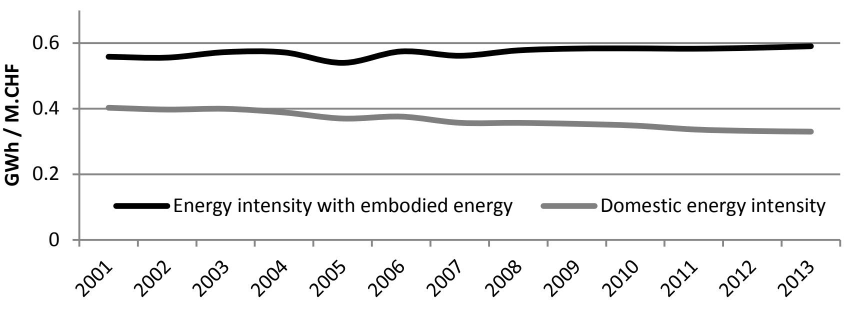

Figure 8: Energy intensities with and without embodied energy in trade, in GWh per million CHF2011

Conclusions

The main conclusion from this research is that Switzerland has not succeeded in decoupling economic growth from energy consumption, unlike what national statistics might display. Rather, Switzerland has converted some of its final energy consumption into embodied energy in imported products, thus giving the illusion of decoupling. We call it virtual decoupling. This result has broad and strategic implications as it challenges national policy objectives.

Economic activities in Switzerland continue to rely on trade and simultaneously increase the share of embodied energy in the total energy balance. The objective to reduce the country's energy dependence seems even further when accounting for indirect consumption. Our results show that the proportion of energy embodied in imports went from 38 % to 61 % of total energy in 2001 and 2013 respectively. Therefore, despite all the efforts to implement energy efficiency measures and renewable energy technologies, the energy independence is rapidly decreasing.

Decomposition analysis shows that energy efficiency measures compensate little more than the growth in energy consumption. At the level of economic sectors the main exception among the energy intensive activities is manufacturing where structural effects are more important than scale. Deindustrialization has been greatest in manufacturing, shifting energy use abroad. The impact of such changes is compounded by the fact that the energy terms of trade are unequal, energy intensity is higher in foreign than domestic production. Structural changes in the transportation and telecommunication sector essentially result from tertiarization which affects direct rather than indirect energy consumption.

The dual methodological approach shows that there is an optimal level of disaggregation for economic activities which are least represented in IOTs. In other words the hybrid IO approach proves more suitable when very few industries are active in each sector. In spite of their significance and magnitude, the results of this approach are support by those derived from MR IOTs, which might overestimate embodied energy in some sectors.

Finally, we conclude that when accounting for total energy use, including energy trade balance, the energy intensity of economic activities in Switzerland is increasing more rapidly than GDP. In other words there is no observable decoupling between economic growth and rising energy use. These results give new evidence that a consumption perspective is highly relevant for comprehensive energy policies, particularly in the case of trade oriented countries such as Switzerland.

Acknowledgments

The authors wish to thank their colleagues at the Energy Center for fruitful discussion on the subject of this article. Vincent Moreau also thanks the College of Humanities for funding under the special energy funds.

References

Ang, B.W., 2005. The LMDI approach to decomposition analysis: a practical guide. Energy Policy 33, 867–871. doi:10.1016/j.enpol.2003.10.010

Baiocchi, G., Minx, J.C., 2010. Understanding Changes in the UK's CO2 Emissions: A Global Perspective. Environ. Sci. Technol. 44, 1177–1184. doi:10.1021/es902662h

Bullard, C.W., Herendeen, R.A., 1975. The energy cost of goods and services. Energy Policy 3, 268–278. doi:10.1016/0301-4215(75)90035-X

Chitnis, M., Sorrell, S., Druckman, A., Firth, S.K., Jackson, T., 2013. Turning lights into flights: Estimating direct and indirect rebound effects for UK households. Spec. Sect. Long Run Transit. Sustain. Econ. Struct. Eur. Union Beyond 55, 234–250. doi:10.1016/j.enpol.2012.12.008

Dietzenbacher, E., Los, B., Stehrer, R., Timmer, M., de Vries, G., 2013. The construction of world input-output tables in the WIOD project. Econ. Syst. Res. 25, 71–98. doi:10.1080/09535314.2012.761180

ESA, 2010. European system of accounts. Eurostat.

European Commission, 2011. Energy Roadmap 2050.

Frischknecht, R., Nathani, C., Büsser Knöpfel, S., Itten, R., Wyss, F., Hellmüller, P., 2014. Entwicklung der weltweiten Umweltauswirkungen der Schweiz. Umweltbelastung von Konsum und Produktion von 1996 bis 2011 (No. 1413), Umwelt-Wissen. Bundesamt für Umwelt, Bern, Switzerland.

Hoekstra, R., van den Bergh, J.C.J.M., 2003. Comparing structural decomposition analysis and index. Energy Econ. 25, 39–64. doi:10.1016/S0140-9883(02)00059-2

Jungbluth, N., Nathani, C., Stucki, M., Leuenberger, M., 2011. Environmental Impacts of Swiss Consumption and production. A combination of input-output analysis with life cycle assessment (Environmental studies No. 1111). Federal Office for the Environment, Bern.

Mayer, H., Flachmann, C., 2011. Extended Input-Output Model for Energy and Greenhouse Gases (No. 5850011-11900–4). Statistisches Bundesamt, Wiesbaden.

Minx, J.C., Baiocchi, G., Peters, G.P., Weber, C.L., Guan, D., Hubacek, K., 2011. A "Carbonizing Dragon": China's Fast Growing CO2 Emissions Revisited. Environ. Sci. Technol. 45, 9144–9153. doi:10.1021/es201497m

Munksgaard, J., Pade, L.L., Minx, J., Lenzen, M., 2005. Influence of trade on national CO2 emissions. Int. J. Glob. Energy Issues 23, 324. doi:10.1504/IJGEI.2005.006950

Muradian, R., O'Connor, M., Martinez-Alier, J., 2002. Embodied pollution in trade: estimating the "environmental load displacement" of industrialised countries. Ecol. Econ. 41, 51–67. doi:10.1016/S0921-8009(01)00281-6

Nathani, C., Sutter, D., van Nieuwkoop, R., Kraner, S., Peter, M., Zandonella, R., 2013. Energiebezogene Differenzierung der Schweizerischen Input-Output-Tabelle 2008. Bundesamt für Energie, Bern, Switzerland.

Peters, G.P., Minx, J.C., Weber, C.L., Edenhofer, O., 2011. Growth in emission transfers via international trade from 1990 to 2008. Proc. Natl. Acad. Sci. 108, 8903–8908.

Schaffartzik, A., Mayer, A., Gingrich, S., Eisenmenger, N., Loy, C., Krausmann, F., 2014. The global metabolic transition: Regional patterns and trends of global material flows, 1950–2010. Glob. Environ. Change 26, 87–97. doi:10.1016/j.gloenvcha.2014.03.013

Schuerch, R., Kaenzig, J., Jungbluth, N., Nathani, C., 2012. 45th Discussion forum on LCA—environmentally extended input–output analysis and LCA, September 15, 2011, Berne, Switzerland. Int. J. Life Cycle Assess. 17, 840–844. doi:10.1007/s11367-012-0428-5

SFOE, 2014. Gesamtenergiestatistik. Swiss Federal Office of Energy, Bern, Switzerland.

SFSO, 2015. National Accounts: Gross Domestic Product. Swiss Federal Statistical Office.

Su, B., Ang, B.W., 2012. Structural decomposition analysis applied to energy and emissions: Some methodological developments. Energy Econ. 34, 177–188. doi:10.1016/j.eneco.2011.10.009

Swiss Confederation, 2013. Energy Strategy 2050.

Swiss Customs Administration, n.d. Swiss-Impex database.
Tukker, A., de Koning, A., Wood, R., Hawkins, T., Lutter, S., Acosta, J., Rueda Cantuche, J.M., Bouwmeester, M., Oosterhaven, J., Drosdowski, T., Kuenen, J., 2013. EXIOPOL - Development and illustrative analyses of a detailed global MR EE SUT/IOT. Econ. Syst. Res. 25, 50–70. doi:10.1080/09535314.2012.761952
Tukker, A., Dietzenbacher, E., 2013. Global multiregional input-output frameworks: an introduction and outlook. Econ. Syst. Res. 25, 1–19. doi:10.1080/09535314.2012.761179
Warr, B., Ayres, R., Eisenmenger, N., Krausmann, F., Schandl, H., 2010. Energy Use and Economic Development: A Comparative Analysis of Useful Work Supply in Austria, Japan, the United Kingdom and the Us During 100 Years of Economic Growth. Ecol. Econ. 69, 1904–1917. doi:10.1016/j.ecolecon.2010.03.021
Wiedmann, T., Lenzen, M., Turner, K., Barrett, J., 2007. Examining the global environmental impact of regional consumption activities — Part 2: Review of input–output models for the assessment of environmental impacts embodied in trade. Ecol. Econ. 61, 15–26. doi:10.1016/j.ecolecon.2006.12.003
Xu, Y., Dietzenbacher, E., 2014. A structural decomposition analysis of the emissions embodied in trade. Ecol. Econ. 101, 10–20. doi:10.1016/j.ecolecon.2014.02.015