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Where is the money ? A decomposition of monetary flows behind fossil fuels

Xiang Li[a],*, Jonas Schnidrig[a],*, Raphaël Briguet[a],*, and François Maréchal[a]

[a] *Ecole Polytechnique Fédérale de Lausanne, Sion, Switzerland, xiang.li@epfl.ch*
[a] *Ecole Polytechnique Fédérale de Lausanne, Sion, Switzerland, jonas.schnidrig@epfl.ch*
[a] *Ecole Polytechnique Fédérale de Lausanne, Sion, Switzerland, raphael.briguet@epfl.ch*
[a] *Ecole Polytechnique Fédérale de Lausanne, Sion, Switzerland, francois.marechal@epfl.ch*
** Authors contributed equally to this manuscript.*

Abstract:

Transition from fossils to renewables is leading to radical societal changes. Shifting the capital from fossils to renewables is commonly accompanied with political concerns, such as energy autonomy, domestic employment etc. Despite a decreasing trend in recent decades, energy cost remains the major bottleneck for a massive penetration of renewables, resulting in diverse policies with respect to carbon taxes and renewable subsidies.

This study focuses on analysing the opportunities for Switzerland within the energy transition, through a systematic assessment on the curent petroleum supply chain with associated cost decomposition. By modeling a fossil fuels supply chain, it is within reach to estimate the final price decomposition of petroleum products. To be more precise, the aim of this study, based on open source data, is to highlight how the money spent in fossil fuels is distributed in the industry and to examine opportunities an energy transition could offer to the country in question. Applied to Switzerland, but applicable to any other country, the results show that more than 30% of the final price is spent and invested outside the country. For instance, the Swiss net import of fossil fuels alone amounted to 7.2 billions CHF in 2019. If this capital had been invested in PV, Switzerland could have produced 33.5 TWh/year, constituting 60% of Swiss electric production in 2020. In the near future, this reinvestment in PV would contribute more generally to the full development of solar energy, whose walls and roofs potential in the Swiss context is estimated to be around 67 TWh/year.

Keywords:

Supply chain, Cash flow, Energy policy, Sustainability.

1. Introduction

In 2019, coal, natural gas and oil represent 81% of the world's total energy supply (respectively 26.8%, 23.2% and 30.9%) [1]. Concurrently, fossil fuels are also the primary source of carbon dioxide as they generate 65% of the global greenhouse gas emissions [2]. Despite a high penetration of renewable electricity, Switzerland is still fossil-dominant, with 59% energy demands covered by fossil fuels in 2020 [3]. In addition to global warming and human health concerns related to the consumption, fossil fuels guarantee of supply is significantly influenced by political and economical context.

Despite all these challenges, energy autonomy is becoming increasingly essential, especially for countries that lack of alternative energy sources. A holistic understanding of the current cash flows in the energy system is thus necessary for strategy-making towards a low-carbon society.

Some estimations of the breakdown of fossil costs can be found in the following literature. The French government [4] assesses the local refinery and distribution cost for France by relying upon the market prices and open source data. *TotalEnergies* decomposes the French fuel into four shares, respectively refined fuel price, taxes, distribution and French margin [5] while [6] deals with crude oil price, refinery, distribution and taxes.
If the previous methods do decompose the price in several categories, they however only consider and analyse processes occurring inside the country and hence neglect the price construction abroad. Moreover, the methodologies are not clearly stated and the results are generally not thorough.

To overcome these difficulties, this paper tries to answer the following questions: what is the composition of the fossil fuel costs and how are they attributed ? How are consumers impacted by the market ? What is the potential of shifting these expenses made abroad to domestic investment in renewable energy ?

For this purpose, we have modelled the fossil fuel monetary flow applied to Switzerland. It describes the lifecycle prices of fossil fuels from production to consumption, based on the decomposition of process cost and open source data.

2. Modelling of the prices of fossil fuels

The model, that describes the cost decomposition from the producer to the consumer, is illustrated in Fig. 1, with three typical fossils: natural gas, gasoline, and diesel. In this respect, Switzerland has almost no fossil fuel reserves [3], which consequently leads to an import of the totality of the consumption. In addition, the country can import either raw materials to locally refine them or directly import derivative products.

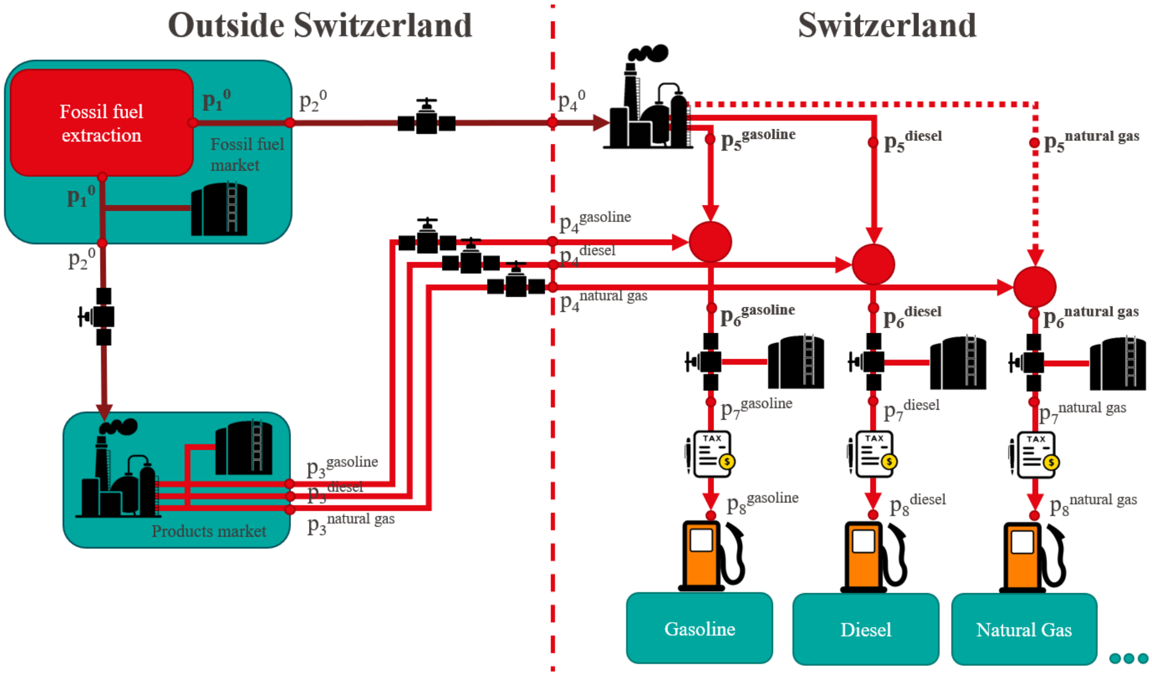


Figure 1: Fossil fuel supply chain model with intermediate steps represented by a price p_s^f. The two steps are separated by one or many processes that add value to the product (e.g. refining, transport, ...). The pipes stand for the transporation of the aforementioned fuels. The natural gas line is dashed since Switzerland does not locally refine natural gas. The prices in bold indicate that the value is not available in the literature and therefore, that an estimation is required.

In Fig. 1, the model can be decomposed with intermediate prices. The price in the form p_s^f corresponds to the price of a fossil fuel product $f \in \mathcal{FF}$ at the step $s \in \mathcal{STEP}$ of the supply chain. Table 1 provides a summary of these prices. The values that cannot be found in the literature are highlighted in **bold** and point to the industrial non-transparency regarding processes such as extraction and refinery.

In this paper, we define the cost $c^f_{s\rightarrow s+1}$ by the difference between the two consecutive prices p_s^f and p_{s+1}^f. It includes the costs of all transformations or processes that add a value to the product from step s to $s+1$, i.e. $c^f_{s\rightarrow s+1} = \sum_\rho c^{f,\rho}_{s\rightarrow s+1}$ with $\rho \in \mathcal{PROCESS} = \{transport, refining, taxes, ...\}$ and $f \in \mathcal{FF}$ including gasoline, diesel, heating oil, natural gas. The general expression is:

$$p_j^f - p_i^f = \sum_{s=i}^{j-1} c^f_{s\rightarrow s+1} = \sum_{s=i}^{j-1} \left(\sum_\rho c^{f,\rho}_{s\rightarrow s+1} \right) \qquad \rho \in \mathcal{PROCESS}, \quad f \in \mathcal{FF} \tag{1}$$

Our methodology consists in a deep breakdown of specific processes with available cost information and this, in order to reduce the degree of freedom in the blackbox question.

For the sake of clarity and uniformity with respect to our results, this study shows the outcomes in CHF/kWh. The exchange rate is assumed 0.93 €/CHF in average for year 2021. The units used by the data sources can however differ. Table 8 of Annex B summarises all the values used for conversion throughout this study. In order to reduce the volatility of oil/gas markets, the results of this study are based on the average of the annual values from 2009 to 2019.

Table 2 depicts the average values that are needed for further calculations.

Table 1: Summary of the model's prices. The source is indicated when available. If it is not the case, the section of the corresponding estimation is mentioned.

	Description	Type of Source
$\mathbf{p_1^0}$	The real price of crude oil	Evaluated in Section 3.1.
p_2^0	Crude oil market price	Brent crude oil spot market [7]
p_3^f	Refined products market price	Refined products spot market [8]
p_4^0	Import price of crude oil	Swiss foreign trade statistics [9]
p_4^f	Import price of refined products	Swiss foreign trade statistics [9]
$\mathbf{p_5^f}$	Product price after local refining	Evaluated in Section 3.2.
$\mathbf{p_6^f}$	Refined products price before distribution	Evaluated in Section 3.2.
p_7^f	Final selling price without taxes	Calculated in Section 5. using taxes data [10]
p_8^f	Final selling price with taxes	Consumer price statistics [11]

Table 2: Average cost for fossil fuels from literature

2009-2019 [cts.CHF/kWh]	Selling Price p_8^f	Swiss Taxes $c_{7\to8}^{f,Tax}$	Import Price p_4^0, p_4^f	Spot Market Price p_2^0, p_3^f
Crude oil	-	-	4.84	4.61
Heating oil	9.24	2.79	5.42	5.09
Gasoline	18.77	9.34	6.33	5.97
Diesel	17.40	9.04	5.91	5.74
Natural gas (heating)	9.75	2.38	4.88	2.71
References	[11]	[10]	[9]	[8]

3. Estimation of the missing prices

3.1. Real cost of fossil fuels p_1^0

The fossil fuels products are traded on the market at a price fixed by the law of supply and demand, but the latter does not however reflect their real value. Nevertheless, by knowing the world annual up-stream investments $C_y^{inv,\uparrow}$ made in the extraction of fossil fuels and the annual production of crude oil, coal and natural gas E_y^{Prod}, the specific cost of producing those resources p_1^0 can be estimated by (2).

$$p_1^0 \text{ [CHF/kWh]} = \frac{\sum_y C_y^{inv,\uparrow} \quad \text{[CHF/year]}}{\sum_y E_y^{Prod} \quad \text{[kWh/year]}} \qquad \forall \quad y \in \mathcal{YEARS} \tag{2}$$

The data collected for this section's estimation only engage with upstream investments, which include the exploration, drilling and extraction of the fossil fuels [12].

3.2. Refined products price before distribution p_5^f and p_6^f

In this paper, it is assumed that the local and imported fossil products share the same transportation and distribution infrastructure within Switzerland, modelled by the process cost $c_{6\to7}^f$. In addition, both types are understood to be sold at the same price according to the Nash equilibrium assumption, reading:

$$p_5^f = p_4^f = p_6^f \qquad \forall f \in \mathcal{FF} \tag{3}$$

3.3. Selling price without taxes p_7^f

The Swiss fossil fuels taxes depend on the type, but also on the use of products. It includes Mineral Oil Tax, VAT and CO_2 Tax and is applied, regardless of the origin of the product, at the last step before being sold to the consumer. The detailed composition of the tax $c_{7\to8}^{f,Tax}$ for each product can be found in the literature [10]. It allows to write the following relation and to calculate p_7^f:

$$p_8^f - p_7^f = c_{7\to8}^f = c_{7\to8}^{f,Tax} \iff p_7^f = p_8^f - c_{7\to8}^{f,Tax} \tag{4}$$

4. Estimation of the processes cost outside the borders

This section focuses on assessing the processes occurring between each step of the model, as for instance before entering the border of the country, and then giving an estimation of their cost. Two cases can be distinguished: the product is refined locally ($p_1^0 \to p_4^0$) and abroad ($p_1^0 \to p_4^f$).

4.1. Local refining : $p_1^0 \rightarrow p_4^0$

After extraction, the fossil fuel is traded on the market at a price p_2^0 which does not correspond to the real price of extraction p_1^0. This difference is considered to be the gross margin of the producer $c_{1\rightarrow 2}^{Gmarg}$. In order to maximize the net margin $c_{1\rightarrow 2}^{Nmarg}$, the producers commonly limit the supply compared to the demand by using storage, which induces an additional cost, named $c_{1\rightarrow 2}^{Sto}$. The gross margin can be calculated by writing the relation:

$$c_{1\rightarrow 2}^{Gmarg} = c_{1\rightarrow 2}^{Sto} + c_{1\rightarrow 2}^{Nmarg} = p_2^0 - p_1^0 \tag{5}$$

The cost of the storage $c_{1\rightarrow 2}^{Sto}$ is difficult to be estimated, due to heterogeneous arbitrage strategies, which will be elaborated in Section **??**. Additionally, when Switzerland imports crude oil to refine it, transport has to be paid as well. In this respect, the transport cost $c_{2\rightarrow 4}^{Trans}$, from the producer to the border, is measured by the difference between the market price of raw product p_2^0 and the import price p_4^0:

$$c_{2\rightarrow 4}^{Trans} = c_{2\rightarrow 4} = p_4^0 - p_2^0 \tag{6}$$

4.2. Abroad refining : $p_1^0 \rightarrow p_4^f$

When the country does not have sufficient refining capacity, importation of refined products is needed. It is considered that between the crude oil market price p_2^0 and the refined product market price p_3^f are included: the transport cost of the raw material to the refinery $c_{2\rightarrow 3}^{f,Trans}$, the refining cost $c_{2\rightarrow 3}^{f,Tef}$ and the gross margin of the refinery $c_{2\rightarrow 3}^{f,Gmarg}$:

$$p_3^f - p_2^0 = c_{2\rightarrow 3}^f = c_{2\rightarrow 3}^{f,Trans} + c_{2\rightarrow 3}^{f,Ref} + c_{2\rightarrow 3}^{f,Gmarg} \tag{7}$$

In contrast to the extraction of crude oil, the refining is mainly located in EU. It can then be estimated that, in average, the cost for transporting the crude oil to the European refinery $c_{2\rightarrow 3}^{f,Trans}$ is in the same order of magnitude as transporting it to Switzerland ($\Rightarrow$ $c_{2\rightarrow 3}^{f,Trans} = c_{2\rightarrow 4}^{Trans}$), e.g. from Nigeria. Similarly, the refining operating cost $c_{2\rightarrow 3}^{f,Ref}$ can be apprehended as similar to the local refinery $c_{4\rightarrow 5}^{f,Ref}$. Section 5.1. features the methodology deployed for valuing $c_{4\rightarrow 5}^{f,Ref}$. Using these assumptions, (7) can be adapted and eventually allows $c_{2\rightarrow 3}^{f,Gmarg}$ to be estimated:

$$c_{2\rightarrow 3}^{f,Gmarg} = p_3^f - p_2^0 - c_{2\rightarrow 4}^{Trans} - c_{4\rightarrow 5}^{f,Ref} \tag{8}$$

Finally, the transport cost of the refined products $c_{3\rightarrow 4}^{f,Trans}$ from the refinery to the border of the country (from p_3^f to p_4^f) is expressed through the difference between the market price p_3^f and the import price p_4^f:

$$c_{3\rightarrow 4}^{f,Trans} = p_4^f - p_3^f \tag{9}$$

5. Estimation of the processes cost inside the borders

Considering that the model outside the country is now developed, this chapter deals with the estimation and composition of fossil fuels' cost, from the border to the consumer. In this case, the fuels sold to Swiss consumers come either from a local refinery or from abroad.

For each type of product, the price can be modelled as following:

$$\begin{cases} p_5^f - p_4^0 = c_{4\rightarrow 5}^f = c_{4\rightarrow 5}^{f,Ref} + c_{4\rightarrow 5}^{f,Gmarg} \\ p_7^f - p_6^f = c_{6\rightarrow 7}^{f,Distr} \end{cases} \tag{10}$$

With the refining operating cost $c_{4\rightarrow 5}^{f,Ref}$, the gross margin of the refinery $c_{4\rightarrow 5}^{f,Gmarg}$ and the cost of distribution $c_{6\rightarrow 7}^{f,Distr}$ in the country including transport and storage.

Using the assumption (3), (10) can be rewritten in order to isolate $c_{6\rightarrow 7}^{f,Distr}$ and $c_{4\rightarrow 5}^f$:

$$\begin{cases} c_{6\rightarrow 7}^{f,Distr} = p_7^f - p_6^f = p_7^f - p_4^f \\ c_{4\rightarrow 5}^f = c_{4\rightarrow 5}^{f,Ref} + c_{4\rightarrow 5}^{f,Gmarg} = p_5^f - p_4^0 = p_4^f - p_4^0 \end{cases} \tag{11}$$

In the case of Switzerland, the selling price p_8^f [11], the importation prices of petroleum products p_4^0 and p_4^f [9] as well as the Tax [10] can be found in the literature. According to (11), the unknowns $c_{4\rightarrow 7}^{f,Distr}$ and $c_{4\rightarrow 5}^f$ can then be estimated. The latter two are analysed in more details in the dedicated Sections 5.2. and 5.1..

5.1. Refinery cost

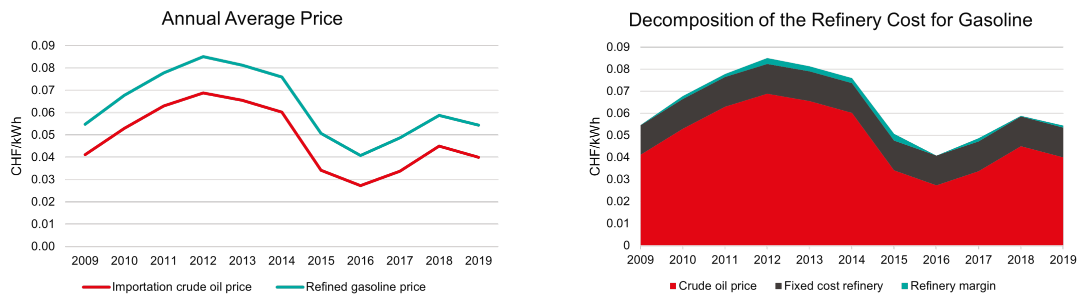
It is assumed that the cost $c^{f}_{4\to5}$ (given by (11)) involves a fixed investment and operating cost $c^{f,Ref}_{4\to5}$ and a variable margin $c^{f,Gmarg}_{4\to5}$. The approach developed in this part does not calculate the exact value of the margin made by the refinery industry, but aims to give an order of magnitude of a lower bound, by building upon the annual data from 2009-2019. On a given time range, the minimum difference between the import crude oil price p^{0}_{4} and the price of the products after the refinery p^{f}_{5} draws an upper bound of the fixed investment and operating cost $c^{f,Ref}_{4\to5}$:

$$c^{f,Ref\lceil}_{4\to5} = \min_{y}\left(p^{f}_{5,y} - p^{0}_{4,y}\right) \quad \forall \quad y \in \mathcal{YEARS} \tag{12}$$

Once the operating cost is fixed, the annual minimum margin $c^{f,Gmarg}_{4\to5}$ corresponds to the average of what remains between the two curves and can be calculated as:

$$c^{f,Gmarg\lfloor}_{4\to5} = Average_{y}\left(p^{f}_{5,y} - p^{0}_{4,y} - c^{f,Ref}_{4\to5}\right) \quad \forall \quad y \in \mathcal{YEARS} \tag{13}$$

Fig. 2 shows these two prices and the decomposition between margin and operating cost for each year.



(a) (b)

Figure 2: Example of the lower bound and margin estimation for gasoline. Fig. 2a shows the price of the crude oil when entering the refinery and the price of gasoline when leaving it. The minimal difference is observed in 2016 and serves here to fix the higher bound value of the fixed investment and operating cost $c^{f,Ref}_{4\to5}$ (see Fig. 2b). The lower bound of the refinery margin $c^{f,Gmarg}_{4\to5}$ is then equal to what remains between the two curves (green area in Fig. 2b)

5.2. Distribution cost

The cost of distribution $c^{f,Distr}_{6\to7}$ represents all the infrastructures and expenses that allow to establish the relation between the border (or the refinery) and the final consumer. The estimation is given by (11). In this section, the cost $c^{f,Distr}_{6\to7}$ is divided into three elements:

- $c^{f,Trans}_{6\to7}$: the cost to transport the fuels inside the country.
- $c^{f,Sto}_{6\to7}$: the cost to store the fossil fuels. The storage assures consumers a secure fuel or heating oil supply.
- $c^{f,Other}_{6\to7}$: all other expenses during the distribution. For instance, it consists of the logistic, marketing or tank-station amortisation.

The cost of distribution can then be detailed as:

$$c^{f,Distr}_{6\to7} = c^{f,Trans}_{6\to7} + c^{f,Sto}_{6\to7} + c^{f,Other}_{6\to7} \tag{14}$$

6. Results and Discussion

6.1. Processes cost

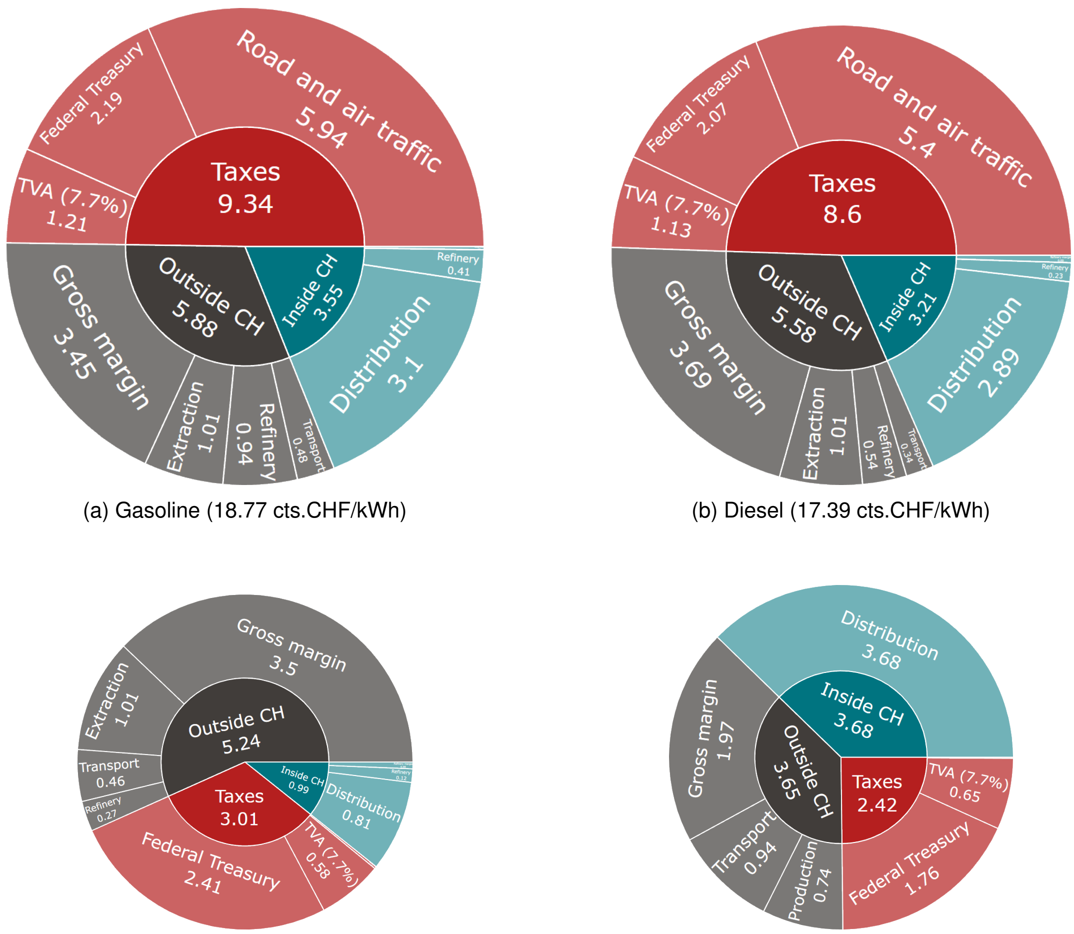
Firstly, the real prices of fossil fuels, as developed in Section 3.1., are calculated. It costs 1.01 cts.CHF/kWh to extract crude oil, 0.73 cts.CHF/kWh for natural gas and 0.21 cts.CHF/kWh for coal. Detailed tables of the annual cost, upstream investments and production can be found in the Appendix B, Table 5, 6 and 7.

Using 11, the refinery cost $c^{f}_{4\rightarrow5}$ (for products refined in Switzerland) and the distribution cost $c^{f,Distr}_{6\rightarrow7}$ (from border/refinery to the consumer) can be calculated. The results are shown in Table 3. It can be noted that, as natural gas is not produced in Switzerland, there is no value for $c^{Natural\ gas,Ref}_{4\rightarrow5}$.
The results demonstrate that, in terms of volume (i.e. litre), the diesel and the gasoline have a comparable cost of distribution, which corroborates the fact that their distribution system is indeed similar.

Table 3: Cost details of fossil refined in Switzerland

	$c^{f}_{4\rightarrow5}$		$c^{f,Distr}_{6\rightarrow7}$	
	[cts.CHF/kWh]	[cts.CHF/l]	[cts.CHF/kWh]	[cts.CHF/l]
Heating oil	0.58	6.28	0.81	8.76
Gasoline	1.49	13.40	3.10	27.81
Diesel	1.07	10.57	2.89	28.48
Natural gas (heating)	-	-	3.68	-

The Section 5.1. describes a method that estimates the minimum margin that a refinery can make by assuming a fixed cost of operation. The results are presented in Table 4 of Annex A.



(a) Gasoline (18.77 cts.CHF/kWh)
(b) Diesel (17.39 cts.CHF/kWh)
(c) Heating oil (9.24 cts.CHF/kWh)
(d) Natural gas (9.75 cts.CHF/kWh)

Figure 3: Breakdown of the selling price for different fossil fuel products on the Swiss market expressed in cts.CHF/kWh. The area of the charts is proportional to the selling cost per kWh of product. The charts are divided into 3 main parts in order to highlight how the money is used.

6.2. Breakdown of the selling price

For each type of products, a certain number of processes have been identified from the extraction to the distribution to the consumer. From this point, the breakdown of the price can be made. It can be noted that, as suggested above, the decomposition of the price is different depending on where the product is refined. The refinery's share of the domestic sales allows to compute the weighted sum of each process cost to generate only one general breakdown for each type of fossil fuels. For the case of Switzerland, the Fig. 3 illustrates the results. When summing up all the taxes for mineral oil tax and CO_2 tax respectively, the numbers match well the tax revenue reported by SFOE.

Concerning the **mobility fuels** (see Fig. 3a and 3b), the first important point to highlight is that the taxes account for 50% of the bill. However, a large part of this tax (32% of the total) is used for the maintenance of the Swiss roads. This remark put indeed into question the manner in which this income will be replaced with the electrification of mobility. More concerning, for the gasoline, 31% of the final price are expenses outside Switzerland. In addition, the gross margin made by the industries outside the country accounts for 18% of the total price. The share that corresponds to the cost to produce gasoline (extraction and refinery) accounts only for 10% of the selling price.
It is observed that the transport cost to import crude oil accounts for 2.5% which is very low compared to the cost of distribution of gasoline inside Switzerland (16%). It can be explained by the fact that the crude oil is transported to Switzerland in large quantities and mainly by pipeline, ship and rail [13], which are greatly cheaper than truck transport [14], that is widely used to supply the local gas station. Moreover, the distribution accounts for the transport but also for the cost of storage and other expenses (see Section 5.2.). The breakdown of the cost of diesel is similar to gasoline in terms of shares.

Regarding the price of **heating oil** (see Fig. 3c), the taxes are less impacting compared to the mobility fuels, and are logically not used for roads maintenance. However, 57% of the final cost is spent outside the country. Moreover, 38% is directly linked to the margin of the producer. Compared to mobility fuels, a CO_2-Tax is collected on this product, representing 85% of the total tax and 27% of the heating oil price.

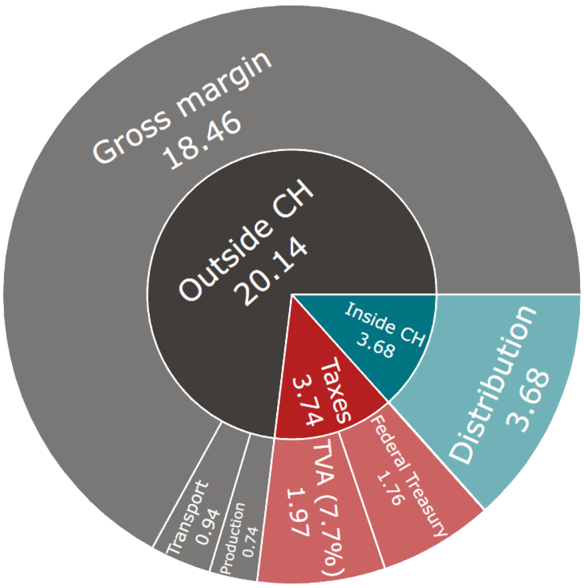


Figure 4: Natural gas (27.56 cts.CHF/kWh). Breakdown of the selling price of natural gas according to the European market price during the week of the 28 of February 2022. The area is proportional to the graphics of Fig.3 in terms of selling price in cts.CHF/kWh.

Finally, for **natural gas** (see Fig. 3d), 37% of the cost are expenses outside Switzerland. The cost of distribution in Switzerland takes the largest part of the total price (38%). Additionally, the transport cost is higher than for liquid fossil fuels.

As aforementioned, the data used for the Swiss case is the average on 10 years to mitigate high volatility. Black swan events, like the explosion of the price of natural gas between the end of 2021 and 2022 with the beginning of the Russia-Ukraine war. The European natural gas market price ($p_3^{natural\ gas}$) (Dutch TTF Gas) reached, in average, 192 CHF/MWh during the first week of March 2022 [15] while the average for 2009-2019 is 27 CHF/MWh. Considering that the taxes (except TVA), the costs of distribution, transport, extraction and refining remain constant ($c_{3\rightarrow 7}^{natural\ gas} = cst$), the Fig. 3d can be adapted to the 192 CHF/MWh to highlight what this extra is used for. By keeping the proportions for the area of the chart, the result is presented in Fig. 4. The shares *inside CH*, *Federal Treasury*, *Transport* and *Production* remain unchanged while the *Gross margin* represents now 67% of the total selling price while it is "only" 20% for the 2009-2019 average (Fig. 3d). The selling price has increased by 183%. It can also be noted that the Swiss confederation takes advantages of high prices since the TVA (Value Added Tax) is a percentage of the selling price. The selling price can be related to the market price $p_3^{natural\ gas}$ $[cts.CHF/kWh]$ with the function:

$$p_8^{natural\ gas} = 1.077 \cdot p_3^{natural\ gas} + 6.874$$

It is also interesting to look at it in terms of quantity. Fig. 5 represents the mass flow of fossil fuel products in Switzerland in 2019. One quarter of the petroleum consumption is supplied by the imported products. Only a small part is exported. In regard to the capital invested each year, the net importation of fossil fuels amounted to 7.2 billions CHF. In terms of comparison, the investment cost for a small scale PV system is typically 2.6 CHF/W with a lifespan of 20 years [16]. Assuming an interest rate of 5%, the annualized investment cost is 0.209 CHF/W/year, meaning that the annual expenses of 7.2 billions CHF/year could be invested in 34 GW in PV rather than in fossil fuels. With a specific yield of 985 kWh/kW per year [17], the annual PV production of electricity would be 33.5 TWh (50% of estimated roof and wall solar potential by Swiss Federal Office of Energy) according to Energy Strategy 2050+, which corresponds to 60% of Swiss electricity production of 2020 [18].

Storage technology is an essential element when switching to renewable energy, however, the size and the cost remain difficult to evaluate. Considering that 50% of the 3.9 millions Swiss households are equipped with PV panels and a typical 10,000 CHF battery system [19], the additional cost for storage would be, in the order of magnitude of 19.5 billions CHF. With a lifespan of 10 years, the annualized cost amounts to 2.5 billions CHF/year.

7. Conclusion

All along this study, a model that describes the price of fossil fuels has been developed. A large number of processes from the production to the consumer have been identified and a strategy to estimate their prices has been established. This study is dedicated to Switzerland. However, the methodology could be regarded as universal by changing the input data. Within the framework of Switzerland, our results show that a large part of the selling price of fossil fuels is used outside Switzerland: 31 % for gasoline, 32% for diesel, 57% for heating oil and 37% for natural gas. Moreover, more than half of these shares are estimated to be margin made by the producer. The annual abroad expenses made in petroleum products could allow to produce 60% of the Swiss electricity if it was invested in PV systems.

The substitution of fossil fuels by renewable energies is an important challenge for the near future. The potential of replacing the annual expenses in fossil fuels by renewable technologies was pointed out. However, when comparing the fossil fuels imports expenses to the PV investment cost, an important element is not taken into account, namely the storage to alleviate the intermittency of renewables. The infrastructure involves an important investment that needs to be accounted. This aspect is often neglected when speaking about the cost of renewable energy.

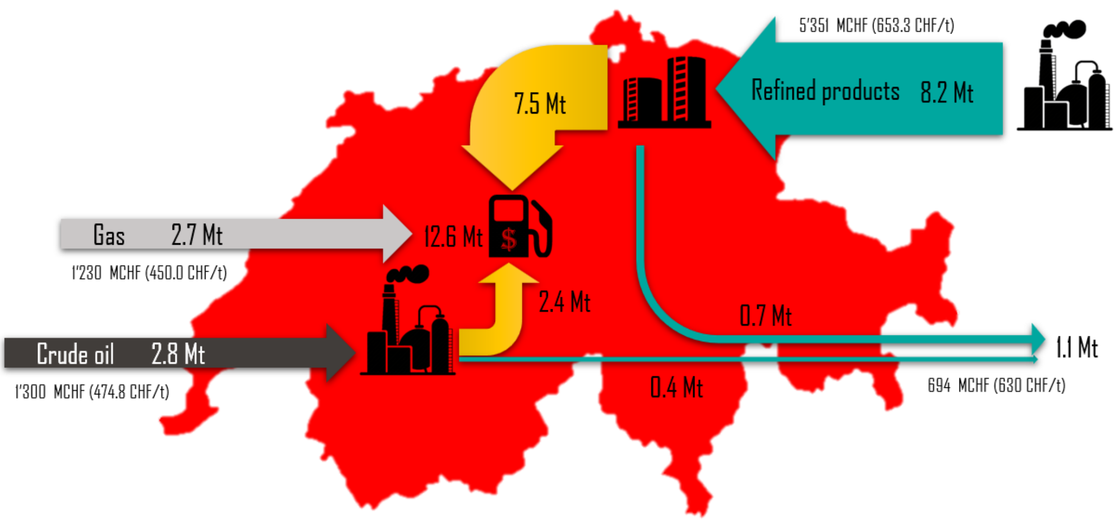


Figure 5: Oil Products Flow (2019) [20]

Appendix A Additional results

Table 4: Decomposition of the Swiss refinery cost

2009-2019 [cts.CHF/kWh]	Maximum fixed operat./invest. cost $c^{f,Ref\lceil}_{4\rightarrow 5}$	Average minimum margin $c^{f,Gmarg\lfloor}_{4\rightarrow 5}$
Heating Oil	0.390	0.194
Gasoline	1.348	0.143
Diesel	0.777	0.294

Appendix B Data tables

Table 5: Real price of fossil fuels

[cts.CHF/kWh]	2015	2016	2017	2018	2019	2020	Average p_1^0
Crude Oil	1.23	0.98	1.02	1.03	1.03	0.78	1.014
Natural Gas	0.95	0.80	0.78	0.73	0.69	0.48	0.733
Coal	0.24	0.21	0.19	0.18	0.21	0.20	0.205

Table 6: World investment in fossil fuel upstream in billion CHF [21]

(billion CHF 2019)	2015	2016	2017	2018	2019	2020	2021
Crude Oil	553.4	445.1	460.1	472.8	472.8	328.9	361.6
Gas	329.5	284.3	285.1	281.0	275.9	188.6	235.3
Coal	106.5	88.9	80.9	82.9	98.1	89.3	89.7
Total	989.4	818.3	826.1	836.6	846.8	606.8	686.7

Table 7: World production of fossil fuel

[TWh]	2015	2016	2017	2018	2019	2020	Reference
Crude Oil	45061	45525	45084	46048	45729	42099	IEA - Oil [22]
Gas	34670	35333	36694	38433	40111	38992	IEA - Natural Gas [23]
Coal	44905	42306	43702	45432	46470	44328	IEA - Coal [24]

Table 8: Energy density of fossil fuels

	MJ/kg	kWh/kg	KWh/Litre	kg/m3	kg/litre
Gasoline	43.4	12.1	8.98	745	0.745
Diesel	42.8	11.9	9.87	830	0.83
Heating oil	45.58	12.7	10.76	850	0.85
Crude oil	42.7	11.9	10.23		0.862
Natural gas	48	13.3			
Coal	22.7	6.3			

Source: EngineeringToolbox [25], Total Energies [26], FioulMarket [27]

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