# Exergy assessment of future energy transition scenarios with application to Switzerland

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## Abstract:

Using an exergy based indicator is highly desirable to compare future national energy strategies. A new web-based information platform called energyscope.ch, informing the general public on the Swiss energy transition was presented at ECOS2016. This paper presents a new extension of the approach that we plan to call exergyscope.ch, clearly stating exergy and distinguishing between primary exergy, final exergy and useful exergy. This allows for a graphical interpretation of the exergy efficiency of each conversion step from primary exergy to final exergy, all the way to useful exergy. Different future energy scenarios for Switzerland are compared to illustrate the gain in exergy efficiency between different strategy choices. Monthly variations in exergy supply are considered by using an average reference temperature for each month. The analysis assesses the useful exergy requirement for all energy services including building and transportation. For heating and cooling services, the proposed framework is coherent with the introduction, reported earlier, of an exergy efficiency indicator in a Law on energy. Accordingly the global exergy efficiency for providing a given useful exergy service can be calculated by multiplying the individual exergy efficiency of each conversion steps. The useful industrial thermal exergy is introduced in a simplified manner with an average service temperature.

## Keywords:

Primary, final, useful exergy, national energy scenarios, energy services.

# 1. Introduction

Even if the interest of the concept of exergy has been known by thermodynamicists [1] for many years it is not yet recognized by the major groups of policy makers planning energy strategies. Exergy efficiency, as one of the sustainability indicators, was introduced in a simplified form in a local law on energy [2] to provide guidance to planners of heating and cooling systems. However it did not yet percolate to broader areas. Energy transition scenarios are being studied in many countries like France, Germany and Switzerland to cite only a few, but they usually do not refer to the concept of exergy. In the scenario calculator energyscope.ch, presented at ECOS2016 [3] and intended for the general public as well as for swiss policy makers, exergy was not directly mentioned. However it was indirectly introduced by adding the waste heat from power plants to the statistics of final energy use in the country. Adding the waste heat to the electricity production of centralized power plants producing only electricity was like extending the system boundary to consider the fuel heating value input to these plants. It was a way to be able to see, in future scenarios, the benefits of a better use of these fuels in cogeneration units for example. Since for most fuels the heating values are closed to the exergy values the approximation was tolerable.

Proper indicators are essential to be able to judge on progress, in other words, on how good technologies or policies are to achieve a better use of resources in a modern society. First Law efficiencies just cannot do a good job in this context. It is interesting to note that Switzerland used a First Law efficiency in detailed annual reporting from 1972 to 1997 (see Fig. 1).

However the Swiss office of energy decided to cancel it in future reports, since they realized that they had more and more difficulties to explain that, in spite of energy conservation efforts, this First

Law indicator was dropping from year to year. This drop was showing the shift in modern societies from pure combustion for heating purposes in fuel boilers to more modern energy uses of fuels and electricity for transportation, mechanical work and communication. Even though graphical representations using Grassmann diagrams based on exergy, instead of Sankey diagrams based on energy, have been known since many years as shown for the swiss energy system of the year 1974 (see Fig.10.44-45 in [1]), they are not yet very common. Note that some authors use the term “Sankey exergy” instead of Grassmann. Similar comparisons of diagrams exist for other countries like in reference [4] for Canada or US-UK [5].

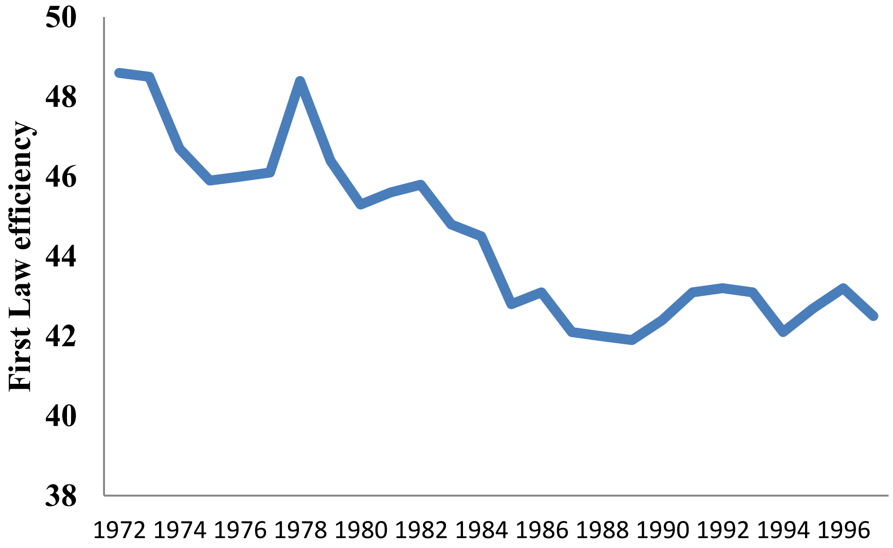

*Fig. 1 First Law efficiency evolution from Swiss early statistics* [6]

This paper intends to review the proposed approach to include exergy in the calculator energyscope.ch, to hopefully become an exergyscope.ch calculator in the future, to better illustrate the benefits of future scenarios.

## 1.1. The energy/exergy conversion chain

The chain of conversion processes from primary energy to intermediate energy, to distributed (final) energy and to useful energy was analysed for example in [7]. Note that the concept of energy versus exergy was the object of confusion throughout history. The original greek word “energeia” meant “that can do work”, that is what we call exergy today, while the term energy is used for a conservative thermodynamic entity since the mid 19th century. It often results in a confusion that is still present in modern analyses related to energy strategies. In the same reference, the distinction between energy stocks (non-renewable) and natural energy streams (renewable) is made and the different hypotheses that can be used to calculate the exergy of both are discussed. Because of the inevitable uncertainties linked to future scenario approaches, only a simplified step approach of primary exergy to final exergy and to useful exergy is done in this paper. The embedded exergy of the energy system components is not yet considered.

# 2. Methodology

## 2.1. Energy consumption

The Swiss energyscope.ch calculator divides the final energy consumption into eleven entries, which are:

- Waste heat: is the waste heat from thermal power generation. It is well known that when electricity is produced from various fuels only one part of the resulting thermal power can be converted into electricity. In this calculator the waste heat corresponds to the difference between the lower heating value of fuel consumed and the electricity produced. The waste heat related to electricity import is also taken into account. In the particular case of Switzerland the model assumes that the average energy efficiency of conventional thermal electricity production in the EU-25 is 38.2%. If useful heat is considered (cogeneration), the average energy efficiency rises up to 47.8% [8]. As mentioned before this indicator parameter was originally introduced to better illustrate the influence of cogeneration when comparing scenarios, without having to use the concept of exergy.
- Transportation: lower heating value of the fuels that are used in the transportation sector.
- Industry (th.): heat supplied by industrial cogeneration systems and lower heating value of the fuels used in boilers for industrial processes.
- Hot water (th.): heat for sanitary hot water supplied by cogeneration, solar or geothermal heat; and lower heating value of the fuels used in boilers for sanitary hot water production.
- Space heating (th.): heat for space heating supplied by cogeneration, solar or geothermal heat; and lower heating value of the fuels used in boilers for space heating.
- Transport (el.): Electricity that is consumed in the transportation sector (train and other electric vehicles).
- Industry (el.): Electricity that is consumed in industrial processes, for either heating through direct electric heating or producing work (engines).
- Hot water (el.): Electricity that is used for producing sanitary hot water through direct electric heating.
- Heat pump (el.): Electricity that is consumed by the heat pump, which mainly provide heat for hot water and space heating.
- Space heating (el.): Electricity that is used for space heating by electric direct heating.
- Other (el.): Electricity that is consumed for other purposes that have not been previously mentioned such as lighting, cooking, IT, ventilation and air-conditioning systems, etc.. In other words uses for which electricity is not in competition with other forms of final energy.

Table 1 shows the lower heating value (LHV) and the higher heating value (HHV) of the fuels together with their exergy value. Several approximations are made to simplify the approach. The exergy value for liquid fuels is assumed to be equivalent to their HHV [9]. On the other hand the exergy valu of gaseous fuels varies [1]. The exergy value of solid fuels is calculated as the average between the LHV and the HHV. Note that more precise exergy values could be substituted but differences are not relevant when considering the various levels of other uncertainties in scenario based approaches. The basic idea for these simplifications is to give the opportunity for non-specialists to introduce new fuels in a simple way.

*Table 1. Fuel properties*

| Fuel | *LHV, MJ/kg* | *HHV, MJ/kg* | *Exergy content, MJ/kg* |
|---|---|---|---|
| Methane [1] | 50.0 | 55.5 | 51.8 |
| Hydrogen [1] | 119.7 | 141.5 | 116.4 |
| Gasoline [10] | 43.4 | 46.5 | 46.5 |
| Diesel [10] | 42.8 | 45.8 | 45.8 |
| Coal [10] | 22.7 | 24.0 | 23.4 |
| Wood (Hu. = 50%) [11] | 8.55 | 10.3 | 9.42 |
| Waste [11] | 12.4 | 14.9 | 13.6 |

## 2.2. Useful exergy

The useful exergy represents the minimum amount of exergy required to deliver an energy service. The useful exergy for the transportation sector is calculated as the exergy content of the consumed fuels times the average efficiency of the mean of transportation. The average efficiency of the internal combustion vehicles is 18% [12], considering stops and partial load. The useful exergy linked to the kerosene consumption in the aviation sector is estimated with an average exergy efficiency of 30% [13]. For estimating the useful exergy for the electric mobility, the electricity consumption is multiplied by an exergy efficiency of 69% for electric vehicles, value backcalculated from [14].

The entries having heat delivery as final energy service, like in the case of "industry (th.)", "hot water (th.)", "space heating (th.)", "industry (el.)", "heat pump (el.)" and "space heating (el.)", have the useful exergy computed following Eq. (1).

$$Ex = Q * (1 - \frac{T_{amb}}{T_h}) \quad (1)$$

In Eq. (1), the exergy is equivalent to the product of the heat delivered times the Carnot factor, where $T_{amb}$ is the ambient temperature and $T_h$ is the temperature at which the heat is delivered. Table 2 and Table 3 contain the service temperatures for the different heat uses and the ambient temperature for each month of the year, respectively.

*Table 2. Service temperatures*

| Energy service | *Temperature, K* |
|---|---|
| Process heating | 473 |
| Hot water | 313 |
| Space heating | 293 |

*Table 3. Ambient temperature for each month of the year for the city of Bern, Switzerland [15].*

| Month | *Jan.* | *Feb.* | *Mar.* | *Apr.* | *May* | *Jun.* | *Jul.* | *Aug.* | *Sep.* | *Oct.* | *Nov.* | *Dec.* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Temperature, K* | 271 | 273 | 277 | 283 | 285 | 290 | 293 | 290 | 286 | 282 | 278 | 272 |

Finally the useful exergy for the "Other (el.)" entry is judged to be equal to the electricity consumption, thus no conversion factor is required.

## 2.3. Final exergy

Final exergy is defined as the exergy that the consumers buy or receive, which can be reduced to fuels, electricity and renewable heat from solar thermal panels and geothermal plants. Hence the entries representing electricity consumption, "el.", do not need any conversion factor, since the conversion from electricity consumed to final exergy is 1 to 1.

The final exergy associated to the fuels consumption in the transport sector is equal to the sum of the exergy content of all fuels consumed for mobility. A change from LHV basis to exergy content basis is performed using the values in Table 1.

The final exergies for "Industry (th.)", "Hot water (th.)" and "Space heating (th.)" are calculated in the same manner as for the fuels for mobility or consumed in boilers. On the other hand the final exergy for the heat from cogeneration systems is calculated as the exergy content of the "fuels-for-heat" consumption. "Fuels-for-heat" is defined as the heat supplied by the cogeneration system divided by 0.9 (0.1 being lost to atmosphere, since there are inevitable thermal losses in any cogeneration system). The calculation of "fuels-for-heat" answers to the problem of resources allocation between electricity and heat generation from cogeneration systems. "Fuels-for-heat" is equivalent to the fuel consumption if the heat from cogeneration was supplied by a boiler with 90% efficiency.

When it comes to renewable heat, the final exergy is estimated with Eq. (1) where $Q$ is the heat obtained by the consumer and $T_h$ is the temperature at which the consumer receives the heat from the environment, which is 328K [16] for thermal solar panels and 393K for geothermal heat [17].

## 2.4. Primary exergy

The primary exergy is equivalent to the exergy obtained from the environment. The primary exergy of the fuels consumed in vehicles, boilers and cogeneration system ("fuels-for-heat") is obtained considering 10% losses in the extraction/production processes of the fuels, which is equivalent to say that the primary exergy for the fuels is equal to the final exergy divided by 0.9.

The primary exergy of the renewable heat is obtained from the values of renewable energy consumption, which are converted into primary exergy using the conversion factors in Table 4. The values in Table 4 are calculated for an ambient temperature ($T_{amb}$) of 282K, as they are dependent to the ambient temperature they vary along the year.

*Table 4. Conversion factors from primary exergy to renewable heat*

| Technology | *Factor, -* |
|---|---|
| Geothermal[1] | 0.33 |
| Solar thermal[2] | 0.48 |

[1] The conversion factor is equal to the Carnot factor (0.33, with $T_{amb}$ = 282K and $T_H$ = 423K, corresponding to the assumed underground temperature).

[2] The conversion factor is equal to the product of the Carnot factor (0.95, having $T_{amb}$ = 282K and $T_H$ = 5800K, corresponding to the temperature of the sun surface [18]), by the thermal solar panel efficiency (0.5 [16]).

In order to calculate the primary exergy of the entries representing electricity consumption (from "Transport (el.)" to "Other (el.)" it is necessary to know the specific primary exergy content of the electricity mix in Switzerland, which is computed as the sum of all primary exergy dedicated to electricity supply divided by the amount of electricity generated. The calculation is done on a monthly basis.

The primary exergy consumption of the technologies converting fossil or biogenic fuel is equivalent to the primary exergy of their fuel consumption subtracting the part corresponding to the "fuels-for-heat", to avoid double counting. Just as for the primary exergy calculation of the fuels for boilers, 10% losses in the extraction/production process of the fuels are assumed.

Table 5 contains the conversion factors for the evaluation of primary exergy use for electricity generation with renewable and nuclear technologies. Note that, as explained in [19], the conversion factor for nuclear should be much lower but a standard approach is used here.

*Table 5. Conversion factors from primary to final exergy for renewable and nuclear electricity supply technologies*

| Technology | *Factor, -* |
|---|---|
| PV | 0.17 [1] |
| Wind | 0.44 [2] |
| Hydro Dam | 0.88 [2] |
| Hydro River | 0.88 [2] |
| Geothermal | 0.23 [3] |
| Nuclear | 0.32 [19] |

[1] Exergy efficiency is equal to the product of the Carnot factor (0.95, having $T_{amb}$ = 282K and $T_H$ = 5800K, corresponding to the temperature of the sun surface [18]), the PV panel efficiency (0.19 [20]) and the converter efficiency (0.94).

[2] Exergy efficiency is equal to the product of the recoverable energy of the intercepted wind kinetic energy (16/27, defined by the Betz formula [21]) and a factor taking into account the electro-mechanical losses of the turbine (0.75).

[3] Exergy efficiency of Húsavík plant (Kalina cycle) [17].

The electricity mix in Switzerland also includes electricity imports depending on the energy scenario. In 2011, the main suppliers of electricity to Switzerland were Germany and France [22]. The electricity production mix of these two countries is taken into account to calculate the primary exergy content of the imported electricity. Table 6 contains this data and the corresponding primary exergy. The efficiencies in Table 7 together with the data in Table 1 are used for the calculation of the primary exergy. The imported electricity in Switzerland has a primary exergy content of 2.79 $\text{GWh/GWh}_{\text{ImportedElec}}$. This value is calculated taking into account the net electricity imports in Switzerland in 2011, which correspond to 25 TWh from France and 1.4 TWh from Austria [22]. The primary exergy content for the French and Austrian electricity mixes are 2.85 $\text{GWh/GWh}_{\text{Elec}}$ and 1.61 $\text{GWh/GWh}_{\text{Elec}}$, respectively. The primary exergy contents are computed using the French and Austrian electricity mix in 2011 [23]. This value is calculated in an annual basis, and it must be considered as a strong assumption, since it is not possible to know neither the electricity mix of the neighbouring countries of Switzerland in the future, or the size of the electricity imports from each country.

*Table 6. Electricity production and primary exergy consumption for power generation in 3 neighbouring countries in 2011*[23].

| Technology | *Elec. production, TWh* | | | *Primary exergy, TWh* | | |
|---|---|---|---|---|---|---|
| | Italy | Germany | France | Italy | Germany | France |
| Coal | 50 | 272 | 17 | 133 | 720 | 46 |
| Oil | 20 | 7 | 3 | 47 | 17 | 8 |
| Gas | 145 | 87 | 27 | 245 | 148 | 45 |
| Biofuels | 9 | 33 | 3 | 26 | 99 | 9 |
| Waste | 5 | 11 | 4 | 15 | 38 | 14 |
| Nuclear | 0 | 108 | 442 | 0 | 337 | 1382 |
| Hydro | 48 | 24 | 50 | 54 | 27 | 57 |
| Geothermal | 6 | 0 | 0 | 25 | 0 | 0 |
| Wind | 11 | 20 | 2 | 64 | 115 | 12 |
| TOTAL | 10 | 49 | 12 | 22 | 111 | 27 |
| Exergy content, $(TWh_{Ex}/TWh_{El})$ | | | | 2.09 | 2.64 | 2.85 |

*Table 7. First law efficiencies for the technologies for the technologies supplying the electricity imports*

| Technology | *Efficiency, %* |
|---|---|
| Coal | 40 |
| Oil | 45 |
| Gas | 58 |
| Biofuels | 40 |
| Waste | 35 |

# 3. Results

The methodology is applied to the year 2011 and to the Business as Usual (BAU) and New Energy Policies (NEP) scenarios for 2050. The BAU scenario is the most conservative scenario of the three scenarios proposed by the Swiss Federal Office of Energy (SFOE) [24]. By 2050, it has a 17% reduction on the $CO_2$ emissions in comparison to 2011, which was achieved with 17% energy from renewable sources in its energy mix. On the other hand, the NEP is the most optimistic scenario. It reduces the $CO_2$ emissions by 67% compared to 2011 values, with 71% renewable penetration in its energy mix [25]. Note that the electricity demand is larger in the BAU scenario than in the NEP.

Fig. 2 presents the three types of exergy consumption together with the final energy consumption for the above listed years and scenarios. 2011 presents the highest primary exergy and final exergy consumption, followed by the BAU and NEP scenarios, respectively. This order is not respected for the useful exergy indicator. The change is explained by the fact that the useful exergy indicator represents the minimum exergy required for supplying the energy services, thus the inefficiency of the exergy conversion chain in not reflected. The indicator only regards the energy service demand. In this case, the BAU scenario presents the highest "Other (el.)" electricity demand which is translated 1 to 1 into useful exergy.

Including the waste energy from power plants in the final energy consumption approximates the final energy consumption values to the primary exergy consumption. In 2011, the difference between the two indicators is 7%. This difference can be attributed to the conversion factor from primary to final exergy for the hydro power plants (see Table 5). Nonetheless, the difference increases when the scenarios integrate higher percentages of renewable resources, as in the NEP scenario.

The percentages below the columns in Fig. 2 compare the final exergy, useful exergy and final energy consumption of each year and scenario with its respective primary exergy consumption. It depicts the exergy efficiency of the conversion chain. The percentage of primary exergy converted into useful exergy in the NEP scenario is lower than in the BAU scenario. The low factors for the renewable electricity sources in Table 5, particularly for PV, explain the lower efficiency of the NEP scenario. The NEP scenario has an important share of photovoltaic electricity, while the BAU scenario promotes the combined cycle gas turbine (CCGT) (see Fig. 3). Considering 60% first law efficiency for CCGT, its conversion factors from primary to final exergy is 0.59, which is 3 times higher than the one for PV (0.17).

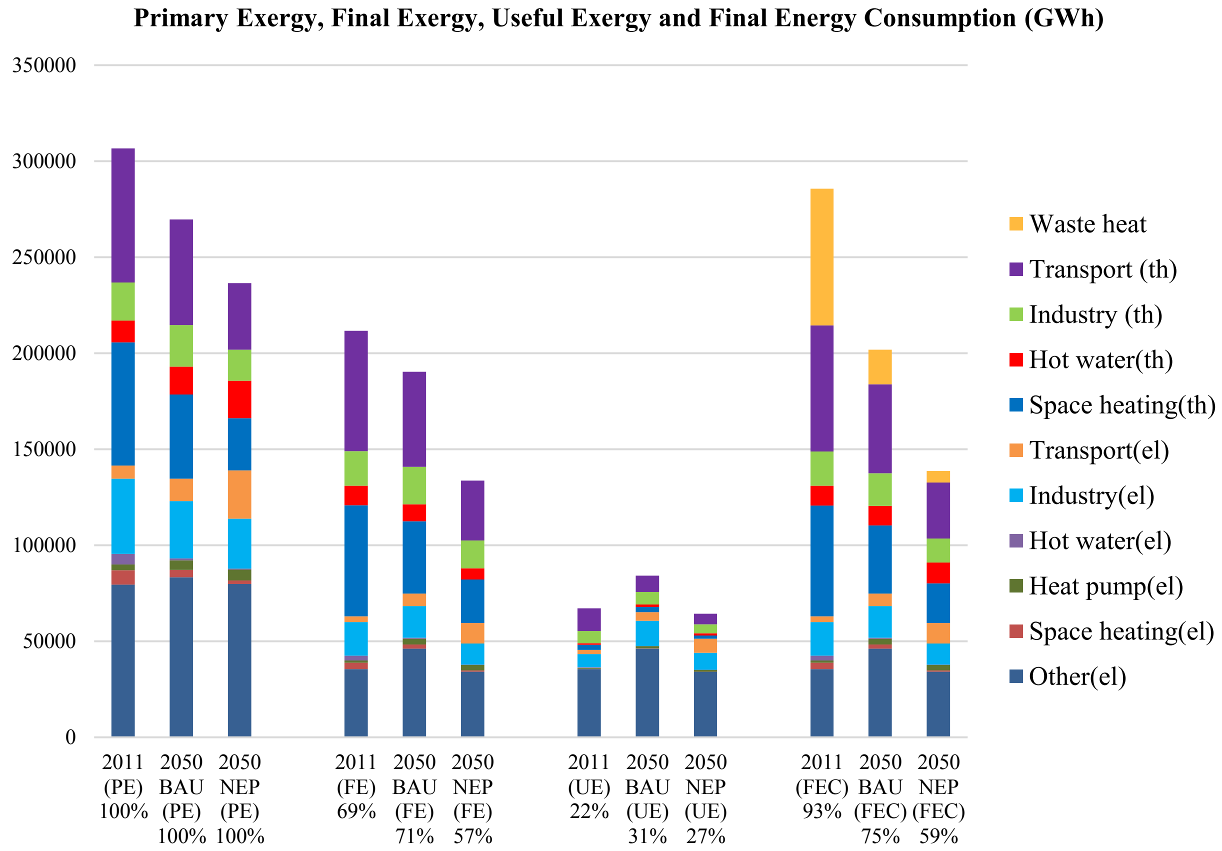

*Fig. 2 Primary Exergy (PE), Final Exergy (FE), Useful Exergy (UE) and Final Energy Consumption (FEC) for 2011, Business as Usual scenario (BAU) in 2050, and New Energy Policies scenario (NEP) in 2050.*

Fig. 4 compares the primary exergy, final exergy useful exergy and final energy consumption by season (winter and summer) for the NEP scenario. The primary exergy consumption for "Other (el.)" is 20% higher in summer than in winter, while the final energy consumption for the same entry is constant along the year. The difference is due to the change in the electricity mix, which contains more electricity from PV in summer than in winter, hence there are more primary exergy apparent losses.

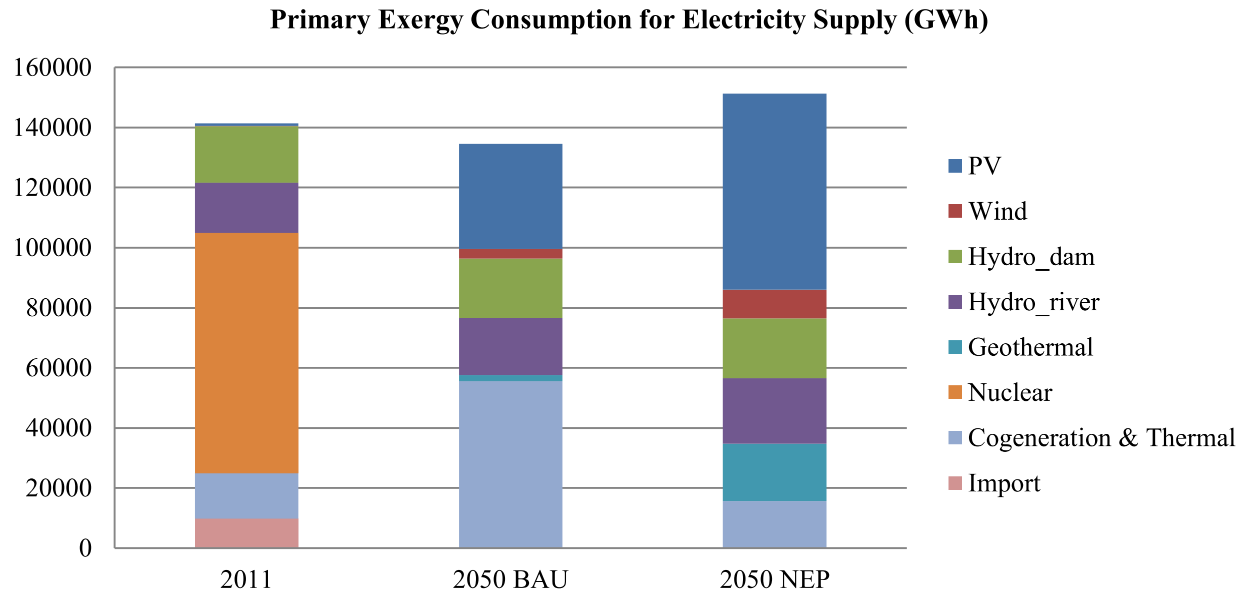

*Fig. 3 Primary Exergy consumption for electricity supply in 2011, Business as Usual scenario (BAU) in 2050, and New Energy Policies scenario (NEP) in 2050.*

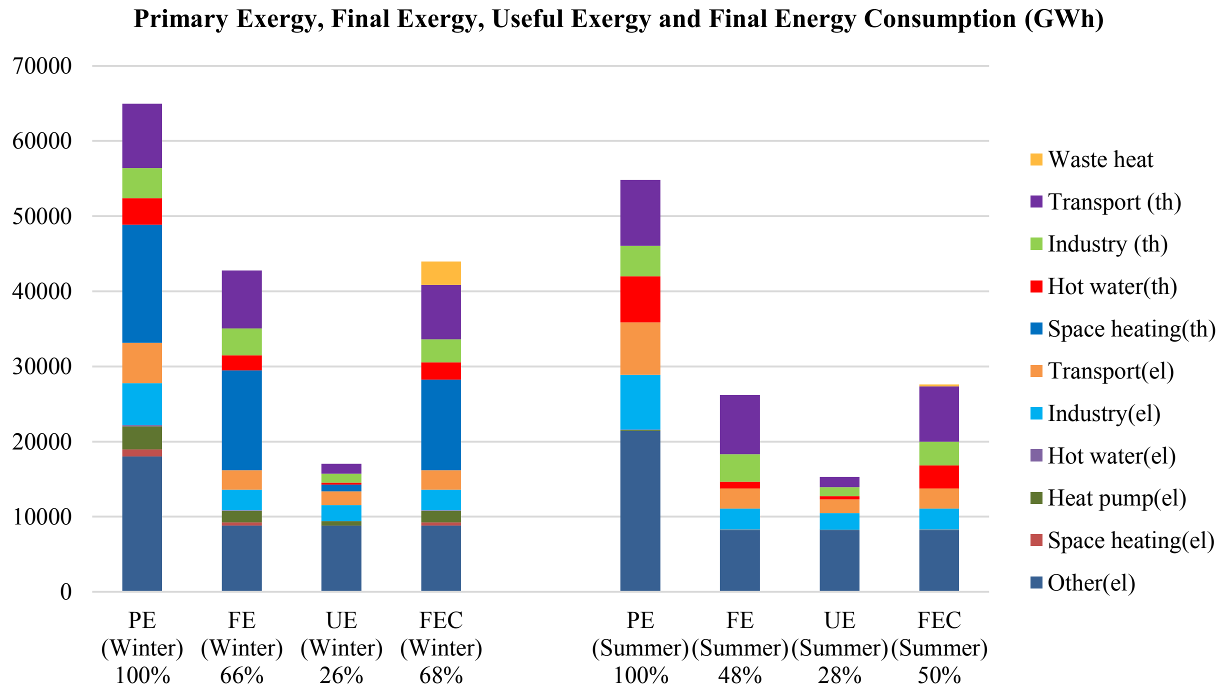

*Fig. 4 Primary Exergy (PE), Final Exergy (FE), Useful Exergy (UE) and Final Energy Consumption (FEC) for the New Energy Policies scenario (NEP) in summer and winter 2050.*

On the other hand, the conversion efficiency from primary exergy to useful exergy is better in summer (28%) than in winter (26%). The difference between the two of them is the lack of space heating in summer.

## 6. Conclusions

The development of a new exergy indicator to assess scenarios of national energy transition provides a more coherent way to quantify the exergy efficiencies linked to each transformation steps from primary to final and useful exergies. It also highlights in which sector of use of energy progress can be made. Nevertheless further work is needed, in particular to see if the fact of adding the primary exergies of flux based renewables, like solar, to the primary exergies of stock based energies, like fuels, brings useful elements when comparing scenarios. The role of embedded exergies in the components of the energy system is also to be further studied.

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