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GHG Emissions Reduction by Improving Efficiency of Utilities' Transport and Use and Cross-Sectorial Energy Integration

Andreja Nemet[a], Jiří J. Klemeš[b], Zdravko Kravanja[a,*]

[a]Faculty of Chemistry and Chemical Engineering, University of Maribor, Smetanova ulica 17, 2000 Maribor, Slovenia
[b]Sustainable Process Integration Laboratory – SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology- VUT Brno, Technická 2896/2, 616 69 Brno, Czech Republic
zdravko.kravanja@um.si

The demands and consumption of energy in the world are increasing, despite major developments towards more efficient energy production and use. Most energy supply still comes from non-renewable sources, and greenhouse gas emissions are constantly increasing, despite the development of various international policies on climate change, such as the Kyoto Protocol or the not yet ratified Paris Agreement. In this study, the potential for enhancing the efficiencies of utility transport and use, as well as cross-sectorial energy integration, are estimated for the current state of energy production, energy conversion, and energy use within and between the main sectors. Improving energy integration between different sectors can lead to significant savings in energy sources, resulting in significantly lower greenhouse gas emissions. Integrating different sectors is not a straightforward task since they use different types and loads of utilities at different levels. The first step toward integration of different energy sectors is to properly assess the primary energy source demand. A methodology for estimating primary energy requirements by tackling different types of and loads on utilities was developed. The results indicate that the primary energy source utilisation can be 2.6 times higher compared to the initial energy consumption in different sectors. The energy consumption should be addressed holistically considering at least three different aspects: i) utility transport efficiency, ii) energy efficiency within the sectors (intensification) and iii) energy integration between different sectors.

1. Introduction

Methods and techniques for advanced Heat Integration in the industry have been continuously developed over the last forty years for an overview, see Klemeš and Kravanja (2013). The widening of the scope the problem came with the proposal for heat and power integration of different plants (Dhole and Linnhoff, 1993). An extension of this Total Site methodology came with consideration of any unit, including service and residential sectors, by Locally Integrated Energy Sectors (Perry et al., 2008). The aspect of the integration of renewables has also been developed (Varbanov and Klemeš, 2011). An overview of the latest developments in Total Site planning and design for industrial, urban and renewable systems can be found in Liew et al. (2017). All of these approaches have focused on the integration of already produced energy, considering utility systems in a very simplistic way. There have been many attempts to consider the utility system in specific cases, such as Walmsley et al. (2017). It should be noted that these consider the utility system within the Total Site. Another large group of researchers focused on the detailed planning of the utility system in a particular region. One of these proposals involves the widely used EnergyPLAN tool. A review of EnergyPLAN tool applications and performance criteria for energy systems can be found in Østergaard (2015). This tool enables simulation of different utility system designs with special emphasis on renewable energy sources. A similar tool is H2RES, which is based on a RenewIslands methodology (an overview can be found in Duić et al. (2008)). The H2RES aims to achieve designs based 100 % on renewable energy systems in a selected region (Krajačić et al., 2009). The usual criteria in these approaches are Primary Energy Saving (PES). Other criteria were also used, such as the single combined criteria Sustainable Process Index (SPI) (Narodoslawsky and Krotscheck, 1995) or Sustainable Profit (Zore et al., 2017).

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Each group of researchers developed sophisticated methods for addressing the problem of either heat integration or the planning of a utility system. In this study, a more holistic view is presented, where a regional utility system is considered together with the requirements of different economic sectors (industry, transport, residential, service, and agriculture). It can be seen from the literature that energy losses are still significantly high; for example, the Sankey diagram of US electricity generation and use (Yong et al., 2016) derived from data presented in (EIA, 2014) indicates that 67.1 % of energy sources are consumed in operation, conversion, transmission and distribution losses and that only 32.9 % is used for the net electricity production – 12.1 % for residential use, 11.3 % for commercial, 8.3 % for industrial use and 1.2 % for direct use and transportation. It is interesting to note that the fraction of losses almost exactly matches the fraction of fossil fuels in overall energy sources. Focusing on GHG emission distribution between different economic sectors globally, it can be observed that the sector with the highest GHG emissions is the electricity and heat production sector (25 %), second is agriculture, forestry and other land use (24 %) and only in third place one can find industry (21 %). The transportation (14 %) and building (6 %) sectors also contribute significantly (EPA, 2014). Achieving better energy efficiency in the industry can contribute only partially to overall savings in energy consumption, with limited enhancement potential. Energy efficiency enhancement should focus not only on industrial processes, but on all sectors, and exploit the cross-sectorial potential of energy integration, focusing on those energy types used for production and those most utilised, since most of the energy from sources is lost during energy conversions. This study presents the development of a methodology for determining the primary energy source use analysing potential of enhancing the efficiency of utility transport and use, as well as cross-sectorial energy integration. The detailed energy flow description indicates the potential for improvement. The methodology developed was applied to the case of the EU, revealing the main potentials for improvement.

2. Methodology

The correlations between energy savings in different sectors and primary utility requirement savings are derived from the energy flows for a certain region as presented in Figure 1.

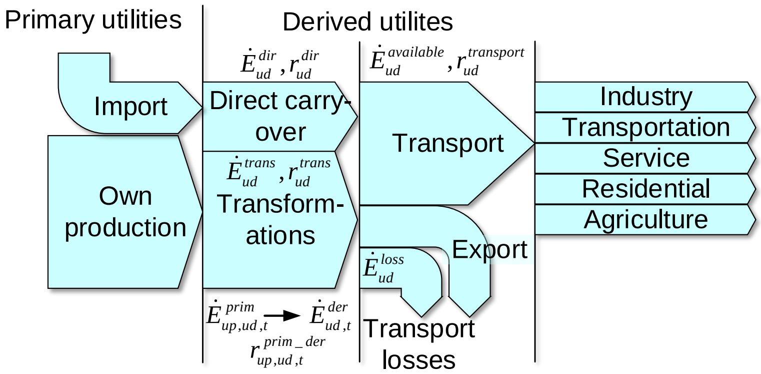

Figure 1: Energy flow from production to the place of utilisation

The aim of the methodology is to determine the ratio of the primary energy mix needed to cover the demand of a certain utility in an energy sector. The ratio calculations were derived from the demand in various energy sectors (Industry, Transportation, Service, Residential, Agriculture in Figure 1), following step-by-step the transport and transformation until reaching the primary utilities (Own production and Import in Figure 1). During transportation, losses can be considerable; and these losses are taken into account by determining the ratio of energy available after transport $r_{ud}^{transport}$ divided by the sum of available energy flow $\dot{E}_{ud}^{available}$ and energy flow of losses $\dot{E}_{ud}^{loss}$ - Eq(1).

$$r_{ud}^{transport} = \frac{\dot{E}_{ud}^{available}}{\dot{E}_{ud}^{available} + \dot{E}_{ud}^{loss}} \qquad \forall\ ud \in UD \tag{1}$$

The ratio is determined for every utility *ud* from the set of derived utilities *UD*. The export is excluded from this ratio. Before transportation, there are two main options for obtaining derived utilities. The primary utilities are either directly transported to the energy sector or derived from different primary utilities via energy transformations. The share of direct carry-over r_{ud}^{dir} is determined from Eq(2), while the share of energy flow from transformation r_{ud}^{trans} is determined from Eq(3), both for every utility *ud* from the set of derived utilities *UD*.

$$r_{ud}^{dir} = \frac{\dot{E}_{ud}^{dir}}{\dot{E}_{ud}^{dir} + \dot{E}_{ud}^{trans}} \qquad \forall ud \in UD \qquad (2)$$

$$r_{ud}^{trans} = \frac{\dot{E}_{ud}^{trans}}{\dot{E}_{ud}^{dir} + \dot{E}_{ud}^{trans}} \qquad \forall\ ud \in UD \qquad (3)$$

In the case of direct carry-over, the derived utility type is the same as the primary utility. During the transformation, the utility types changes; therefore, the ratios of transformations $r_{up,ud}^{prim\_der}$ have to be determined for every derived utility $ud \in UD$ and from every primary utility $up \in UP$. This ratio presents how much and which type of different primary utility is required to produce $\dot{E}_{up,trans}^{prim}$ the utility derived after any transformation $t \in TRANS$ $\dot{E}_{ud,t}^{der}$. In transformation, different derived utilities can be produced. Firstly, the share of primary utility flow for a certain derived utility during a certain transformation is determined (Eq(4)). The overall ratio between primary utility and derived utility $r_{up,ud}^{prim\_der}$, considering all transformations, is determined as the ratio between the sum of primary utility energy flow share over each transformation $\dot{E}_{up,ud,t}^{prim}$ and sum of derived utility energy flow $\dot{E}_{ud,t}^{der}$ (Eq(5)).

$$\dot{E}_{ud,up,t}^{prim} = \frac{\dot{E}_{up,trans}^{prim} \cdot \dot{E}_{ud,t}^{der}}{\sum_{ud'} \dot{E}_{ud',t}^{der}} \qquad \forall\ up \in UP,\ ud \in UD,\ t \in TRANS \qquad (4)$$

$$r_{up,ud}^{prim\_der} = \frac{\sum_{t \in TRANS} \dot{E}_{up,ud,t}^{prim}}{\sum_{t \in TRANS} \dot{E}_{ud,t}^{der}} \qquad \forall\ up \in UP,\ ud \in UD \qquad (5)$$

The overall ratio of primary utility $r_{up,ud}^{primary}$ is recalculated from the previously determined ratios. It presents the ratio of primary utility to ensure a unit of derived utility required at the place of utilisation (Eq(6)).

$$r_{up,ud}^{primary} = \frac{r_{ud}^{dir} + r_{ud}^{trans} \cdot r_{up,ud}^{prim\_der}}{r_{ud}^{transport}} \qquad \forall\ up \in UP,\ ud \in UD \qquad (6)$$

From the available energy flow $\dot{E}_{ud}^{available}$ for each energy type required at different sectors, the energy flow of each type of primary energy flow can be determined $\dot{E}_{up,ud}^{primary}$ (Eq(7))

$$\dot{E}_{up,ud}^{primary} = \dot{E}_{ud}^{available} \cdot r_{up,ud}^{primary} \qquad \forall\ up \in UP,\ ud \in UD \qquad (7)$$

The final energy production $\dot{E}_{up}$ required for one sector is determined for each primary utility separately by summation of energy requirement for each derived utility $\dot{E}_{up,ud}^{primary}$ (Eq(8)).

$$\dot{E}_{up} = \sum_{ud} \dot{E}_{up,ud}^{primary} \qquad \forall\ up \in UP \qquad (8)$$

The GHG emissions are recalculated from the energy flow of the primary utility energy flow.

3. Case study

A case study was performed based on energy flow statistics (EUROSTAT, 2017a), also available from the web source (EUROSTAT, 2017b), for the case of the EU. Different utility groups have been considered as solid fuels (e.g. coal, peat, oil shale and oil sand), total petroleum products (e.g. crude oil, natural gas liquids, refinery feedstocks, gasoline, naphtha, gas/diesel oil), gas (natural gas, coke oven gas, blast furnace gas), renewable energy (hydropower, wind power, solar thermal, solar photovoltaic, tide wave and ocean, biogas, geothermal energy), waste and derived heat and electricity. Table 1 presents the share of direct carry-over and energy flow used for transformations for every primary utility. It should be noted that electricity has a direct carry-over share due to import; however, the electricity should be produced from primary energy sources. It was assumed that all of the electricity was produced by transformation. This assumption essentially means the electricity imports have similar transformation as in the EU. Table 2 presents the ratio between the primary and derived utilities during transformation, as presented in Eq(5). It should be noted that transformations having an output of derived heat have an input of electricity. This requirement was recalculated to primary energy sources and included in the ratio. Table 3 presents the ratio of available energy content after transportation. This ratio serves to account for transportation losses. Table 4 presents the overall ratios of utilities required to cover the demand in various sectors and shows that for 1 GWh of solid fuels in a sector, 1.094 GWh of solid fuels is required, 0.0002 GWh of petroleum products, 0.0043 GWh of gas and 0.0002 of renewable energy because of different transformations and transport.

Table 1: Ratios between direct carry-over and transformations for different utilities for the EU for 2015 recalculated from EUROSTAT (2017b)

Utility/ratio	Solid fuels	Total petroleum products	Gas	Renewable energy	Waste	Derived heat	Electricity*
r_{ud}^{dir}	0.725	0.329	0.966	1	1	0	0 (0.113)
r_{ud}^{trans}	0.275	0.671	0.034	0	0	1	1 (0.887)

*The imported electricity has to be transformed; the assumption is that the transformations are similar to those in the EU.

Table 2: Ratios between the primary utility and derived utility in transformations

Utility	Solid fuels	Total petroleum products	Gas	Derived heat*	Electricity
Solid fuels	1.0796	0.0020	1.0710	0.8090	0.5245
Total petroleum products	0.0005	0.9686	0.0103	0.0705	0.2702
Gas	0.0147	0.0024	0.0025	0.5434	0.2738
Renewable energy	0.0005	0.0270		0.3133	0.3095
Waste	0			0.0506	0.0251
Nuclear	0			0.0035	0.8029

*Heat production requires some electricity for transformation; these needs were recalculated with respect to primary resources needs to be based on electricity transformation.

Table 3: Shares of available energy content (consideration of losses)

Utility	Solid fuels	Total petroleum products	Gas	Renewable energy	Derived heat	Electricity
$r_{ud}^{transport}$	0.9329	0.6985	0.8689	0.9913	0.8317	0.8523

Table 4: Overall ratios between utility used in a sector and the utility production requirement

$r_{up,ud}^{produced}$	Solid fuels	Total petroleum products	Gas	Renewable energy	Waste	Derived heat	Electricity
Solid fuels	1.0954	0.0019	0.0415	0		0.9727	0.6153
Total petroleum products	0.0002	1.4014	0.0004	0	0	0.0848	0.3170
Gas	0.0043	0.0023	1.1122	0	0	0.6534	0.3213
Renewable energy	0.0002	0.0260	0	1.0088	0	0.3767	0.3631
Waste	0	0	0	0	1.0232	0.0608	0.0294
Nuclear	0	0	0	0	0	0.0042	0.9420
TOTAL	1.1000	1.4315	1.1541	1.0088	1.0232	2.1527	2.5881

Four different scenarios were analysed. In the first scenario, the demands were calculated based on the methodology described presenting the current state. In the second scenario, it was assumed that the transport losses will be reduced by 5 %. In the third scenario, the energy efficiency in each sector was forecasted from historical data presented by ODYSEE-MURE (2015) for a 10 y forecast and using this data, the energy demand was re-calculated. In the fourth scenario, both transport efficiency enhancement and energy sector efficiency forecasts were considered. The results are presented in Figure 2a for each sector separately. The solid fuel and gas consumption in industry is expected to be further decreased as a result of enhanced energy efficiency within the sector. All the other primary energy sources are expected to decrease in the scenarios studied. In transport, the dominant primary energy source used is petroleum products. The enhancement of efficiencies in this sector can significantly contribute to the primary energy consumption decrease of petroleum products. In this case, the primary source change to an environmentally friendlier one should be studied as well. In the service sector, considering enhanced transport efficiency leads to decreased consumption of primary energy sources. When observing trends of energy efficiencies in the service sector, it was found that electricity consumption per employee is increasing, not decreasing. Primary energy consumption in this sector is higher in the third scenario. In the residential sector, energy efficiency is expected to increase, leading to decreased energy consumption. In agriculture, there is an insignificantly low energy efficiency improvement expected, but energy transport efficiency can lower consumption. The developed methodology enabled to evaluate/reveal different integration options. For example, considering improved energy efficiency in industry, 170,020 GWh electricity can be saved.

This electricity could be used to cover increasing electricity demands in services. This would lead to a 123.8*106 t CO_2 equivalent decrease. With further development of the methodology, other cross-integration options could be revealed in a systematic way, such as waste heat utilisation from industry in the residential sector. The GHG emission for each utility group was considered for the energy source type that has the highest rate. The GHG emission reduction was calculated between the first scenario and the last scenario and presented in Figure 2b. It can be seen that the highest GHG emission reduction is expected from the decreased utilisation of petroleum products in transport. A high share in GHG emission reduction can be achieved by decreased consumption of solid fuels in industry.

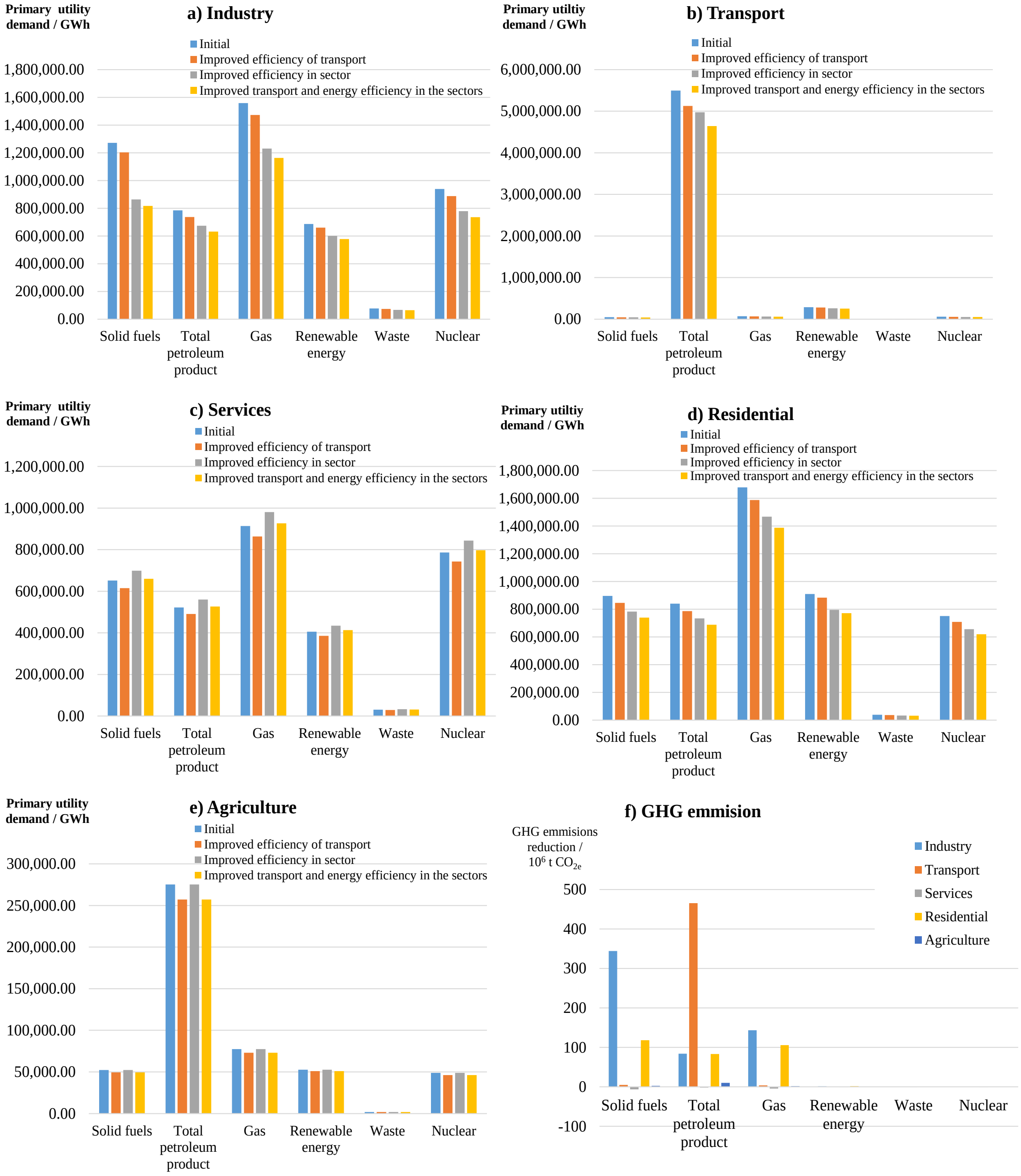

Figure 2: Primary energy source demand for each type of utility, shown separately for a) industry, b) transport, c) service sector, d) residential sector and e) agriculture considering initial, enhanced transport and enhanced sector expected energy efficiency and the enhanced transport and sector expected energy efficiency scenarios, f) GHG emission reduction between the initial case and the scenario, considering enhanced transport and energy efficiency within each sector

4. Conclusions

A methodology for recalculation of primary energy source utilisation has been developed. It enables to calculate the primary energy consumption from the final utility consumption at different sectors in a certain region. As can be seen from the case study, the primary energy used can be up to 2.6 times higher than the utility demand at the place of use. Analysing the energy flows shows that there are three main potentials for primary energy reduction: i) improving the efficiency of utility transport, ii) improving energy efficiency within the sectors and iii) integration of different sectors. From the case study for the EU, it can be seen that the largest GHG emission reduction can be achieved by improving transport. In future studies, a more detailed analysis of cross-sector integration options will be analysed, and the environmental impact will be studied from different perspectives, not only that of GHG emissions.

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