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Potential of Cross-Sector Energy Integration for Gas Emission Mitigation

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Global energy demands are increasing, and various forecast have indicated a continuing growth trend in the future. The increased demand often leads to a more stringent impact on the environment and, consequently, on humankind. To obtain a more efficient energy supply and utility network, analysis should consider improvement in i) efficiency of utility transport, ii) energy efficiency within various energy sectors (intensification), and iii) integration of different sectors. The potential of this last improvement has been only vaguely analysed, considering the business-as-usual approaches. To reveal the potential in the integration of different energy sectors, it is necessary to define the energy needed rather than considering traditional utility levels. Instead of using the top-down approach of first selecting the type and level of utility and only consequently covering the needs from available utilities, using a bottom-up approach can be beneficial. In the latter, the type and level of energy are derived for energy demands in a certain sector for the most common activities, and based on derived energy type and level requirement, the energy supply and utility network can subsequently be constructed. The aim of this study was to decrease overall primary energy source utilisation, while still covering the increasing energy demands. In this study, the types and levels of energy demands were first derived within each sector for the most common activities. The resulting solution based on cross-sector energy integration indicated heat demand reduction of 43 % and 41 % reduction of EU fossil-based GHG emissions in 2016.

1. Introduction

The main focus of Heat Integration is usually within or between industrial processes (Klemeš, 2013). There have been some studies extending the Total Site approach to include different sectors (Perry et al., 2008) e.g. for Slovenian municipality (Kostevšek et al., 2015); however, the number of those studies is rather limited. There are studies on industrial parks (Kastner et al, 2015), especially from the CO_2 emission reduction (Hassiba et al., 2017). Liew et al. (2017) presented a review of methods for planning and design of different sectors. On the other hand, energy reports focus mainly on the distribution of primary energy sources among different sectors, region, energy type etc. but they do not provide insight into how efficiently the primary energy sources are used. In previous work (Nemet et al., 2018) the influence of transport and transformation losses of primary energy sources were studied. This study aims to develop a connection between those two analyses, namely, to consider the energy integration between different sectors with the aim of increasing efficiency of the primary energy used. For this purpose, the most energy-consuming processes are identified within each sector, and cross-sector Heat Integration of those processes is performed. This aim can be seen as part of circular economy planning focusing on a primary energy source conservation. The connections between circular economy and process integration has been described by Walmsley et al. (2018).

2. Methodology

The methodology consisted of three consecutive steps. Step 1 comprised the identification of sectors and processes representing the majority of the overall energy demand. In Step 2, the identified processes were analysed and the heating and cooling demand identified and the corresponding cold and hot streams derived.

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In Step 3, the Pinch Analysis was performed for those streams to evaluate the Heat Integration potential within and between different sectors. The ΔT_{min} in all cases was assumed to be 10 °C. It should be noted that heat integration was performed without considering the current technology development level. The reason for this approach was to highlight the direction of the future development of the technology with high benefits.

3. Case study

3.1 Step 1 - Identification of sectors and processes with greatest energy demand

The Case study was performed for 2016 in the EU, since newer data has not available for all sectors considered. The main sectors, their subsectors and the processes representing the majority of the overall energy demand were identified in the first step. The sectors with the highest primary energy source utilisation, based on the energy flow-diagram, were the industry, transport, service, residential and power generation sectors. In the case of the industry sector, the following process/operations were identified as the most energy-demanding.

Table 1: The derived streams for various sectors

Stream /sector	Q (GWh y^{-1})	Tin (°C)	Tout (°C)	Fcp (GWh $°C^{-1}$)
Tuyére injection/iron and steel- BF	164,606	2,000	2,001	164,606
Stoves/iron and steel- BF	59,625	900	1,350	133
BF gas/iron and steel- BF	81,245	2,000	900	74
BOF inlet iron and steel -BOF	24,720	1,600	1,700	247
BOF gas/iron and steel -BOF	14,222	1,600	300	11
Steam/iron and steel -BOF	6,217	300	20	22
Heat requirement/iron and steel -EAF	20,995	1,600	1,601	20,995
Furnace/polyolefin-steam cracker	151,450	1,100	1,101	151,450
Steam/polyolefin-steam cracker	128,733	600	601	128,733
Hot stream polyolefin-steam cracker	2,252	600	599	2,252
Ammonia production/Haber-Bosch (ammonia)	91,089	350	550	455
Unrecovered process heat/Haber-Bosch (ammonia)	13,302	350	100	53
Flue gas heat/Haber-Bosch (ammonia)	3,041	1,000	350	5
Heating/Polyethylene and Polypropylene production	4,065	180	300	34
Heating (direct fire)/Glass production	38,845	1,575	1,576	38,845
Losses/Glass production	28,318	1,575	300	22
Heat demand/Ceramic industry	12,889	100	900	16
Losses/Ceramic industry	6,702	100	20	84
Heat demand/Cement production	109,390	1,400	1,500	1,094
Cooling/Cement production	27,631	1,400	300	25
Heat demand/Lime production	34,203	900	1,200	114
Bayer process/Aluminium production	16,113	280	281	16,113
Pulp mill process/Paper and pulp	87,909	155	175	4,395
Paper mill process/Paper and pulp	151,552	80	85	30,310
Heat demand / Food production	167,482	90	100	16,748
Freight-used/Transport	145,772	700	701	145,772
Freight -losses/Transport	218,658	700	20	322
Passenger -used/Transport	684,914	700	701	684,914
Passenger-losses/Transport	1,598,132	700	20	2,350
Space heating/Residential	2,143,250	80	81	2,143,250
Water heating/Residential	480,326	60	61	480,326
Heat demand/Service	907,397	80	81	907,397
Cold stream/Thermal Power stations	4,169,105	700	701	4,169,105
Flue gas losses/Thermal Power stations	416,911	700	300	1,042
Condensation losses/Thermal Power stations	1,645,160	21	20	1,645,160
Hot process stream (losses)/Nuclear Power stations	1,679,367	21	20	1,679,367

In the subsector Iron and steel, the Blast Furnace (BF) for pig iron production was the most energy consuming followed by the basic oxygen furnace (BOF) for primary steel production. For secondary (recycled) steel production, the electric arc furnace was the site with the highest energy consumption. In the Chemical and Petrochemical subsector, the steam crackers for production of petrochemicals, the Haber-Bosch process for ammonia production and the polyethene production processes were the most energy consuming processes.The non-metallic minerals production included the glass, ceramic, cement and lime production processes. Non-ferrous metal production included aluminium production, consisting of aluminium oxide production by the Bayer process, followed by electrolysis. Paper and pulp production proved to be a subsector with high energy demand.

3.2 Step 2 - Deriving the hot and cold process streams

Table 1 presents the derived streams for various sectors. The data for the energy intensity of these processes were taken from reference documents under the IPPC Directive and the IED (JRC, 2018). The production rates of different products were taken from Eurostat tables (mainly DS-066342) whenever possible or from the data available from the related associations. Data for the transport, residential and service sectors were also taken from Eurostat database. For transport, the losses were derived from the typical efficiency of the internal combustion engine. The losses for power production plants were taken from the energy flow diagram (Eurostat, 2017). By multiplication of energy intensities of processes and production rates, the annual heat demands/ surpluses were determined. The *Fcp-s* were derived from the heat demands/surpluses divided by the typical temperature range of related heat demands/surpluses.

3.3 Step 3 - Heat Integration

2.3.1 Heat integration within sectors

The Heat Integration potential was first evaluated within each sector separately. The overall heat demand in the industry sector was 1,263,662 GWh/y in the year 2016 while cooling and heat losses amount to 182,931 GWh/y. By considering heat recovery options the heat demand could be reduced to 1,088,150 GWh/y, which means that 175,512 GWh/y (14 %) of heat could be recovered. The remaining heat that could not be recovered was 7,419 GWh/y (Figure 1a).

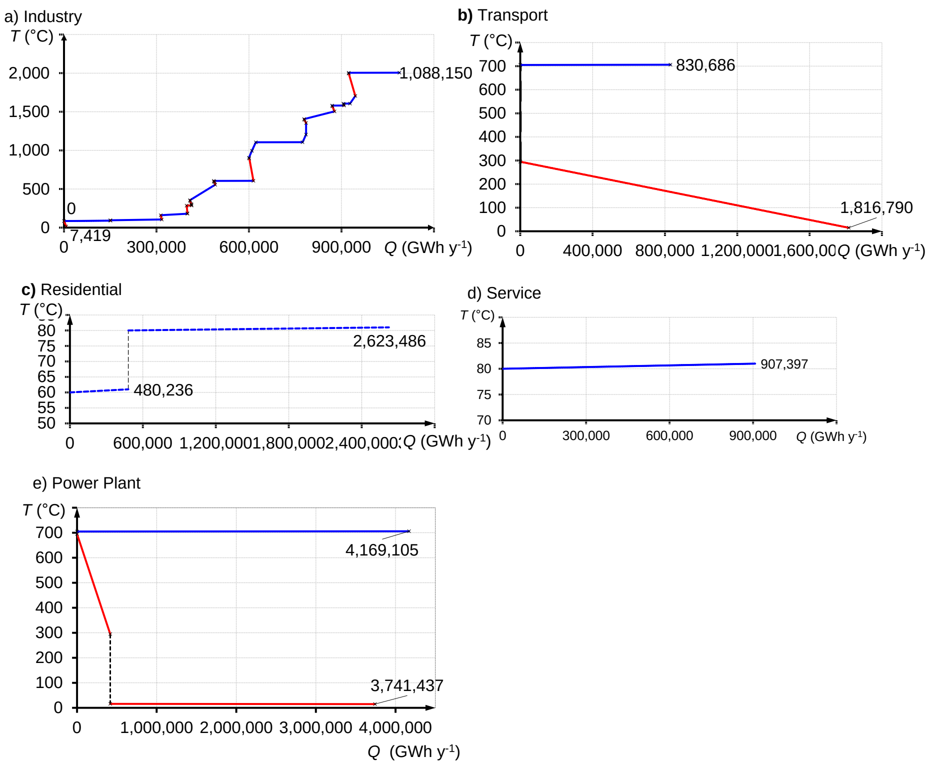

Figure 1: Grand Composite Curves for the (a) industry, (b) transport, (c) residential, (d) service and (e) power production sectors

A promising heat integration option within the industry sector was the integration of the iron and steel industry with an ammonia production plant, which resulted in 97,805 GWh/y heat recovery. This yielded at 27 % reduction of heat demand in those two sectors. Combining the steel and iron sector with aluminum, ammonia and glass production resulted in a 130,668 GWh/y heat demand reduction, which represented a 31 % reduction of the heat demand considered in these processes. Integration of the pulp and paper industry with previously-mentioned combination might also be beneficial.

The overall heat demand in the transport sector was 830,686 GWh/y, while the heat losses (hot streams) amounted to 1,816,790 GWh/y. However, there was no heat recovery option within the sector, owing to thermodynamic requirements. The Grand Composite Curve (GCC) is shown in Figure 1b.

The residential and service sectors have quite similar profiles, since both consume heat. In the case of the residential sector, this heat demand reached 2,623,486 GWh/y (Figure 1c), while in the service sector, it was 907,397 GWh/y (Figure 1d).

Thermal power plants and the nuclear power plants are hugely energy intensive processes, where a tremendous amount of heat is lost. In 2016 the heat demand was 4,169,105 GWh/y, while the heat excess amount to 3,741,437 GWh/y (Figure 1e). The drawback is that this heat is available at low temperatures.

2.3.2 Heat Integration between sectors

When considering all sectors together, it can be seen that there is a heat recovery potential of 1,669,995 GWh/y, representing 17% of the initial heat demand 9,794,336 GWh/y resulting in an 8,124,341 GWh/y heat demand (Figure 2a) after cross-sector integration. Considering the shape of GCC, however, this is a typical case, where heat pump utilization could be beneficial. When considering the heat pump option (Figure 2b), where the temperature of heat from power plants was raised from 20 °C to 90 °C, the heat demand was 5,679,140 GWh/y, representing a 4,115,496 GWh/y (42 %) reduction from the initial heat demand. It is worth noting that cross-integration of the industry sector does not really provide significant opportunities for heat integration, since integration within this sector has been a priority for decades.

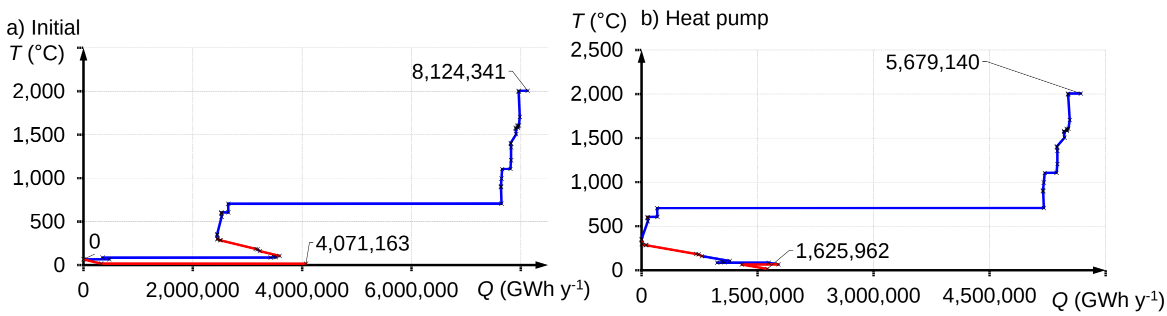

Figure 2: Overall cross-sector heat recovery (a) without and (b) with a heat pump

Integration of between power plants with the application of a heat pump (90 °C) and the residential sector was evaluated as shown in Figure 3.

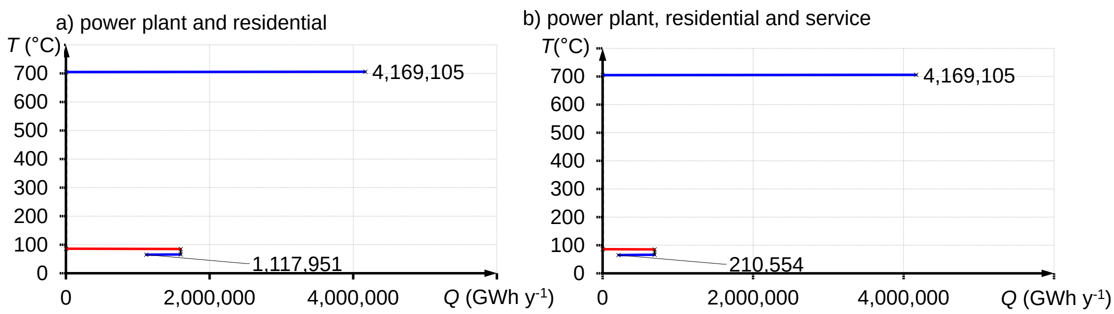

Figure 3: Integration of power production plant with the (a) residential and (b) residential and service sector.

The heat demand for the power production plants and residential sector together was 6,792,591 GWh/y with no heat recovery, while Heat Integration revealed that the heat demand could be decreased by 2,623,486 GWh (38.6 %) resulting in 4,169,105 GWh/y of demand (Figure 3a). If one includes service sector alongside the

residential, the heat requirement would be 7,699,988 GWh/y, while the heat demand of 4,169,105 GWh/y was achieved via heat integration, yielding a 3,530,883 GWh/y (46 %) decrease. As can be seen, a further decrease in heat was not obtained with the inclusion of the service sector, since the cold streams represent the power production plant requirements. Consequently, the heat requirement of the residential and service sectors together could be covered by integrating these sectors with power production plants considering heat pump.
The analysis revealed an integrations option between the transport and residential (service) sectors. The heat demand of all cold streams in the transport and residential sectors was 3,454,172 GWh/y. By integrating these two sectors, the heat demand could be reduced to 1,961,808 GWh/y representing a reduction of 1,492,364 GWh/y (43 %) in the heat demand from those two sectors (Figure 4a). Considering the integration of the transport and service sectors, one can determined that the initial heat demand of 1,738,083 GWh/y could be reduced to 830,686 GWh/y, thus giving a presenting a 907,397 GWh/y (52 %) reduction (Figure 4b).

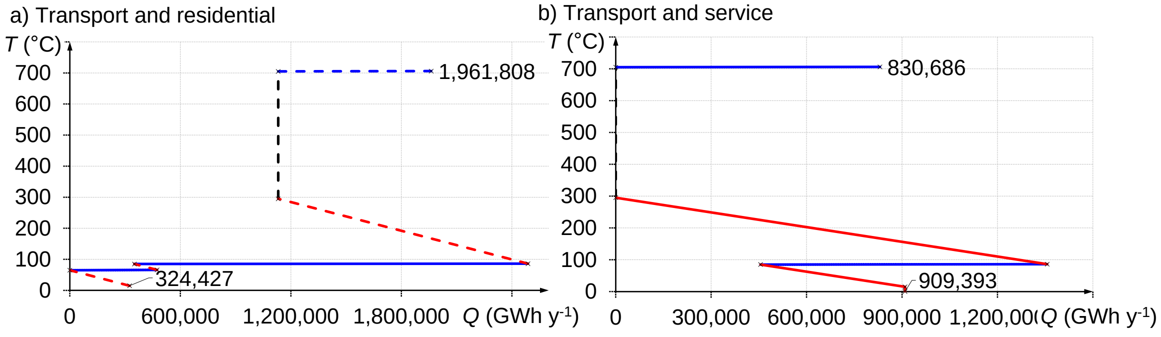

Figure 4: Integration of the transport sector with a) residential, b) service and c) residential and service sectors.

3.4 GHG emission reduction

The GHG emission reduction was determined by considering the average fuel mix and their related GHG emission. As Figure 5 indicates, the GHG emission reduction is the highest, when integration of all sectors is performed, with consideration of heat pumps in the power production sector. In this case 1,830 Mt CO_2-eq could be saved. The greater proportion of it can be saved by integrating of power production plant using heat pump options with the residential sector and service sector (1,570 x 10^6 Mt CO_2-eq) or at least with the residential sector (1,166 Mt CO_2-eq). Another promising solution emerges when integration of all sectors is made, without considering the utilisation of heat pumps, as it saves 742 Mt CO_2-eq.

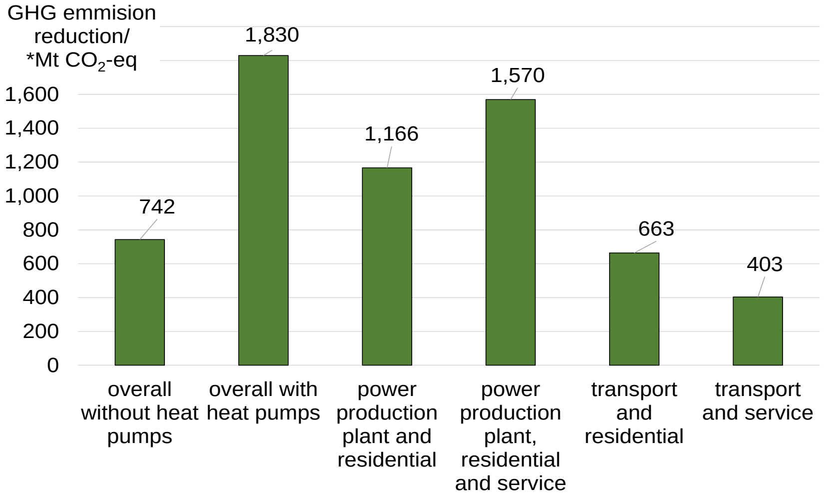

Figure 5: GHG emission reduction achieved with integration of different sectors

In comparison, the use of heat pumps can yield a reduction in GHG emission that is almost two-and-a-half times greater. A further promising option is the integration of the transport (losses) and residential sector (663 Mt CO_2-eq) or the transport and service sectors (403 Mt CO_2-eq). It should be noted that GHG emission reduction when integrating the transport sector with the residential and service sector simultaneously could not be summed up, since the transport sector heat excess does not cover the demand from both (residential and service) sectors.

4. Conclusions

Evaluation of potential cross-sector Heat Integration for gas mitigation has been performed in this study. The potential was evaluated within the European Union. The results indicate huge potential for cross-sector heat integration, since with the utilization of heat pumps in power production plants, heat demand reduction could reach 43 %, representing a 1,830 Mt CO_2-eq GHG emission reduction or a 41 % reduction of EU fossil-based GHG emissions in 2016. Note that this figure was achieved by analyzing sectors and processes that represent a 60 % share of energy in the overall EU energy demand. Even without heat pumps, a significant 17 % reduction in the heat demand could be achieved, resulting in 742 Mt CO_2-eq GHG emission reductions. The main potential options for cross-sectorial heat recovery are the integration of power production plants with the residential and/or service sector. Further good options are the integration of transport sector with residential or service sectors. It would thus be advantageous to invent suitable technological solutions for this kind of integration. Interestingly, integrating the industry sector with other sectors shows considerably less potential for heat integration. However, process intensification can further contribute to GHG emission mitigation. In the future, the analysis will be extended to other (sub)sectors and processes across the world by simultaneously integrating heat and power between processes in order to determine approximate energy saving potential at the world level through better integration.

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