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Greenhouse gas emissions consequences of utilization of excess heat from an oil refinery

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Abstract:

Increasing utilization of industrial excess heat is an important step towards reaching EU targets for increased energy efficiency and decreased greenhouse gas (GHG) emissions. There are many options for harnessing excess heat. However, the corresponding impact on GHG emissions differ significantly depending on the assumed marginal production technology replaced in the surrounding energy system. In order to identify robust solutions and avoid sub-optimization, different possibilities for utilizing excess heat need to be compared and evaluated using a systems perspective with different future energy markets scenarios. The purpose of this paper is to investigate and compare different utilization options in terms of GHG emission reduction potential. The paper presents an illustrative case of a large modern refinery on the West Coast of Sweden with a crude oil capacity of 11.4 Mt crude/y. The potential for producing electricity with an Organic Rankine Cycle (ORC), delivering excess heat to a district heating (DH) network and using it for post combustion carbon capture (CCS) are quantified using pinch analysis tools. Consequences for GHG emissions are evaluated based on different assumptions for future grid marginal electricity production. The results indicate that the GHG emission reduction potential is larger for CCS and DH than for electricity production via ORC. CCS achieves the highest GHG reduction potential per MW of recovered excess heat whereas DH shows the largest total potential for GHG reduction. It is possible to combine CCS and DH, and it is recommended to utilize first the maximum amount of excess heat in CCS and the remaining in DH. This combination results in GHG emission reduction corresponding to up to 40 % of the onsite CO_2 emissions.

Keywords:

Industrial excess heat, Organic Rankine Cycle, Carbon Capture, District heating, GHG emission reduction. Oil Refinery

1. Introduction

In the European Union's Energy Efficiency Directive (EED) [1], increased use of excess heat is highlighted as significant in order to reach the EU target of increasing energy efficiency by 20% by the year 2020 compared to 1990 levels [2]. Excess process heat can be recovered and used to provide energy services at the process site or elsewhere, thereby saving primary energy. Hence, utilization of excess heat can be seen as an energy efficiency measure. Many different technologies for utilization of excess heat are possible and a wide range of them are described and evaluated in the literature, see for example reference [3]. However, few studies have compared and evaluated different recovery options in terms of their GHG emissions reduction potential.

The aim of this paper is to investigate and compare the GHG emissions reduction potential of different uses of excess process heat. Three options are considered: (1) as heat source for electric power generation using Organic Rankine Cycle (ORC) technology; (2) as heat source for regeneration of the absorbent in post-combustion carbon capture (CCS); (3) as heat source for a district heating (DH) network.

Assessing the different options in detail is beyond the scope of this paper. Instead they are screened with respect to their GHG emissions reduction potential so as to provide guidance for further analysis. The systematic scanning method is illustrated through a case study of a large refinery on the West Coast of Sweden that has large amounts of excess heat available at temperatures high enough to allow different utilization options, as discussed in previous studies [4].

In the Energy Roadmap 2050 report, the European Commission proposes strategies to reduce annual greenhouse gas (GHG) emissions by 80–95 % by the year 2050, compared to 1990 levels [5]. The cost for this emission reduction can be reduced if industrial excess heat is utilized in district heating system according to a recent publication by Connolly et al. [6]. This makes district heating (DH) delivery an interesting option to evaluate.

Even highly efficient refineries emit large amounts of GHG and European petroleum refineries accounted for around 3% of the total GHG emissions in EU28 in 2012 [7]. To achieve reduction of GHG emissions in the near to mid-term future, post-combustion CCS has been identified as the most suitable technology within the refinery industry sector [8]. Post-combustion CCS is rather energy-intensive, due to the heat demand of the stripper section required for regeneration of the CO_2 solvent in typical capture plant layouts, and access to low cost steam has been pointed out as an important factor to keep operating costs down [8]. Using excess heat from the refinery process to provide heat is therefore highly interesting and the reason why CCS is included as an option in this paper.

However, implementation of CCS requires access to a collection network for CO_2, and DH delivery requires access to a district heating network, which may well eliminate these options for excess heat utilization for most refineries. All refineries consume electric power and are connected to the power grid, thus using excess heat as heat source for power generation which can be used on-site or exported to the grid is an option that is available at all refinery sites. The GHG reduction potential per unit of heat utilized is expected to be lower for power generation using ORC than for other technologies due to the low efficiency of converting low temperature heat to electricity. However, it may well be the only option for excess heat recovery and it is therefore interesting to quantify the reduction potential and compare with that of other options.

To evaluate the potential of utilizing the refinery excess heat for the different options considered, we used Pinch Analysis, an energy targeting method described in [9] and [10].

2. Method

2.1. Case study description

The refinery considered in the case study has a crude oil capacity of 11.4 Mt crude/y and it is one of the most modern in Europe, with total CO_2 emissions of 1.8 Mt/y [11]. Pinch analysis diagrams have previously been used to quantify and visualize the theoretical amount of excess heat at the net of the potential heat integration between the refinery parts [4]. Fig.1 shows the grand composite curve (GCC) of all heating and cooling requirements of the refinery, which is the net heating and cooling needs at different temperature levels under ideal heat recovery conditions. The GCC was constructed assuming a minimum required temperature difference for heat exchanging of 10 to 15 K, depending on the process stream characteristics. As shown in the figure, the refinery has a pinch temperature of around 125°C and a minimum theoretical cooling demand of around 360 MW [4].

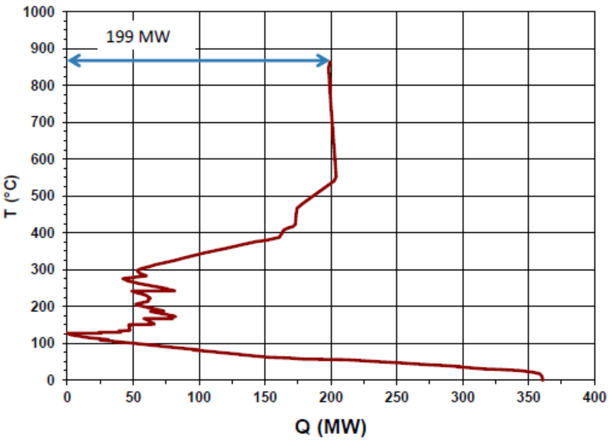

Fig.1 GCC showing minimum utility demands and pinch temperature for the Case study refinery, minimum hot utility 199 MW, minimum cold utility 360 MW.

Although the refinery GCC provides an idea of the "true" amount and temperature levels of the refinery excess heat, it does not represent the actual situation of the refinery, where heat integration is not fully implemented. Furthermore, reaching the target heating and cooling demands shown in the GCC, through extended retrofit of the refinery energy system, would be very costly and most likely unprofitable given the current energy market conditions. In this paper, we therefore consider a more realistic view of the refinery excess heat, i.e. that provided by the actual cooling load curve, abbreviated hereafter as ACLC. This curve shows the cumulative load of all process streams in air and water coolers at the refinery, i.e. the heat that is currently dispersed to the environment [12]. Note that using all this heat for providing off-site energy services reduces future possibilities for increased internal heat recovery within the refinery since the heat availability shown by the ACLC includes heat at temperatures above the pinch. In other words, increased internal heat recovery could be an equally interesting option for reduction of refinery GHG emissions. However, the evaluation of a realistic internal heat recovery scenario implies taking into account practical limitations and operability issues in more detail than when excess heat is utilized externally. To limit the scope of this paper it will focus on external use of excess heat only.

2.2. Estimation of excess heat recovery potentials

The potential for utilization was estimated using the Pinch Analysis energy targeting method. A prerequisite for Pinch analysis is the flowrate, temperature and heat capacities of all process streams being heated or cooled. This data was extracted from previous studies, as discussed in the following paragraphs. The estimation of available excess heat in the refinery was based on process stream data gathered previously [4] with minor updates during the fall of 2014.

The case study refinery consists of sixteen process units of which only nine were evaluated since these units account for a large share of the available excess heat [13]. In this study, these nine process units were grouped into seven areas, based on proximity, and each area was analysed individually. This limits the possible combinations of hot process streams and thereby the complexity of heat exchanger network necessary to collect the excess heat to be utilized.

The refinery was assumed to operate 8200 full hours per year and this was also the operating time assumed for the different heat recovery technologies, unless stated otherwise.

2.2.1 Heat supply for solvent regeneration in a CCS unit

In oil refineries the partial pressure of CO_2 in flue gases makes chemical absorption the preferred post-combustion technology for carbon capture and storage [14]. The process using monoethanolamine (MEA) as solvent is widely considered as a benchmark technology [15], and was therefore assumed as the solvent for CCS in this work. MEA was assumed to be regenerated in a stripper at 120°C, with a specific heat demand in the reboiler of 3370 kJ/kg CO_2, as used in a previous study of CCS at the case study refinery [13]. The temperature level of the stripping section strictly requires steam heating. Thus, the potential for excess heat utilization for CCS was estimated by evaluating the steam production potential from the process heat sources contributing to the ACLC. A minimum temperature difference of 5 K was assumed for heat exchange between process streams and condensate/steam. This means that only hot process streams at a temperature of 130°C or higher could be utilized.

2.2.2 Electricity generation with ORC technology

Organic Rankine cycles can be arranged in many different ways and it is theoretically possible to optimize the cycle parameters to match the temperature profile of the heat source [16]. In this study, we performed a conceptual screening of electricity production opportunities by means of an exergy analysis of each area in the refinery. The analysis was conducted by first converting the temperature scale of the ACLC into the Carnot factor, as defined in eq. (1) and then evaluating the area between the ACLC curve and the ambient temperature. This area gives the exergy rate i.e. the potential for electricity production, For a more detailed description the procedure please refer to [17].

$$\eta_{carnot} = 1 - \frac{T_C}{T_H} \qquad (1)$$

An ambient temperature of 15°C was used when establishing the Carnot Actual Cooling Load Curve and a sample Carnot ACLC from the refinery is given in Fig.2.

To estimate the practical opportunities for electricity production at the refinery, a cut-off principle was used and only the portion of the Carnot ACLC with a Carnot factor above 25 % was retained. This corresponds to only utilizing heat from process streams at a temperature of 111°C or higher. The actual electricity production was then estimated assuming that only 60 % of the theoretical potential can be achieved in practice, the rest being cycle and heat transfer irreversibilities, which is in line with efficient ORC design according to [17].

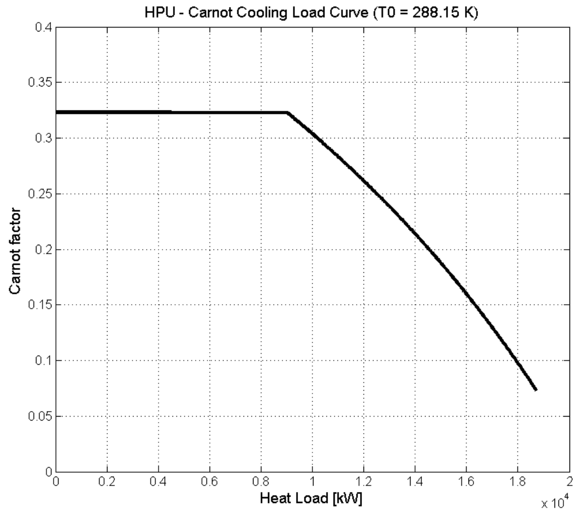

Fig.2 Carnot Actual Cooling Load Curve for the hydrogen production unit (HPU) of the case refinery

2.2.3 Heat Supply to a District Heating network

The potential for delivery of heat to a district heating network was established using the ACLCs of the different areas and a cold composite curve representing the heat demand of DH. The minimum temperature difference required for heat exchange between process streams and hot water was set to 10°C and the supply temperature in the district heating network was fixed to 80°C and the return to 50°C. To avoid risk of leakage from process plants into the DH system and vice versa, a closed-loop circulating hot water collection system was assumed, picking up heat from process streams and

delivering the heat to the DH network via a plate heat exchanger. The return and supply temperature levels of the circulating hot water circuit were set at 60°C and 90°C, respectively.
To reflect the fact that the demand for district heating varies over the year the number of operating hours with full delivery was reduced to 75 % of the refinery's operating hours.

2.3. Estimation of GHG emissions Reduction potential

Excess heat utilization affects the surrounding energy system in different ways for the three emissions reduction options investigated. To estimate the potential for GHG emission reductions, the system boundary must include the marginal technologies affected. In all cases considered, excess heat utilization has implications for the electricity system. In order to identify robust excess heat utilization options, the emissions associated with production or consumption of electricity were therefore estimated assuming different marginal electricity production technologies. Possible future values for emission factors associated with electricity were taken from [18-19] for the year 2030, as shown in in Table 1.

*Table 1. Emissions factors for different marginal electricity production technologies for the year 2030.*NGCC =Natural Gas Combined Cycle*

NGCC*	376	kg $CO_{2,eq}$/MWh
Coal with CCS	259	kg $CO_{2,eq}$/MWh
Coal	805	kg $CO_{2,eq}$/MWh

In the following section, the assumptions made when estimating reduction of GHG emissions are discussed for each technology. Note that for all three options the electricity needed in the different heat collection systems, i.e. for pumps, was neglected.

2.3.1. CCS

When implementing CCS, the resulting reduction of GHG emissions is the sum of: a) the direct reduction of CO_2 emissions in the CCS plant, and b) GHG emissions connected with electricity consumption in the compressor train of the CCS plant. Estimation of the electricity needed in the compressor train was taken from a previous study of the refinery [13].

2.3.2. ORC

For electricity production with ORC, the reduction of GHG emissions is directly linked to avoided emissions associated with marginal electricity production.

2.3.3. DH

The GHG emission reduction of excess heat based DH production is equal to avoided emissions associated with the marginal heat production in the DH network which can be a combined heat and power plant (CHP). A delivery of exess heat therefore implies: a) reduction of fuel used in the marginal heat technology, b) reduction of electricity production in marginal CHP plants, c) increased use of fuel for marginal electricity production and d) increase marginal use of biomass. Biomass is assumed to be limited so if less is used within the DH network more can be used to replace fossil fuel or feedstock elsewhere.

Emission factors for estimating the resulting change in GHG emissions were based on [18-19] and are listed in Table 2 for different marginal electricity production technologies. These emission factors are based on a Swedish cost ranked DH system. In this DH system a CHP fired with biomass is price setting and the marginal user of biomass is co-firing in coal fired power plants.

Table 2. Emission factors for utilizing excess heat in a Swedish cost ranked DH system depending on different future marginal electricity generation technologies (year 2030).

NGCC	397	kg $CO_{2,eq}$/MWh heat
Coal with CCS	425	kg $CO_{2,eq}$/MWh heat
Coal	265	kg $CO_{2,eq}$/MWh heat

2.3.4. Limitations

The potential GHG emission reduction from utilizing excess heat is highly dependent on the assumed marginal electricity production technology and marginal user of biomass. When excess heat is exported to a DH network it will replace the marginal heat technology, which can be CHP plants fired with biomass. This biomass can then be used elsewhere. In this analysis, the marginal use of biomass is assumed to be co-firing with coal and the marginal electricity generation technology is assumed to be based on fossil fuels. In the future, marginal electricity generation may be based on other types of renewables and the marginal use of biomass may possibly switch to biofuel production. A complete analysis of how this will affect the GHG reduction potential is beyond the scope of this paper. However, it is clear that such assumptions will affect the GHG emissions reduction potential of DH delivery and electricity generation using ORC technology more than usage in a CCS plant since CCS achieves direct reduction of emissions whereas for the other technologies the emission reduction is dependent on the marginal technologies they replace.

3. Results

3.1. Excess heat utilization potential

Table 3 summarizes the excess heat available for utilization within each of the selected refinery areas. For the ORC option, both available useful heat and resulting electricity generation are shown. The amount of heat that can be recovered and delivered to a DH network is clearly largest, as expected since it has the lowest temperature requirement. The different temperature requirements for the heat recovery technologies makes it possible to see from Table 3 at what temperature excess heat is available in the refinery, and also within the different areas. For instance the total potential for CCS within the refinery is only a quarter of the potential for DH while in some areas of the refinery this ratio is far lower or higher.

*Table 3. Heat available for utilization with different heat recovery options in each area of the refinery.*Heat available as heat source for the ORC unit according to assumptions.*

Process area	*CCS [MW]*	*ORC electricity/heat * [MW]*	*DH [MW]*
FCC: Fluid Catalytic Cracking	0.33	0.23/ 0.82	12.7
ICR: Hydrocracker	2.63	5.62/ 19.8	57.9
HPU: Hydrogen production	10.9	3.91/ 12.5	16.0
ARU: Amine Recovery	0	0.17/ 0.66	22.8
CRU_NHTU: Catalytic Reformer and Naphta Hydrogen Treatment	11.6	4.74/ 15.4	32.2
MHC_SS: Mild Hydro Cracker and Synergetic Saturation	19.9	6.73/ 21.7	48.0
VB : Visbreaker	6.45	3.51/ 11.6	20.8
Total	51.8	24.9/ 82.4	210.4

3.3. Reduction of GHG emissions

The potential to reduce GHG emissions is highest for DH delivery except when marginal electricity is produced with coal in which case CCS achieves the highest reduction (see Fig 3). In fact, DH delivery shows a large variation in GHG emission reduction with respect to marginal electricity production with a span from 0.34-0.55 Mt $CO_{2\text{-eq}}$/y. The reason for this large variation is that delivery of excess heat will reduce the electricity produced in the DH system and thereby link the emission reduction tightly to electricity on the margin.

Using excess heat as heat source for power generation with ORC technology achieves the smallest potential to reduce GHG emissions but it also has the largest variation with respect to marginal electricity production technology since the emissions reduction is directly linked to the amount of electricity produced. Hence the more carbon intensive the reference grid power generation technology is, the larger the global emissions reduction from implementation of ORC will be. The opposite is true for DH export and CCS since both of them will lead to increased marginal electricity production. The difference between ORC and the other two technologies is therefore smallest for coal power plants as reference power generation technology. In this case, ORC achieves about 25% of the emissions reduction of DH and CCS whereas when Coal with CCS is the marginal power generation technology it was only about 10 %.

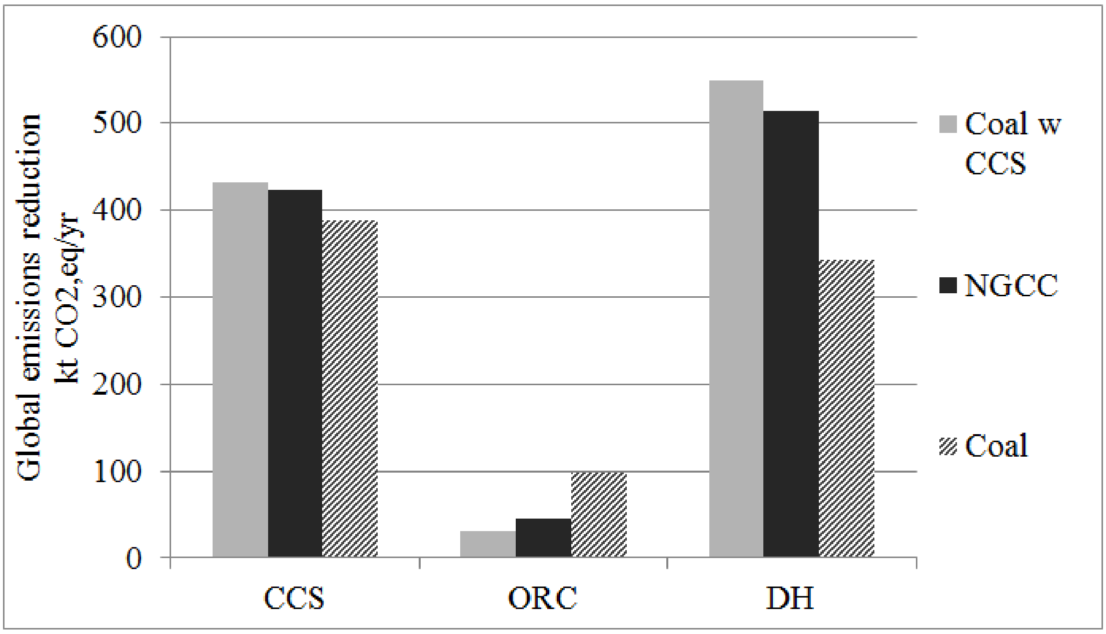

Fig.3 Potential GHG emissions reduction for different excess heat utilization options evaluated assuming different marginal grid electricity generation technologies (Coal, NGCC, Coal with CCS)

The specific emissions reduction potential per MW of excess heat is shown in Fig.4. The specific emissions reduction is clearly highest for the CCS option for all different grid marginal electricity production technologies. The reason for this is that CCS leads to direct reduction of CO_2 emissions whereas the emissions reduction achieved by the other options are dependent on the marginal grid power generation technology assumed. CCS is more or less independent on the assumed marginal power generation technology since the emissions related to the electricity consumption in the CO2 compression unit are small compared to the process CO2 captured, regardless of the grid generation technology assumed.

As expected, the specific reduction for the CCS and DH options are higher than that of ORC. Again the smallest difference occurs with coal as the assumed fuel for grid power generation. CCS and ORC differ by an order of magnitude unless coal is the marginal power plant fuel, in which case ORC achieves 16% of the GHG reductions from CCS per MW excess heat utilized. For DH the specific reduction per MW excess heat is only 20-30% of that achieved with CCS.

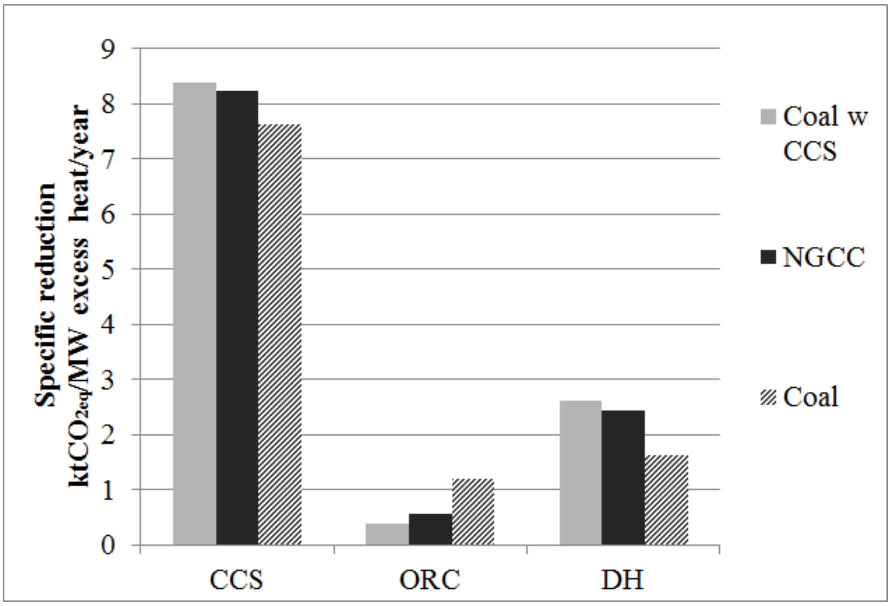

Fig.4 Specific GHG reduction potential evaluated for different marginal grid electricity generation technologies.

3.4. Opportunities for combining utilization options

Since CCS and DH delivery clearly have the largest potential for reduction of GHG emissions, the possibility to combine these two technologies was also evaluated. The remaining potential for DH delivery was estimated after the potential for CCS had been fully exploited. CCS was exploited first due to its higher specific reduction of GHG emissions. When estimating the DH delivery potential, two alternatives were evaluated: one where remaining excess heat in the hot process streams involved in CCS could be utilized ($DH_{CCS+part\ load}$) and one where only excess heat in process streams not included in CCS was included (DH_{CCS}). In Table 5 it can be seen that there is still a large potential for DH delivery after implementing CCS, especially if one also uses the remaining heat in process streams utilized to provide heat for CCS. When combing the two technologies, the total GHG reduction potential reaches up to 40 % of the total CO_2 emissions from the site.

Table 5. Excess heat utilization potential for DH delivery after CCS has been implemented, and the resulting total GHG emissions reduction for the combination of DH delivery and CCS. NOTE NGCC is assumed as grid power generation technology.

	DH_{CCS}	$DH_{CCS+partload}$	
Heat available for DH delivery	69.6	122.9	MW
DH delivery target capacity	430	755.7	GWh/year
Emissions reduction for DH delivery	0.171	0.300	Mt $CO_{2,\ eq}$/year
Total emissions reduction for CCS+DH	0.59	0.72	Mt $CO_{2,eq}$/year

It is also possible to combine utilization of excess heat for ORC power generation and DH delivery but since ORC has considerably lower specific GHG reduction potential than CCS, this combination was not evaluated.

3.5. Discussion

When comparing the three options for excess heat utilization, the highest specific reduction can be achieved with CCS. The specific reduction is the GHG emissions reduction achieved per MW excess heat utilized, so it indicates how effective the different technologies are at reducing emissions. Our estimates indicate that for DH delivery, the GHG emission reduction per MW is about 20 to 30% of that obtained with CCS. If excess heat is used for ORC power generation, only 5 to 16 % of the specific reduction achieved with CCS can be obtained. Hence, if excess heat is available at temperatures making all three utilization options possible, the highest reduction of GHG emissions can be achieved if the heat is used in a CCS plant.

The GHG emission reduction for CCS is also less sensitive to the assumed grid power generation technology than ORC power generation and DH delivery, since CCS leads to direct reduction of on-site emissions. The highest emissions reduction associated with ORC power generation is obtained when high emissions are assumed for grid power generation, whereas the opposite is true for DH delivery and CCS since electricity is produced with ORC while it is consumed in the DH delivery and CCS options. From a GHG emission standpoint, if ultra-low grid power generation emissions are assumed, excess heat driven ORC power generation would perform even worse compared to DH delivery and CCS.

Overall, utilizing excess heat can reduce the refinery’s emissions significantly. Combining CCS and DH delivery, e.g. by first maximizing excess heat utilization in CCS and using the remaining excess heat for DH delivery, up to 40 % of the on-site CO_2 emissions can be avoided.

The pinch temperature for the complete refinery site is 125 °C. Heat above this temperature should not be used for CCS, ORC power generation or DH delivery since such usage will inevitably lead to reduction of the potential for internal heat recovery, i.e. fuel savings in boilers and furnaces. Increasing heat recovery within the refinery to reach the minimum heating target identified with pinch analysis tools will be too costly. For this reason some external utilization of excess heat above the pinch temperature might be justified. Note however that a share of the fuel consumed in the refinery’s boilers and furnaces could be saved if heat recovery within the refinery was increased. Thus it is reasonable to assume that a portion of GHG emitted by such fuel usage should be allocated to the excess heat. Including an estimate of the on-site emissions related to excess heat is important when studying the competition between external and internal utilization of excess heat. The final trade-off between the two needs to include both GHG emission consequences and economic performance in order to identify robust solutions.

The total potential for emissions reduction established for each technology is case specific and depends on the temperature levels at which there is excess heat available in the process. However, the results regarding specific reduction can be generalized for CCS and DH delivery. For ORC the conversion efficiency of heat to electricity is dependent on the temperature of the excess heat, due to the limiting Carnot efficiency, making the emission reduction per MW excess heat case specific. A process with the same amount of excess heat available for ORC power generation as the case study refinery but at different temperatures will have a different specific emission reduction.

Results obtained in this paper were based on real data reflecting the present situation in the refinery, hence possible future changes of the process units were not taken into account. One possible strategic change of the refinery industry is towards increased use of renewable feedstock. Evaluating the implications of such a change on the amount of excess heat is recommended since it would provide guidance towards robust utilization options. An example of a possible future scenario for the case refinery is fully substituting the current natural gas based hydrogen production unit with one using biomass as feedstock. For this scenario, as for any scenario where biomass is used, the possibility to use refinery excess heat to dry biomass is highly interesting. An investigation of a possible future scenario with bio-based feedstock should therefore also include estimation of the potential for and benefits of drying biomass with excess heat.

4. Conclusions and future work

Utilizing excess heat has a large potential to reduce the GHG emissions from the refinery. Of the three options evaluated, CCS clearly achieves the highest potential for reduction of GHG emission per MW of excess heat utilized. Our estimates indicate that for DH delivery, the GHG emission reduction per MW is about 20 to 30% of that obtained with CCS whereas ORC only reaches 5 to 16 % of the reduction that CCS can achieve. The GHG emission reduction for CCS is also less sensitive with respect to the assumed level of emissions associated with grid power generation than ORC power generation and DH delivery since CCS leads to direct reduction of on-site emissions.

From a GHG emissions reduction perspective, it is recommended that excess heat should be utilized for CCS in combination with DH delivery if there is a DH network with a sufficient heat demand within the vicinity of the plant. When CCS and DH delivery are combined, a reduction of up to 40 % of the onsite CO_2 emissions can be achieved. Further evaluation is necessary in order to assess the costs of such measures and compare with possible future costs associated with such emissions.

Primary energy is saved when industrial excess heat is utilized instead of being dissipated to the environment. However, using excess heat can lead to reduced potential for heat recovery, i.e. fuel savings, within the refinery. It is therefore important to investigate possibilities for internal heat recovery, the resulting GHG emissiosn reduction and how external use of excess heat may diminish these opportunities if one wishes to find robust uses of excess heat. The potential reduction of heat recovery opportunities due to utilizing excess heat from the ACLC is important to study in future work.

Acknowledgements

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