

# Bottom-up methodology for assessing electrification options for deep decarbonisation of industrial processes

Holger Wiertzema  
Chalmers University of Technology  
Department of Space, Earth and Environment  
Division of Energy Technology  
412 96 Göteborg  
Sweden  
holgerw@chalmers.se

Prof. Simon Harvey  
Chalmers University of Technology  
Department of Space, Earth and Environment  
Division of Energy Technology  
412 96 Göteborg  
Sweden  
simon.harvey@chalmers.se

As. Prof. Max Åhman  
Lund University  
Department of Environmental and Energy Systems Studies  
221 00 Lund  
Sweden  
max.ahman@miljo.lth.se

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## Abstract

Industrial processes currently account for a significant share (25–35 %) of the world's total energy demand and related emissions. During recent years, the amount of low-carbon electricity from renewable energy sources (such as wind and solar) has increased continuously. There is therefore an increasing interest in electrification of industrial processes in order to achieve long-term decarbonisation goals.

Structural changes in the capital-intensive processing industry take a long time to implement. Furthermore, the number of possible technologies and systems for electrification of industrial processes is high, and different technologies and combinations of technologies will have different performance both in terms of economy and carbon footprint. For industrial decision-makers, it is important both to understand such systemic effects of electrification technologies and to discard low-performing candidates at an early stage. So far, studies on industrial electrification have focused on top-down approaches using explorative scenarios for analysing the consequences of a sector-wide full electrification assuming greenfield investments. There is a lack of studies adopting a bottom-up perspective for investigation of partial electrification options in brownfield investments at existing sites including process integration aspects and system consequences as well as the impacts on overall energy efficiency.

The objective of this paper is to propose a methodology for bottom-up assessments of industrial electrification options and

to demonstrate this methodology with a case study. For this purpose, a bottom-up methodology that especially accounts for the systematic effects of increased electrification on a plant level was developed and then applied to the steam system of an oil refinery plant in Sweden. The results show that the energy and carbon footprint consequences of such measures are hard to predict without detailed modelling studies since industrial process unit operations are highly interlinked. Furthermore, the results from the techno-economic as well as carbon footprint bottom-up assessments can be used to compare electrification with other decarbonisation options and to formulate detailed roadmaps for decarbonization of energy-intensive industrial processes.

## Introduction

Industrial processes currently account for a significant share of the total energy demand and related emissions. In 2014, the industrial sector accounted for 36 % (154 EJ) of global final energy use and 24 % (8.3 GtCO<sub>2</sub>) of global CO<sub>2</sub> emissions. Furthermore, five energy-intensive sectors, namely chemicals and petrochemicals, iron and steel, cement, pulp and paper as well as aluminium have a share of 69 % of the industrial energy use (IEA 2017a). In Sweden, the industrial sector accounts for approximately one third of the total final energy use as well as one third of the total greenhouse gas emissions. The pulp and paper industry, the iron, steel and non-ferrous metals industry and the chemical industry alone are responsible for three-quarters of the industrial final energy use (Energimyndigheten 2015, Naturvårdsverket 2017).

Recent years have seen a growing interest on the possibilities of expanding the use of electricity in the industrial sector in Eu-

rope. Several publications have explored the implications of increased electrification (Lechtenböhmer et al. 2016, UBA 2014, Berenschot et al. 2017, Fahnstock et al. 2017, IEA 2017b). As a consequence, the overall future use of electricity could increase substantially as a result of fuel shifting where electro-thermal or electrolytic technologies replace natural gas, oil, coke and biomass for industrial heating purposes (EPRI 2009, Åhman et al. 2012) and electricity derived methanol/hydrogen replace fossil feedstocks in petrochemical plants (Palm et al. 2016).

The main driver for this interest in electricity as a future energy carrier in industry is the combined effects of the demand for deep decarbonisation in industry in order to meet ambitious climate targets (80 to 95 % decrease by 2050) together with the concurrent rapid growth of renewable electricity. Over the last 5 years, there has been a change in perceptions regarding both the long-term cost of renewable electricity, and electricity from solar and wind power is anticipated to overtake the role as the “primary fuel” from coal, oil and gas in a future zero emission world (Lechtenböhmer et al. 2016). CCS is still an attractive option as a backstop technology for reducing residual CO<sub>2</sub> emissions in the energy intensive processing industry (see e.g. IEA 2017c) but several actors (D’Aprile 2016, Lupion et al. 2013) have doubts regarding the cost, public acceptability, and the political support for this option.

Another driver for electrification of industry is the opportunities that stem from the changing functioning of power systems in Europe. With rapidly growing shares of variable renewable electricity, the power system needs substantial demand-side flexibility (Haas et al 2013). In such a system, demand response in one of the largest user sectors, industry, could become vital for the system and with an increasing number of hours with extremely low prices (due to variable renewable energy sources), there is also a potential for industrial electricity consumers to benefit from “arbitrage” by demand response and interacting actively on the balancing market (Paulus and Borggrefe 2011, Fahnstock et al. 2017).

As a result, there is an increased activity related to industrial electrification at the company level as well as in research. In the Netherlands, the VoltaChem consortia was established to develop and implement electrification technologies for the chemical industry (VoltaChem 2017). As part of the VoltaChem programme, the project “Industrial Hybrid Energy System” started in 2018. Other ongoing projects focus on specific industries (e.g. the Swedish projects “HYBRIT” (SSAB 2017) and “CemZero” (Vattenfall 2017) for emission free iron and cement production, respectively) while others are more related to certain technologies (e.g. flexible use of electrolyzers in “ELECTRE” (ECN 2016)) or products (e.g. electricity-based plastics (Palm et al. 2016, Siemens AG 2016). Also, the Kopernikus project “Power-To-X” (RWTH Aachen 2016) was launched with the aim to develop electricity-driven technologies to produce materials, energy carriers and energy-intensive chemical products. Furthermore, the objective of the Swedish project “PROCEL” is to build up knowledge about the opportunities to shift towards carbon-free industrial processes through increased electrification by analysing the technical, economical and emissions related implications of the introduction of a variety of techniques (Energimyndigheten n.d.).

Structural changes in the capital-intensive processing industry take a long time to implement. Furthermore, the number

of possible options for electricity-based technologies and systems is high, and different technologies and combinations of technologies will have different performance both in terms of economy and carbon footprint. For industrial decision-makers, it is important both to understand such systemic effects and to discard low-performing candidate electrification technologies at an early stage. So far, studies on industrial electrification have focused on top-down approaches assuming greenfield investments (new sites), using e.g. explorative scenarios for sector-wide full electrification (Lechtenböhmer et al. 2016). In an EU context, greenfield investments in major industrial sites are unlikely during the coming decades and there is a lack of studies adopting a bottom-up perspective including process integration aspects and system consequences as well as the impacts on overall energy efficiency for partial electrification of existing sites (brownfield investments).

The objective of this paper is to propose a methodology for bottom-up assessment of partial industrial electrification options at existing sites and to demonstrate this methodology with a case study. The methodology accounts for the process system context and includes process integration aspects. This is of particular importance since industrial process unit operations are highly interlinked and energy and carbon footprint consequences of changing parts of the processes are often hard to predict. The methodology is illustrated by means of a case study for the steam system of an oil refinery plant.

## Introduction of electrification technologies in existing industrial processes

Electrification of industrial processes can take place in different process areas. The left-hand illustration in Figure 1 shows the typical hierarchy of design of such different process-related systems. These systems can be further decomposed to the level of unit operations. The hierarchy can be used to analyse existing processes and to identify options for electrification. Furthermore, the right-hand side of Figure 1 highlights the important interconnections and interactions between these systems. Changes in one of the systems (e.g. the reaction system) will usually affect all following systems (such as the separation or the heat recovery system). However, besides the downstream effects from the reactor there are also upstream effects in the reverse direction. For example, changes in the utility system by switching to another technology to provide heat (e.g. by electricity) can lead to a surplus of heat in the heat recovery system that cannot be used anymore. It is very important to consider these effects, especially for existing processes in which there is already some kind of heat integration and where operational modes are optimized. For increased electrification, one or more unit operations in one or several of the systems can be modified so that electricity-based technologies are used. Electrification options can also be implemented in conjunction with conventional unit operations to form hybrid systems, introducing a certain degree of flexibility.

Understanding existing process systems and their unit operations is essential to identify technologies for increased electrification that are applicable and for which a bottom-up assessment should be performed. Technology inventories (e.g. (EPRI 2009)) are often categorized according to the “Power-to-X” approach (e.g. Power-to-Heat, Power-to-Hydrogen etc.). Details

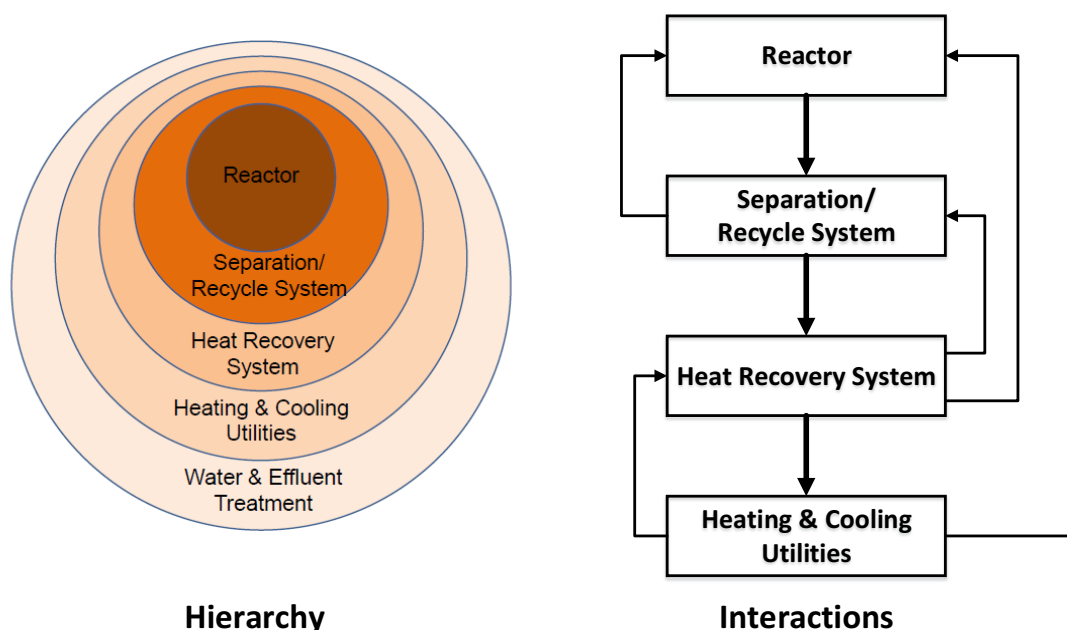


Figure 1. Hierarchy and interactions of industrial process-related systems (Gundersen 2002).

on the operating parameters and dimensioning are important to pre-assess whether such technologies can meet the process requirements. Information on the current development status, often expressed by the TRL, is important to estimate possible implementation times (short-term: 1–3 years, medium-term: 3–10 years, long-term: >10 years) and expected technology developments. Besides electrification of unit operations in existing plants as investigated in this paper, it should be noted that there are also new technologies as well as processes underway that are especially designed for using electricity (e.g. electrolysis-based hydrogen production and electro-separation technologies). Additionally, and by expanding the system boundaries, electro-feedstock and electro-fuels can also be considered as options for increased process electrification. Combining the identified unit operations within the process-related system with appropriate candidate technologies leads to different combinations that can then be evaluated.

### Methodology for bottom-up assessments of electrification

As previously mentioned, increased electrification is a promising way to decarbonise existing industrial processes. However, an appropriate bottom-up methodology is needed to evaluate the impacts of the many electrification options in terms of technical implementation, cost and carbon footprint on the process and plant level. Compared to top-down studies, this approach avoids missing implementation realities at the process level. In this context, it is of particular importance to consider process integration studies to analyse the systemic effects when increasing process electrification. The reason therefore is that industrial processes and unit operations are highly interlinked so that energy and carbon footprint consequences are hard to predict. Thus, process integration studies can show not only how electrification technologies can be implemented but also the effects on other parts of the considered process such as the

utility demands (e.g. electricity, fossil fuels, steam) and changes in greenhouse gas emissions.

The specific steps of the proposed bottom-up methodology for investigating the consequences of implementing a selected electrification technology within a process-related system (e.g. the steam production in the utility system) are illustrated in Figure 2 and described in the following text. The approach is tailored to existing processes and short- to medium-term available technologies but can be expanded to long-term technologies and new processes.

The first step of the methodology after selection of an industrial process is to describe the existing system with its conventional unit operations. As already shown in Figure 1, the whole process can be further divided into different sub-systems. Understanding the current system is important not only to define the reference case for the assessments but also to establish a framework with corresponding system boundaries in which individual conventional unit operations can later be switched to electrification options. One important sub-step is the collection of qualitative (e.g. flow charts and general process descriptions) as well as quantitative data for important technical parameters (e.g. temperatures, pressures, heat load, mass flow rates etc.). Another sub-step is to identify existing energy integration and to describe the surrounding infrastructure (e.g. other plants for integration on a site level or the capacity of the power supply).

Step 2 is then to find suitable electrification options for the current unit operations. As afore-mentioned, technology inventories are available and can be used to find suitable candidate technologies. However, in-depth technical data is required to assess whether such electrification technologies can meet the process requirements as well as for modelling and simulation in the subsequent steps.

In Step 3, process integration studies for one or more modified unit operations are performed. Here, one or more conventional operations are removed from the existing process system and replaced by technologies that primarily run on electricity

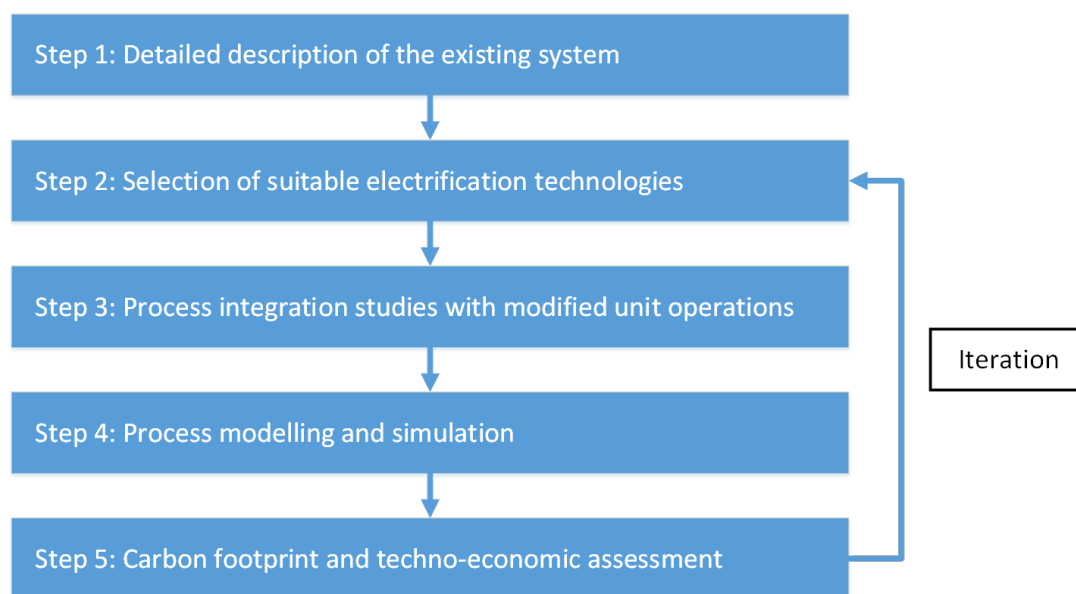


Figure 2. Steps of the proposed bottom-up methodology.

to perform the same operation (e.g. steam supply, separation) as before. The term “process integration” is quite broad and several tools and approaches can be used. However, useful tools for the studies in this paper are heat cascade calculation using pinch analysis. Together with the process decomposition concept shown in Figure 1, the effects of the changes can be changes of mass flows, energy and power demands as well as emissions. These consequences are not trivial because many unit operations in industrial processes are interlinked and usually highly integrated. For example, replacing a current unit operation with an excess of heat which is used in another unit operation by a Power-to-Heat technology might reduce energy demand and emissions for the first unit operation. However, the heat for the other unit operation might now be produced with technologies with high energy demand and emissions.

Step 4, process modelling and simulation, is closely connected to the previous step used to generate mass and energy balances and thus qualitative results for the existing system (reference case) and the systems in which one or more unit operations were modified. For this purpose, models for the electrification technologies need to be combined with models for the current systems. The system boundaries of such models should be set such that the interactions and interconnections identified in Step 1 are considered.

In Step 5, the qualitative results for mass, energy and power balances are used for carbon footprint and techno-economic assessments. In the former, carbon dioxide emission factors are applied to the results on the energy flows in order to assess whether and to what extent increased electrification can reduce correspondent emissions. In contrast to fossil fuels, the emission factors for electricity vary greatly, depending on the electricity production mix. This factor is central for the analysis since electrification implies that on-site emissions from fossil fuel use are shifted to off-site emissions from the electricity system. In the economic evaluation, the costs associated with the changes are assessed by summing up the variable costs from the fuel demand and the brownfield investment costs according to the power ratings of the technologies. Additionally, possible costs

for carbon dioxide emissions (from e.g. a CO<sub>2</sub> tax or and cap-and-trade) are considered. For all the just named assessments, it is important to use consistent market scenarios that reflect the electricity mix and the prices for today and in the future.

The loop in Figure 2 illustrates the recommendation of an iterative approach. This is needed and reasonable as there will usually be several electrification options for conventional unit operations or different combinations of them. Thus, and as the mass, energy and emissions consequences are hard to predict, it is not sure that the initially selection option will lead to the best performance in terms of greenhouse emission reduction and lowest cost. Therefore, additional assessments with other electrification options, more modified unit operations and different sizes of the technologies should be performed.

### Illustrating case study example

To illustrate the proposed bottom-up methodology, a case study for the steam system of an existing oil refinery plant was performed to analyse the possible effects of introduction of electrification technologies. Currently, there exist many oil refining plants that will continue to operate for the next years. As the oil refining process requires large amounts of energy, especially heat in the form of steam, it is important to analyse electrification options to strive for maximum decarbonization. In this context, especially short- to medium-term available technologies are relevant.

Starting with Step 1 of the proposed methodology, Figure 3 shows the general overview of the steam system for a real oil refinery plant in Sweden which is considered in this case study. The steam system provides the heat required for the oil refining process and has by far the highest energy demand as well as greenhouse gas emissions compared to the total process. The oil refining process requires steam at different pressure levels (VHP: very high pressure, HP: high pressure, MP: medium pressure, LP: low pressure). This steam is generated by process coolers, process flue gas waste heat recovery boilers and steam boilers. The latter mainly run on refinery fuel gases, purchased

LNG fuel and, optionally, on vaporized liquid products. Due to environmental regulations, an air condenser is used to condense the desired products at the end of the oil refining process so that they can be separated from refinery fuel gases. Subsequently, the amount of available fuel gases depends on the ambient temperature. Low ambient temperatures lead to a higher share of condensable products and thus less refinery fuel gases. The different steam headers are connected by steam turbines and let-down valves. The individual steam turbine symbols in the figure in fact represent several aggregated steam turbines operating between specific steam headers. During the expansion of steam to a lower pressure level, shaft work is extracted to run more than fifty pumps and compressors. Alternatively, electric motors can be used to run the pumps and compressors. Low-pressure excess steam from the LP steam header is vented to the atmosphere.

For Step 2, technology inventories were screened to identify suitable electrification technologies for oil refinery plants. Table 1 shows the results for selected electrification options. The technologies are sorted in descending order of their TRL to emphasize their possible implementation time-frames. In oil

refineries, it is primarily the substantial heat demand that offers possibilities for electrification. In the short- to medium-term, industrial heat pumps as well as electric steam boilers can be used to convert electricity directly to heat. Furthermore, electrical drives can replace existing steam turbine drives that are used to run pumps and compressors. This will affect the steam balance and thus reduce the heat demand in the utility system of the oil refining process.

Already today, a switchable drive configuration in the existing system allows pumps and compressors to be driven either by steam turbines or electric motors. Hence, and as electric drives have the highest possible TRL according to Table 1, this technology will be evaluated in this case study example. In the current mode of operation (meaning how the owner operates the plant today), steam turbines are the main driver in times with high availability of refinery fuel gases whereas the choice of driver at times with low availability of refinery fuel gases depends on the relative cost for LNG and electricity. Therefore, one option for increased electrification which is examined in the following is to maximise the use of electrical motors to drive pumps and compressors instead of using steam turbines.

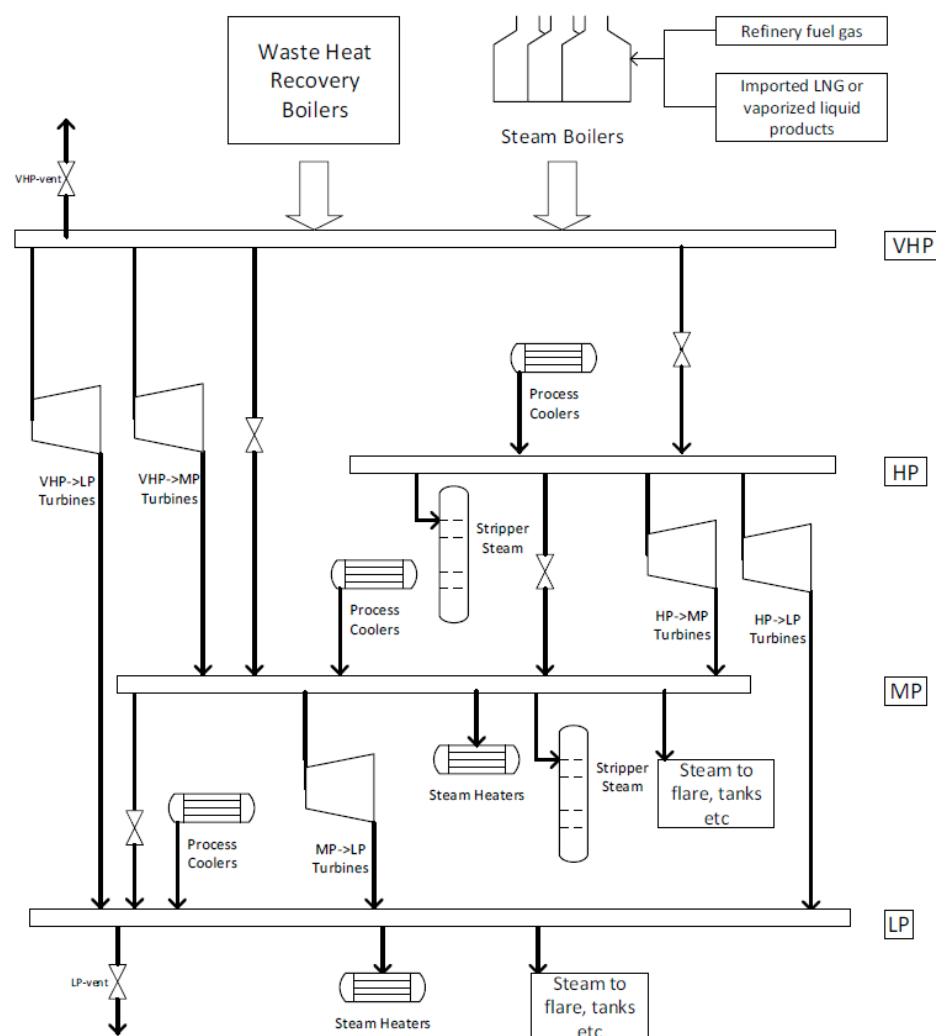


Figure 3. General overview of the refinery's steam network (Marton et al. 2017).

Table 1. Selected electrification options for an oil refinery plant, compiled from (EPRI 2009), (Berenschot et al. 2017) and (DECHEMA 2017).

Technology	TRL	Category	Process system and electrification option
Electric steam boiler	9	Power-to-Heat	Utility system: Replacing conventional (natural gas-driven) boilers
Industrial heat pumps	8–9	Power-to-Heat	Utility system: Heating (low to medium temperatures)
	9		Heat recovery system: High-grade steam production by mechanical vapour recompression of excess, low-pressure steam and thus reduction of steam boiler load.
Electric drives	9	Power-to-Mechanical drive	Utility system: Reducing steam demand by replacing steam turbines to provide mechanical drive for pumps and compressors
Electrolysis	6–9	Power-to-Hydrogen	Reactor system: Replacing conventionally produced hydrogen for hydrotreater and hydrocracker with hydrogen from water electrolysis
Heat pump-assisted distillation	Low	Power-for-Separation	Separation system: Reducing heat demand for the crude oil separation process
Membrane-assisted distillation	Low	Power-for-Separation	Separation system: Reducing heat demand for the crude oil separation process

Table 2. Emission factors used in Step 5.

Energy carrier	Unit	Emission factor
Electricity (Sweden)	tCO <sub>2</sub> e/MWh	0.047
LNG	tCO <sub>2</sub> e/t	2.743
Refinery fuel gases	tCO <sub>2</sub> e/t	3.878

Step 3, process integration studies, can be started with first quantitative predictions on the effects of replacing steam turbines with electrical drives. It is quite clear that this will lead to an increased demand in electricity and to a reduced load of the steam boilers. Subsequently, more off-site greenhouse gas emissions will increase while the on-site emissions will be reduced as less refinery gases and LP steam are used. However, it cannot be predicted how the steam system will react in detail. More LP steam may be vented or there may even be an excess of steam at MP and/or HP levels. It should be observed that this electrification option will not affect the heat demand and heat cascade in the reaction and separation system, but only the utility system of the oil refining plant.

In Step 4, a recently developed model for the described steam system was used (Marton et al. 2017, Subiaco 2016). The model was programmed in Aspen Utilities Planner and validated against measured data for a variety of different steady-state conditions. The model allows to switch the drive for different aggregated pumps and compressors between steam turbines and electric motors and calculates the correspondent mass, energy and power balances. Variables are the conditions of 33 switchable drives (steam turbines or electric drives), the steam flows (also from the steam boilers) as well as the power from the turbines. The optimization is constrained by the steam demand of the process, the power demands for pumps and compressors as well as limits on installed capacities and valve flow rates. In addition, the status of additional non-switchable drives were fixed. At first, mass, energy and power balances were generated

according to how the owner operates the plant today (reference operation, see also the description of Step 2) for typical operating conditions in September. Then, the optimizer function in Aspen Utilities Planner was applied together with extreme prices for electricity in comparison to LNG (as the objective function to be minimized was the total utility cost) so that the model ran into the optimization constraints. These simulations were performed to find the number of switchable drives that can run on electricity without violating technical constraints for the two price levels. In addition, extreme cases in which all pumps and compressors are driven either by electric drives or steam turbines were simulated to obtain the theoretical maximum steam and electricity demands, respectively.

To evaluate the carbon dioxide emission consequences in Step 5, the emission factors according to Table 2 for the Swedish electricity, LNG and refinery fuel gases were used. The savings in CO<sub>2</sub> emissions were then calculated as the on-site savings from the reduced steam boiler load (less combustion of LNG and refinery fuel gases) minus the additional off-site emissions from the electricity system due to the increased electricity usage.

Table 3 shows the resulting values from the calculations in Steps 4 and 5 for the reference operation (that is how the plant is operated today) as well as maximum and minimum electricity usage without violating the model constraints. In case of maximum electricity usage, the electricity demand increases by 1.3 MW (+22.4 %) compared to the reference operation while the fuel demand in the boilers decreases by 2.16 MW (-32 %),

resulting in total CO<sub>2</sub> savings of 37,612 tons per year (-18 %). It should be kept in mind that these yearly savings were extrapolated from the steady-state constant operation whereas the plant operation varies on the course of time. The just mentioned changes stem from seven switchable drives that changed to electric motors instead of steam turbines while five drives switched the other way around. In the simulation, the use of available steam from the process coolers as well as from the flue gas waste recovery was maximized before electric drives were used to decrease the steam boiler duty. This also explains why the corresponding electricity demand of 7.0 MW is far from the theoretical electricity demand of 9.4 MW which would occur if all available switchable drives were to run on electricity only. Furthermore, the amount of low-pressure excess steam which is vented to the atmosphere decreased by 85 % in the maximum electricity usage case.

In the minimum electricity usage case, all but one switchable drives used steam turbines. Accordingly, there was a substantial reduction in electricity demand to 1.3 MW instead of 5.8 MW in the reference operation. However, the fuel demand of the steam boilers was doubled, resulting in twice as much CO<sub>2</sub> emissions and a strong increase in excess steam. The reason why not all drivers are driven by steam turbines lies in the constraints of the optimizer model to use electric drives for some pumps and compressors. Switching all drives to steam turbines lead to feasibility problems of the simulation as some of the constraints were violated. Subsequently, mass energy and power balances did not give reasonable results. The steam production as well as installed capacities and valve limits would have to be increased to get feasible results.

## Discussion

Results from the case study for the oil refinery steam system show that it is not obvious whether certain pumps and compressors should be driven by electric motors or steam turbines. The simulation of extreme cases (only electric motors or only steam turbines) shows that there is a large difference in electricity and fuel demand between the two cases so that much more electricity could theoretically be used. However, using only electric motors for the switchable drives in the utility system conflicts with the heat recovery system which provides steam

from process coolers and flue gas recovery boilers. There is also another interconnection between the reaction and separation processes as well as the utility and heat recovery system as not only LNG but also refinery off-gases are fired in the steam boilers. However, it should be noted that latter effect is not yet implemented in the model.

The results for the maximum and minimum electricity usage cases also showed that increased electrification is possible and that fossil fuel use as well as carbon dioxide emissions can be reduced without violating the technical constraints. However, increasing the electrification in oil refinery plants by an increased use of electric drives is just one possible option. To find the best solution the analysis needs to be done for further options but also other decarbonisation options which can then be compared with each other. This case study, showing the competition between heat available at a site and electricity, is a good example for a general challenge that technologies for increased electrification are facing.

It should also be mentioned that some aspects were not considered here. One of these aspects are the detailed calculations on the economic assessment as part of Step 5. However, switchable drives are installed already today at the case study refinery site so that there is no additional investment cost. Thus, the economic feasibility would depend completely on the change of variable cost, due to cost changes for electricity, fuels and emissions. Furthermore, additional benefits such as possible price arbitrage due to available flexibility (demand response potential) and better process controllability with electric drives were not considered here.

For the simulations, typical operating conditions for September were used. However, the availability of refinery fuel gases depends on the ambient temperature since high ambient temperatures reduce the capability to condense sellable products from the product gas stream, which means that the quantity of fuel gases increases. Subsequently, the mass, energy and power balances will be different when performing the simulations for other seasons so that results from September cannot be simply extrapolated. There is also room for improvement of this as it does not take into account a detailed calculation of the fuel composition for the steam boilers.

The proposed methodology allowed a structured approach to the bottom-up assessments. The first larger challenge in

Table 3. Results from steps 4 and 5 for the reference operation as well as maximum and minimum electricity usage without violating constraints.

Variable	Unit	Reference operation	Max. electricity usage	Min. electricity usage
Electric energy used to move dual-drive pumps	MW	5.819	7.036	1.332
Total fuel fired within the boilers	t/h	6.684	5.439	13.483
Whereof total site LNG consumption	t/h	0.325	0.264	0.655
On-site boiler fuel emissions	tCO <sub>2</sub> e/yr	204,386	166,317	412,297
Off-site emissions related to electric power exchange with the grid	tCO <sub>2</sub> e/yr	2,188	2,646	501
Total emissions	tCO <sub>2</sub> e/yr	206,574	168,963	412,798
Steam production from the boilers	t/h	70.6	57.5	142.4
Number of switchable pump with "turbine driver"	–	15/33	13/33	32/33
Total vented steam into the atmosphere	t/h	16	3	94

this methodology was to find suitable process and technology models for the simulations of mass, energy and power balances. However, another challenge which did not appear in this case study would be the selection of consistent market scenarios for electricity, fossil fuel and emissions prices. These are not only important for the techno-economic assessment but also for the greenhouse gas assessment as the carbon footprint of technologies for process electrification highly depends on the generation mix in the power system.

The presented methodology is tailored for the bottom-up assessment of short- to medium-term available technologies. However, in the future there will be processes that are especially designed to use electricity instead of heat (e.g. membrane separation processes). When comparing these processes with existing processes the methodology must be extended and separate models for the new processes will be needed. However, the key figures for comparison can be the same. It should also be considered that the production levels and the variety of products from industrial processes might change over the course of time. Possible reasons for oil refinery plants in the EU in the future could be a decreased demand of diesel and petrol, the integration with biorefineries and industrial symbiosis as well as the integration of CCS together with an increased production of hydrogen. These trends can highly influence the potential of process electrification.

## Conclusions

This paper presented a methodology for the bottom-up assessment of electrification options for industrial processes including a case study example for the steam system of an oil refining plant. Results from this case study indicate that energy and emission consequences when using more electricity in the steam system are hard to predict without the use of a detailed process model. The case study also pointed out the cost competition between heat, which is often available at a plant, and electricity. The general methodology proved to be useful while splitting the whole process into different systems was good to improve the overview and find options for electrification. It is especially the strong interconnection and often already existing integration (e.g. of heat) that leads to complex systems that need to be analysed in detail but also in the context of the whole plant or even (if connected) industrial complexes with several process plants.

The future work can be split into two parts: the current case study as well as the general methodology. For the case study example, it could be examined if even more pumps and compressors that are currently driven by non-switchable steam drives could be upgraded to electric drives. Also, more technologies that can be used in the utility system should be evaluated. Possible options are the use of mechanical vapor recompression (MVR) heat pumps to upgrade low pressure steam or electric steam boilers (see also Table 1). For all options, including the one presented, the economic assessment should be performed by using adequate energy market scenarios. Additionally, the assessment should also be performed for other seasons and thus different operating conditions. Further investigations should also look into the impact of electrification in other systems of the oil refining process. Examples for the separation process are heat pump- or membrane-assisted distillation.

When it comes to the methodology, a key issue is to develop future market scenarios and the comparability with other decarbonisation options such as CCS and biomass but also with new processes with a high degree of electrification (e.g. processes that rely on hydrolysis of water).

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