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Extended Indicators for Total Site Targeting

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Industrial sites spend a large quantity of energy and emit into the environment a considerable amount of Greenhouse gases (GHG). Heat recovery and power cogeneration at Site level provide important options for energy saving and emission reduction. In designing and optimising Total Site heat recovery and cogeneration, the base indicators related to heat recovery, cogeneration efficiency and operating costs can be advantageously extended to allow designers seeing the complete picture of the system performance. Such additional indicators are suggested in the current work, including capital cost, as well as GHG and Water Footprints. The case study showed that generating an additional 15 t/h of boiler steam (VHP) beyond the 33 t/h that was initially needed, increased power generation by 1.72 MW (112 %), and lowered key targeted intensity indicators of Capital Cost by 7.7 %, GHG Footprint by 31.6 %, and Water Footprint by 44.6 %. These results demonstrate the dynamic link between the Total Site cogeneration system and the extended indicators.

1. Introduction

The synthesis and design of industrial processes, including utility systems, involves many stages, during which certain key criteria are tracked, evaluated and optimised. Some of the main stages are the targeting and synthesis. Targeting identifies the performance bound of the system. Historically these have been the minimum fuel, utility cooling and operating costs. Based on these, some works have also set targets for CO_2 emissions (Linnhoff and Dhole, 1993).

Total Site Integration - TSI (Klemeš et al., 1997) considers an industrial site as a set of processes exchanging utilities – process heating, cooling, refrigeration, power, water via the site utility system as a marketplace. The development of Total Site Integration has gone through heat recovery targeting with Total Site Profiles (Dhole and Linnhoff, 1993), adding evaluation of cogeneration (Klemeš et al., 1997), process-specific ΔT_{min} values (Varbanov et al., 2012), boiler feed water heating (Liew et al., 2014), utility system planning (Liew et al., 2013), and market variations (Nemet et al., 2015).

Those works have formed the set of base indicators for site energy performance used in TSI

- Utility demands and site-wide heat recovery
- Trade-off between unit cost for power generation and grid power price
- Marginal steam price, Power-to-heat ratio

Energy Return On Investment (EROI) is another important ratio applied to CO_2 emissions reduction (Walmsley et al., 2015) and it can be applied in the context of industrial utility systems. Such indicators are important for evaluating, monitoring and managing the site energy and economic performance. These are, however, only part of the whole picture. For making adequate decisions, engineers need to evaluate a whole spectrum of indicators simultaneously. At the stage of preliminary system targeting and design, it is possible, based on the heat recovery and cogeneration targets, to obtain further estimates of the behaviour of the designed site and its utility system. Key additional indicators are the investment cost, GHG and Water Footprints. These

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footprints are especially interesting, allowing to account for the simultaneous use of energy and water, manifesting the energy-water nexus in the industry.
The current work proposes definitions for these indicators adapted to the TSI context and discusses their importance to the design and optimisation decision making. Adding these extended indicators to the overall set of tracked indicators during utility system optimisation (of new design, retrofit, or operation) has not been practiced before. The further research should provide detailed procedures for the application of the indicator sets to the specific optimisation tasks.

2. Suggested extended indicators

Indicator extensions are necessary for embedding several important aspects into the evaluation. Investment into equipment, as well as key environmental impacts, play an essential role in utility systems optimisation.

2.1 Capital Cost

The capital cost of power cogeneration is very important – when combined with the fuel and cooling cost, it completes the cost evaluation of the utility system and enables assessing the capital-operating cost trade-off. Capital cost for steam turbines can be expressed as a function of their power generation capacity, which depends on the turbine efficiency, capacity, and the turbine design. A linear regression model provides in most cases adequate results (Varbanov et al., 2004):

$$CC_{ST} = A_{CC}\,[\mathrm{USD}] + B_{CC}\,[\mathrm{USD/MW}] \cdot W_{ST}\,[\mathrm{MW}] \tag{1}$$

where A is the fixed term for a single steam turbine, related mainly to the cost of turbine installation; B is the coefficient of per unit power generation; CC_{ST} is the turbine capital cost estimate; W_{ST} is the power generation capacity. The values for the regression coefficients A_{CC} and B_{CC} are estimated on a case-by-case basis.
For the case of Total Site Targeting, the capital cost target for power cogeneration is calculated by the following equation (Boldyryev et al., 2013):

$$CC = A_{CC}\,[\mathrm{USD}] \cdot N_{MIN} + B_{CC}\,[\mathrm{USD/MW}] \cdot \sum_{i=1}^{n} W_i\,[\mathrm{MW}] \tag{2}$$

In Eq(2), N_{MIN} is the minimum number of turbines based on the overall power target.; n is the number of expansion zones; and W_i is the power generated by each expansion zone. The value N_{MIN} of is provided by the design engineers. Estimating the minimum number of steam turbines (N_{MIN}) requires consultation with the design engineers with potential suppliers, as many turbine configurations are possible. This number is related to the overall power generation capacity and the maximum capacity per turbine, specified by the project owners. Since at the targeting stage the available information is limited, this parameter can be supplied with several values in a sequence, for evaluating the sensitivity of the obtained targets.

2.2 Greenhouse Gas Footprint

From the environmental impacts, that of the Greenhouse Gases (GHG) emissions is the most widely considered. The main components of the emissions come from the fuel use and equipment manufacturing. Generally, environmental impacts are evaluated by accounting for effects directly and indirectly caused by an activity or accumulated over the life cycle stages of a product (Galli et al., 2012). The rate of GHG emissions from the operation can be approximated by the CO_2 released by fuel combustion. If the fuel production and supply involve additional stages with significant GHG release, those can also be included. For the cases of new system design and targeting, GHG Footprint from equipment manufacturing is added, too. These are the identifiable impacts at the early design stage, for which targeting of heat recovery and power cogeneration are intended (Čuček et al., 2012).
The evaluation of the overall footprint is performed using Eq(3)

$$GF = GF_{fuel} + GF_{steel} \tag{3}$$

here GF_{fuel} [$t_{CO2\text{-}eq}$/y] is the GHG footprint of burnt fuel, GF_{steel} [$t_{CO2\text{-}eq}$/y] is the GHG footprint of steel used for turbine installation.
The fuel component of the footprint is calculated as:

$$GF_{fuel}\,[(\mathrm{t\,CO_2\text{-}eq})/\mathrm{y}] = M_{fuel}\,[\mathrm{t/h}] \cdot EF_{fuel}\,[\mathrm{t\,CO_2\text{-}eq/t}] \cdot OP\,[\mathrm{h/y}] \tag{4}$$

where M_{fuel} is the mass of annual fuel consumption of the site, EF_{fuel} is the CO_2 emission factor of the fuel. The emission factor should be specified based on the GHG emissions over the full fuel Life Cycle, including fuel sourcing, processing, transportation and combustion.

The mass of annual fuel consumption is related to the power generation of the site, which can be calculated as in Eqs(4 - 6), and OP is the annual operating hours per year. This is a simple estimation used in (Boldyryev et al., 2013). If more elaborate models for the utility system components are available, they can be used as well. The fuel flowrate can be estimated using the extimates for the heat load to be covered by fuel (Q_{fuel}) – Eq(5), which is further related to the required VHP steam heat load Q_{VHP} – Eq(6) and the required VHP steam flow – Eq(7):

$$M_{fuel}\ [t/y] = Q_{fuel}\ [MW]/NHV_{fuel}\ [MWh/t] \cdot OP\ [h/y] \tag{5}$$

$$Q_{fuel}\ [MW] = Q_{VHP}\ [MW] \cdot \eta_{boiler} \tag{6}$$

$$Q_{VHP}\ [MW] = M_{VHP}\ [t/h] \cdot \Delta h_{VHP}\ [MWh/t] \tag{7}$$

where NHV_{fuel} is the net heat value of the fuel, η_{boiler} is the boiler efficiency, and Δh_{VHP} is the enthalpy drop of VHP and the boiler feed water.

The GHG footprint attributable to the turbine manufacturing and installation can be estimated as:

$$GF_{steel}\ [(t\ CO_2\text{-eq})/y] = W_{ST}\ [MW] \cdot M1\ [t/MW] \cdot EF_{steel}\ [(t\ CO_2\text{-eq})/t]\ /\ P\ [y] \tag{8}$$

where W_{ST} is the power generation capacity of the turbine, M1 is the mass of steel used for the turbine construction and installation per 1 MW of power generation, EF_{steel} is the carbon emission factor of per unit steel, and P is the lifetime of the turbine.

2.3 Water Footprint

Characterisation of the water use of industrial utility systems is often overlooked during their design and optimisation. Considering the substantial use of fresh water and release of waste water, as well as the water losses from the operation, the water footprint of utility systems carries important information for designers when screening and comparing design and operation options.

The water footprint is a consumption-based indicator for water use (Hoesktra and Hung, 2002), and is defined in three categories of blue, green, and grey water footprints according to the Water Footprint Network (WFN) assessment method (Mekonnen et al., 2015). During the starting stage of the CHP system, the water intake for start-ups are very small and not estimated in this study. The makeup water is considered as the main direct water use for steam generation. The water consumption of materials and fuels is considered as the indirect water footprint, which is mainly blue water. The water footprint of make-up water is calculated as follows:

$$W_{makeup}\ [t/y] = U_{steam}\ [t/h] \cdot (1 - CRR + BR \cdot (1 - WRR)) \cdot OP\ [h/y] \tag{9}$$

Where U_{steam} is the steam use of the system, and CRR is the condensate return ratio, BR is the blowdown rate, WRR is the blowdown water return ratio, and OP is the operating hours per year. The water consumption of fuel and steel used in the CHP system can be calculated as Eq(10) (Hoekstra et al., 2012):

$$WF_{mf}\ [m^3/y] = M_{fuel}\ [t/y] \cdot WF_{fuel}\ [m^3/t] + Q\ [MW] \cdot M1\ [t/MW] \cdot WF_{steel}\ [m^3/t]\ /P\ [y] \tag{10}$$

where the WF_{mf} is the water footprint of materials (steel) and fuels (natural gas) per year, WF_{fuel} is the water footprint of per unit fuel consumption, M1 is the mass of steel used for turbine installation, WF_{steel} is the water footprint for per unit steel production, and P is the lifetime of the turbine. The values of these coefficients should be based on assessing the full life cycles of the fuel and steel.

2.4 Intensity indicators

Based on the capital cost, GHG footprint and water footprint, capital intensity can be defined as the capital cost of per unit capacity I_{CC} - Eq(11), and footprint intensive indicators – GHG Footprint intensity I_{GF} - Eq(12) and WF intensity I_{WF} - Eq(13) can be defined per unit of annualised power generation:

$$I_{CC}\ [USD/MW] = CC\ [USD]/W_{GEN}\ [MW] \tag{11}$$

$$I_{GF}\ [t\ CO_2\text{-eq}/MWh] = GF\ [\ t\ CO_2\text{-eq}/y\ ]/(W_{GEN}\ [MW] \cdot OP\ [h/y]) \tag{12}$$

$$I_{WF}\ [m^3/MWh] = WF\ [m^3/y]\ /(W_{GEN}\ [MW]\ \cdot OP\ [h/y]) \tag{13}$$

These indicators can help in determining which design options are more advantageous, sizing the costs and the impacts of the unit of capacity and unit of product (in this case – power generation).

3. Illustrative example

Consider the Total Site heat recovery target in Figure 1, derived from Boldyryev et al. (2013). The pressure levels and saturation temperatures for the various mains are: VHP: (120 bar, 325 °C), HP: (50 bar, 264 °C), MP: (14 bar, 195 °C), LP: (3 bar, 134 °C), condensate: (0.85 bar, 95 °C). For the current example, the steam turbine capital cost coefficients have been estimated from US Department of Energy (2016) data. The obtained values are A_{CC} = 170,471 USD and B_{CC} = 653,653 USD/MW. The CO_2 emission from steam turbine installation comes mainly from the steel content, and the fuel is assumed as natural gas. Natural gas can be considered as the cleanest fossil fuel. The pollutant emissions from natural gas combustion vary with its composition, given by the source region. In this study, it has been assumed that the main components are methane and ethane, totalling 98.2 % (Uniongas, 2017), while the content of sulphur is less than 0.01 %, which can be neglected. Based on the data of (NaturalGas.org, 2012), the emission factors from natural gas combustion are calculated, as shown in Table 1. Table 2 and 3 lists the parameters and data sources for GF and WF calculation.

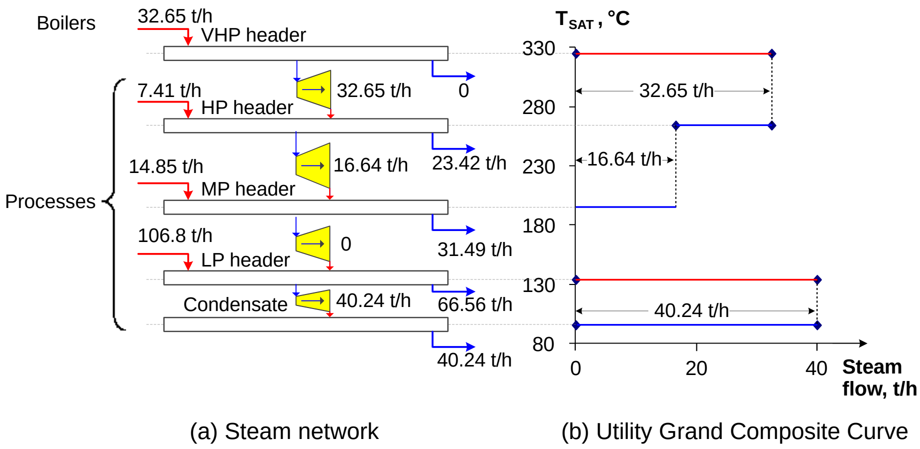

Figure 1: Heat recovery targets (a) and steam flow targets (b) for utility system (Boldyryev et al., 2013)

Table 1: Major air pollutants produced per unit of Natural gas combustion (after NaturalGas.org, 2012)

Air Pollution	Emission (kg pollutant/kg natural gas)	Proportion
CO_2	1.960	0.999
NOx	0.002	0.001
CO	0.001	0.000
SO_2	0.000	0.000

Table 2: Parameters and data sources for GF calculation

Coefficients	Value	Reference
EF_{fuel} [t CO_2-eq/t] (Natural Gas)	0.54	(The Ecoinvent Database, 2017)
NHV_{fuel} [MJ/kg]	38.97	(World Nuclear Association, 2016)
η_{boiler} [%]	82	(Cleaver-Brooks, 2010)
M_{steel} [t steel/MW]	0.9	(Kelly et al., 2014)
EF_{steel} [t CO_2-eq/t]	2.3 - 2.7	(China Steel, 2013)
OP [h/y]	8,760	Estimated Value
P [y]	30	(Gu et al., 2015)

Table 4 lists the values of the obtained indicators for the original state of pinched Site Utility Grand Composite Curve, and for generating extra power by letting more steam through the system and allowing the use of a condensing steam turbine. Since the total power cogeneration targets for both options are relatively small, the parameter for many steam turbines is set to 1.

It can be seen from the results in Table 4, that increased power generation features reduction of ICC, IGF and IWF. It can be concluded that, if extended on-site generation is sufficiently competitive with grid power, the utility system can be sized up to the site power needs.

Table 3: Parameter values and data sources for WF calculation

Coefficients	Value	Reference
Blowdown Rate [%]	5	(Smith, 2005)
Blowdown Water Return Ratio [%]	0	Estimated Value
Condensate Return Ratio [%]	75	(Chem-Aqua, 2011)
WF_{fuel} [m^3/t]	4.29	(Water Footprint Network, 2017)
WF_{steel} [m^3/t]	0.99	(Kruczek and Burchart-Koro, 2014)

Table 4: Calculated targets

Indicators	Unit	Value (Pinched)	Value (extra 15 t/h VHP steam)
Power cogeneration target ($\sum W_i$)	MW	1.53	3.25
Capital Cost (CC)	M USD/y	1.17	2.30
GHG Footprint (GF)	kt CO_2-eq/y	156.6	228.7
Water Footprint (WF)	km^3/y	323.5	381.5
Capital Cost Intensity (I_{CC})	M USD/MW	0.765	0.706
GHG Footprint Intensity (I_{GF})	(t CO_2-eq/y)/MWh	11.72	8.02
Water Footprint Intensity (I_{WF})	m^3/MWh	24.2	13.4

4. Discussion for potential future work

Future work should include also the following considerations:

- Nitrogen Footprint: For fuel-based systems this indicator quantifies the emissions of the reactive nitrogen into the atmosphere, which contribute to various kinds of pollution (Galloway et al., 2014).
- Particulates Footprint: Solid fuel boilers burning biomass and coal emit a significant amount of micro-scale particulates ($PM_{2.5}$ and PM_{10}) into the air. Particulates negatively impact on air quality leading to various health issues, such as asthma, lung cancer, respiratory diseases, and premature death.
- Additional components should be added to the estimation of the capital cost and footprints – such as boilers, steam mains and gas turbines, allowing evaluations of existing sites and retrofits.
- Developing a tool for calculation and visualisation would help to perform such evaluations in an automated way and eventually embed them into the overall design and optimisation procedures.

Another key issue to be investigated is how to prioritise the various footprints when optimising industrial energy systems. To obtain the answer to this question requires further investigation, requiring information beyond the scope of the current work – e.g. which of the impacts GHG or water footprint damages more the environment and sustainability goals. The water-energy nexus also plays a role in this evaluation.
Capital and total cost estimates for the utility system can be further combined with those for the individual processes – including their Heat Exchanger Networks.

5. Conclusions

The current paper proposes extended indicators for evaluation of the performance of utility systems and TSI analysis. Alongside operating costs, adding capital cost estimate allows completing the cost estimates and assessing the trade-off between capital and operating costs. Considering simultaneously the environmental impact on the example of GHG and Water Footprints allows proper quantification. The proposed extended indicators should be considered together with the well-established ones when utility systems are optimised – power-to-heat ratio, total cost consisting of operating and investment components, environmental and health imacts represented by the various footprints.

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