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Footprint Reduction Strategy for Industrial Site Operation

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Industrial sites efficiency and Footprints (FPs) are determined to an extent by the choices made in the Site Utility Systems, which supply the necessary process heating, cooling and power to the core site processes. While the methods for energy efficiency targeting have matured and there are studies evaluating the FPs resulting from utility system operation, a method providing guidance on the measures for FP reduction still need more development. Building upon the previous developments in utility system optimisation, energy targeting and FP analysis, this contribution combines them with the use of FP intensity indicators and analysis of the contributions of the system components to the resulting FPs, to devise a strategy and procedure for reducing the FP values. The obtained results indicate that the fundamental factor-indicator analysis, combined with the exploitation of the structural system links – e.g. the energy-water nexus manifestation, it is possible to achieve significant FP reductions in synergy with potential economic gains.

1. Introduction

Industrial sites consist of production processes, bound together and served by a central utility system. Greenhouse Gas (GHG) emissions from energy users – including industry and the related environmental effects have been put high on the societal agenda. A lot of research, development and organisational efforts are invested to solve this issue. However, GHG this is only part of the overall picture of the environmental pressures exerted by industrial development on the environment and on the living conditions in cities.
There have been previous works on these and related issues: identifying key environmental footprints and their trade-offs for site utility systems (Čuček et al., 2012b), on investment identification for safety (Tan et al., 2016) investment planning for improvement of site safety (Varbanov et al, 2016), as well as on environmental risk management (Wang et al., 2017).
The presented work builds on these ideas and formulates a strategy for reduction of all significant footprints from industrial site utility systems. It takes as inputs the main operating parameters in terms of energy demands, used equipment and energy sources. The important footprints and the key trade-offs are then identified and a strategy for reducing the footprints is proposed, while improving the system energy efficiency performance.

2. Footprint analysis of a site utility system

There are many relevant footprints related to industrial processes (Čuček et al., 2012a). For deriving the base concepts, the current study focuses on the two most common footprints (FPs) – Greenhouse Gases (GHGs) released by the concerned activities and the Water Footprint (WFP) see e.g. (Liu et al., 2017).
While the GHGFP is a well-established metric (Selin, 2018), the WFP concept is less known. The WFP of a product is the volume of freshwater used to produce it, measured over the full supply chain (Aldaya et al., 2012). It is a multidimensional indicator, showing water consumption volumes by source and polluted volumes by type of pollution; all components of a total water footprint are specified geographically and temporally.

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Maximising the system efficiency naturally acts upon reduction of the footprints and their intensities. The following measure tends to reduce both GHG and Water FPs. On-site power generation should be limited to the co-generation mode – i.e. only to the extent enabled by the process steam demands. Such a constraint should be removed only in cases when there is no grid power supply available or if the grid power supply comes with lower efficiency and higher footprint intensities.

The mentioned common-sense efficiency logic should be combined with a systematic approach to the FP reduction analysis. As seen from the overall system perspective, the site utility system has certain resource inputs and other actions, classified as factors and certain indicators of the system performance, impacted by the factors. These are the starting points of the analysis.

Using the utility system model, the core process indicators – heat and power generation efficiency, as well as the energy supply to the processes, are evaluated. Building upon that, the GHG and Water FPs are also estimated. While obtaining the overall FP estimates is necessary and important, this is not sufficient for the intended analysis. Adding breakdown of the FP contributions to the overall sum is another necessary step. The picture is completed by evaluating the FP intensity indicators (Jia et al., 2018).

Starting from the performance indicators, a list of FP reduction options relating the key factors to the indicators is constructed and the sensitivity of the FPs towards those options is evaluated. A suitable tool for this step is a sensitivity table, to rank the options. The procedure is summarised in Figure 1.

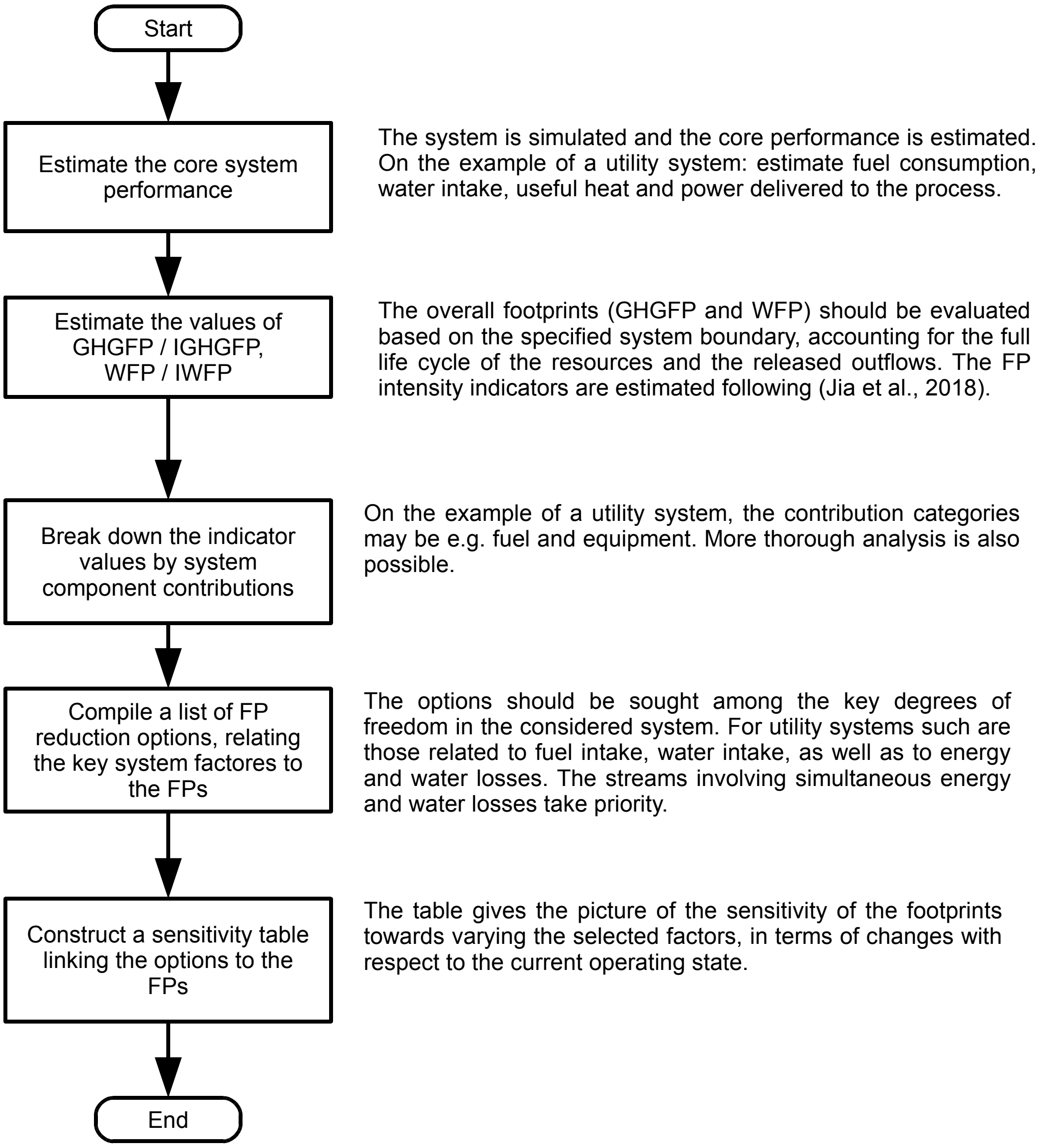
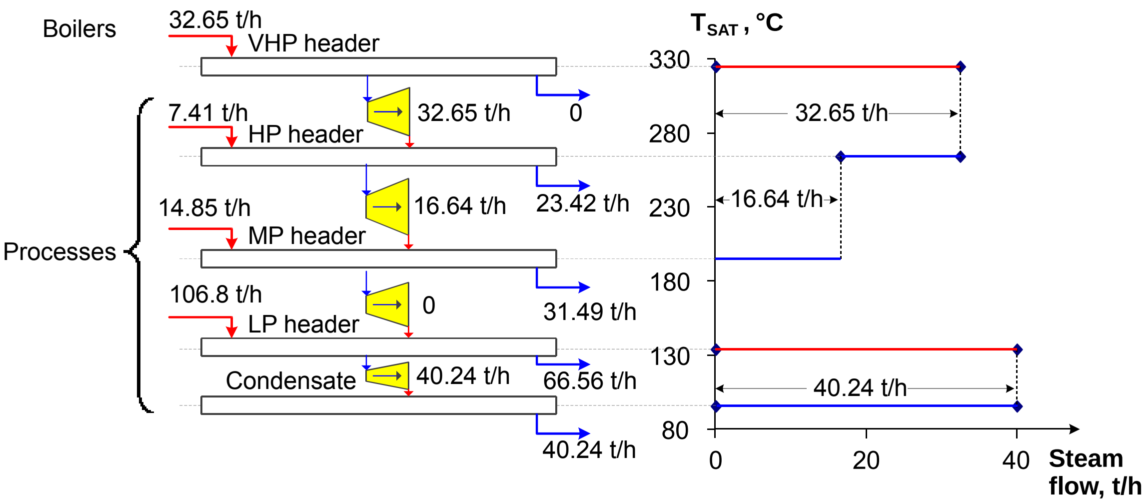


Figure 1: Procedure for FP reduction analysis

3. Illustrative example

Consider the Total Site Utility System and its heat recovery target in Figure 2, 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). The power co-generation from the cascaded steam is potentially performed by steam turbines. Optional turbines are assumed available within each expansion zone (Figure 2). The steam turbine performance is estimated using the regression model from Varbanov et al. (2004).
It is assumed that the VHP steam is generated by boilers running on natural gas (NG, 40 %) and coal (60 %). These and the remaining site specifications are provided in Table 1.
The CO_2 emission from steam turbines and boilers installation comes mainly from the steel content. The pollutant emissions from fuel combustion vary with its type (e.g. coal, natural gas, fuel oil, biomass) and composition.



(a) Steam network (b) Utility Grand Composite Curve

Figure 2: Heat recovery targets (a) and steam flow targets (b) for utility system (Boldyryev et al., 2013)

Table 1: Additional site specifications

T_{Supply}	°C	25	Cooling Water
T_{Return}	°C	45	Cooling Water
COC	(1)	4	Cycles of Concentration (Green and Perry, 2008)
CRR	(1)	0.5	Condensate Return Ratio
Steam Turbine service life	y	30	(Gu et al., 2015)
Steel for construction	t/MW	2.5	(Kelly et al., 2014), [t steel]/[MW power rating]
Boiler blowdown rate	(1)	0.08	(t/h)/(t/h)
GHGFP of steel	t CO_{2e}/t steel	2.5	(China Steel, 2013)
WFP of steel	m^3 / t	0.99	(Kruczek and Burchart-Koro, 2014)
Boiler Efficiency NG	(1)	0.82	
Boiler Efficiency Coal	(1)	0.79	
Net Heating Value NG	MJ/kg = GJ/t	35.0	(WNA, 2018)
Net Heating Value Coal	MJ/kg = GJ/t	23.9	(WNA, 2018)
GHGFP of NG	t CO_{2e}/t	4.207	(ICF, 2012)
GHGFP of Coal	t CO_{2e}/t	6.471	(ICF, 2012)
WFP of NG	m^3/GJ	0.110	(Gerbens-Leenes et al., 2008)
WFP of Coal	m^3/GJ	0.164	(Gerbens-Leenes et al., 2008)

Based on the formulated configuration, the power co-generation targets have been estimated for the situation displayed in Figure 2 and for VHP steam throughput increased by 15 t/h – to test the sensitivity of the system performance in terms of power generation, fuel consumption and footprints, including specific footprints per unit energy delivered. Figure 2 shows the “Pinched Condition” of the site utility system, referring to the “Total Site Pinch” (Klemeš et al., 1997) – the state of minimum possible VHP steam demand, made necessary by the specified process demands for heating and cooling. The results are listed in Table 2. It can be seen that the power generation target doubles.

Table 2: Power co-generation targets

Zone	Steam flow t/h	Power generation MW	Steam flow t/h	Power generation MW
VHP-HP	32.65	0.627	47.65	1.066
HP-MP	16.64	0.227	31.95	0.755
MP-LP	0	0	16.51	0.250
LP-Condensation	40.24	0.672	58.46	1.182
TOTAL		1.526		3.252

Based on the energy evaluation, the GHG and Water FP have been estimated. Table 3 shows the estimates and the breakdown by system components. For the specific case, it can be seen that increasing the VHP steam throughput brings additional power generation in all expansion zones. However, the additional power generation is not “co-generation”, as no additional steam is sent to the processes.
This results in a decrease of the co-generation efficiency from 65 % for 32.65 t/h VHP steam flow down to 59 % for 47.65 t/h VHP steam flow. As a result, the intensities of the GHG and Water FPs increase, as can be noticed from the last two rows of Table 3. This illustrates the benefits of limiting the on-site power generation to the co-generation mode or the closest possible minimum.

Table 3: Footprint estimates

VHP steam (t/h)		32.65	47.65
GHGFP ($ktCO_{2e}/y$)	Fuel	250.854	366.101
	Equipment	0.114	0.244
	Total	250.968	366.345
WFP (m^3/y)	Total	1,235,847	1,513,246
	Fuel	169,172	246,892
	Equipment	0.0453	0.0966
	Make-up water for steam	617,184	600,836
	Cooling tower make-up	449,459	665,517
IGHGFP (tCO_{2e}/MWh)		0.3744	0.5344
IWFP (m^3/MWh)		1.8435	2.2075

Another interesting observation from Table 3 is that the FP contributions of the equipment (estimated by the steel content of the steam turbines), is relatively small, compared with the contribution of the steam system operation components. This observation is in line with the results of Liu et al. (2017). It also indicates that no significant FP reduction can be gained from changes to the turbines.
Several other options for reducing the GHG and Water Footprints from the utility system can be evaluated. Analysing the FP components listed in Table 3, best candidates for seeking FP reductions should be sought in the factors related to the fuel use and the water make-up intakes, causing the most significant FPs. Based on that, in Table 4 are listed several system specifications and decisions, related to these effects. Since the water make-up for steam has already been minimised by limiting the VHP flow to the minimum target for serving the process demands, its sensitivity is excluded from the list in Table 4.
In Table 4, the Condensate Return Ratio (CRR), the Boiler Blow Down Rate (BBDR), the fuel ratio represented by the NG Share in the fuel mix and the boiler efficiencies are strongly related to the fuel intake and the related footprints. The CRR is related to both energy and water use. Increasing it helps saving both resources simultaneously with reducing the related GHG and Water FPs. The decision whether to generate power by condensing steam turbines is related to the Cooling tower water make-up.
The zone for condensing steam turbines spans from the LP header down to the condensation pressure level. If steam turbine placement in this zone is not used, this reduces power generation. It also reduces the huge water losses and the related water footprints. The freed LP steam can be either vented or used for BFW preheating, saving valuable fuel. The second option is evaluated here, assuming a certain loss of heat from the LP steam heat availability until it is transferred to the BFW.

Table 4: Indicators sensitivity as a departure from the current state (Pinched Condition)

	Factor Values				**New values**			**Improvement**		**Ran-king**
	Current	**New**	**Change**	**GHGFP**	**WFP**	**IGHGFP***	**IWFP***	**IGHGFP**	**IWFP**	
Factors			%	($ktCO_{2e}/y$)	(m^3/y)	(tCO_{2e}/MWh)	(m^3/MWh)	(%)	(%)	
CRR (1)	0.5	0.7	40	251	1.236×10^6	0.3744	1.5261	0.0	17.2	3
BBDR (1)	0.08	0.04	-50	251	1.193×10^6	0.3744	1.7800	0.0	3.4	6
NG Share (1)	0.4	0.8	100	176	1.208×10^6	0.2633	1.8019	29.7	2.3	2
$\eta_{NG\ Boiler}$ (1)	0.82	0.90	9.8	246	1.231×10^6	0.3670	1.8368	2.0	0.4	5
$\eta_{Coal\ Boiler}$ (1)	0.79	0.87	10.1	233	1.225×10^6	0.3476	1.8273	7.2	0.9	4
Cond. turbines	YES	NO	-	150	0.718×10^6	0.2260	1.0812	39.6	41.4	1
Indicators (current state)										
.		251		IGHGFP * (t/MWh)	0.3744					
WFP (m^3/y)		1.236×10^6		IWFP * (m^3/MWh)	1.8435					

* per MWh useful energy

Based on the calculated results from Table 4, the considered measures have been ranked from 1 (most beneficial) to 6 (least beneficial). Most attractive is to discard the condensing power generation and rerouting the freed LP steam heat to the reduction of fuel consumption. The benefit comes from the simultaneous reduction of the GHG and water FP. Changing the fuel ratio is also potentially beneficial. If possible to implement, it would bring about good GHGFP reduction, accompanied by a marginal WFP reduction.

4. Conclusions

This paper has presented a conceptual analysis and a procedure for reducing footprints caused by industrial utility systems. It combines the core efficiency analysis and measures with the mapping of key system factors to the tracked footprints (GHGFP and WFP).

It has been shown that, for realising the maximum benefits, it is necessary to explore the possible degrees of freedom jointly with the footprint analysis. The particular tool used has been a sensitivity table, evaluating the footprint reductions as departure from the current operation mode. The analysis has revealed that applying synergy measures is the most beneficial. These are measures exploiting the nexus links between energy and water flows in the system. For the specific case study, the simultaneous reduction of GHGFP and WFP comes by eliminating the condensing power generation, combined with reduction of fuel consumption in the boiler as a result of improved steam use. In this way, it has been demonstrated how to exploit the energy-water nexus as a synergy mechanism, resulting in about 40 % reduction of both major footprints.

The future work should extend the presented analysis into several important dimensions:

- Setting the system boundary. While the demonstrated simple example shows the basic concepts, the system boundaries need to be established based on appropriate Life Cycle Analysis basis, to bring the method as close as possible to modelling the reality (Lee et al., 2017).

Procedure for selecting the relevant footprints. The footprint selection is an important aspect. While GHGFP and WFP are certainly relevant to the analysis of industrial energy systems, other FPs should also be considered and selected for analysis depending on the specific situation. An example of another important FP is the Nitrogen FP.

- Structural analysis. The provided example contains an easily observable steam network. However, real energy systems – including steam networks, are usually much more complicated. This reveals the need to use structural analysis for understanding the systems and discovering the options for FP reduction. One option for performing this task is to apply P-graph (P-Graph Studio, 2018).

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