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Total Site Utility System Structural Design Using P-graph

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This paper explores the macro optimisation decisions of energy sources selection and the structural design of the utility system within the framework of Total Site Heat Integration (TSHI). Most TSHI research on utility systems focuses on optimisation of conventional Combined Heat and Power systems. To build a new Utility Systems Planner (USP) tool, P-graph has been selected as the optimisation tool. A critical element of USP is the inclusion of low-grade heat utilisation technologies within the considered superstructure. The USP outputs include the optimal structure of the utility system including the arrangement and size of each component and estimates for Greenhouse Gas and Water Footprints. The successful application of the USP to a representative industrial case study with district energy integration shows an optimal solution with a natural gas boiler, reciprocating gas engine, condensing economiser, steam turbine, thermocompressor, organic Rankine cycle, cooling tower, and electric chiller with a total cost of 14.893 M€/y. The new tool is a platform for launching further research including site-specific application, multi-period optimisation, and sensitivity analysis.

1. Introduction

Total Site Heat Integration (TSHI) is a proven method that can lead to practical solutions with high energy and resource conservation that progress towards sustainable design (Liew et al., 2017). The concept of TSHI is to link processes via a central utility system to improve overall performance (Klemeš et al., 1997) and has been extended to non-industrial energy users as a Locally Integrated Energy Sectors - LIES (Perry et al., 2008).

Several aspects of TSHI have been improved over the past few years with a focus on the targeting and design of the process-side of TSHI. To mention a few, Liew et al. (2013) looked at Total Site utility systems planning using a sensitivity analysis to set design loads. Chew et al. (2015) analysed the effect of process changes and modifications on TSHI with the view of maximising integration. Tarighaleslami et al. (2017) discussed how to modify and apply TSHI to sites that require non-isothermal utility such as hot water and chilled water. Aziz et al. (2017) introduced a new systemic framework for low carbon emissions industrial site planning.

In TSHI, a central utility system connects the various on-site processes and district demand. In most studies, the design and optimisation of the central utility system concentrate on Combined Heat and Power and Steam Turbine optimisation. Tools such as R-curve analysis were applied to mega industrial sites to express the acute trade-off between heat and power (Matsuda et al., 2009). Boiler, gas turbine and steam turbine hardware models have been formulated to conduct co-generation optimisation and determine the marginal steam price (Sun et al., 2016). An area that needs further attention is the macro decision concerning the optimal energy resource selection and structural design of the utility system (Philipp et al., 2017).

The aim of this study is to optimise the structural design of the Total Site (or LIES) utility system using P-graph as the optimisation tool. To achieve the aim, a new Utility Systems Planner (USP) tool is introduced, which can perform the optimisation and simultaneously quantify GHG and Water Footprints. The study investigates several

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competing and complementary technologies and their application by integrating these into a P-graph superstructure. A LIES case study is presented to illustrate the method and its application.

2. Total Site Utility Systems Planner Tool using P-graph

This study developed a new USP built within the P-graph framework. P-graph is a combinatorial optimisation framework aimed at optimising process networks with high combinatorial complexity (Friedler et al., 1996). The P-graph framework forms the basis of the software tool P-graph Studio (2017), which is used in this study. P-graph Studio offers users the freedom to build superstructures based on sequences and series of vertices that represent materials/energy (circular) and operating units (rectangular). The performance of operating units is based on proportional ratios of inputs and outputs ($y = mx$) while cost functions must follow linear functions (y = mx + c). Material vertices have fixed purchase/sale prices for inputs and outputs.

Figure 1a presents the USP P-graph superstructure for the utility systems with resources at the top, demands at the bottom and energy generation and conversion unit operations and utility balance vertices (e.g. with suffix "_Bal") in between. The model is built to meet inputted demands from a LIES. Resource inputs at the top of Figure 1a are grid Electricity (EL) import, Natural Gas (NG), Biomass, Geothermal heat, Fresh Water, and on-site GHG Emissions liability. The main energy conversion unit operations in the USP are: NG boiler, NG Combined Cycle Gas Turbine (CCGT), NG Gas Engine (GE), biomass boiler, geothermal, steam turbine, Thermocompressor (TVR), Mechanical Vapour Recompression (MVR), Organic Rankine Cycle (ORC), Heat Pump (HPP), Absorption Chiller (ACH), and Electric Chiller (ECH). The intermediate energy levels include: Electricity (EL), Very-High Pressure steam (VHP), High Pressure steam (HP), Medium Pressure steam (MP), Low Pressure steam (LP), High Pressure Hot Water (HPHW), Hot Water (HW), Cooling Water (CW), and Chilled Water (CHW). Dark red lines represent electricity flows, other shades of red and orange lines represent different steam levels including geothermal, blue lines are cold utility, and light blue are water flows.

The USP model requires specifying (i) the industrial site and district energy demands, (ii) unit operation performances, (iii) electricity and fuel prices, (iv) discrete capital cost, (v) annual operating and maintenance costs, and (vi) direct and indirect GHG emissions and water use factors. These data may be inputted via the P-graph Studio graphical user interface.

The objective function for the USP is Total Annual Cost (TAC) as defined in Eq(1).

$$TAC = UC + CC + OM \tag{1}$$

Where UC is the utility cost, CC is the annualised capital cost, and OM is the operating and maintenance cost.

The new USP applies a smart discrete Capital Cost accounting approach, which is carried out by the grey boxes next to each of the major unit operations. Conventional capital cost estimates usually assume continuous power-law functions which relate a key capacity dimension of a system to its cost. This method, although useful, can be problematic for real-world optimisation of utility systems because the capacity is often a series of discrete standard values, not a continuous function. This means, for example, if a site requires a 9.5 MW-fired boiler, which is not a standard rating, it would need to install a 10 MW-fired boiler. The invested capital is then for a 10 MW-fired boiler, which is the next size up of boiler. As a result, continuous power-law capital cost functions are converted into discrete costs based on standard unit operation capacities. These discrete points fall along a common linear function, as required for efficient implementation in P-graph. The applied linear Total Capital Cost, TCC, is presented in Eq(2).

$$TCC = a(S) + b \tag{2}$$

Where S is the size dimension of the unit operation and constants *a* and *b* are specific to a unit operation.

OM cost for the major equipment items is determined using Eq(3).

$$OM = i(TCC \times CF) \tag{3}$$

Where i is the capital cost fraction that is required for OM at full load and CF is the capacity load fraction.

3. Locally Integrated Energy Sector case study

The new USP is applied to meet the energy demands of a LIES, which includes a representative industrial chemical processing site with a Site Pinch between the MP (deficit) and LP (excess) steam mains and district heating and cooling demands. The required energy flows of each utility are provided in Table 1.

In P-graph, the performance values for unit operations are defined by proportional ratios of inputs and outputs. The performance values of primary energy generation and conversion operations are given in Table 2, and in Table 3 for the turbine. Unit operation performance ratios are based on standard thermodynamics and unit operation models, using JSteam Excel (2017) software by Inverse Problem for modelling boilers, Organic

Rankine Cycle, turbine and CCGTs; General Electric Power Generation (2017) for GEs; Kadant Johnson (2011) for TVR; Piller GmbH (2016) for MVR; and Gebhardt et al. (2002) for HPPs ACH, and Chillers.

One of the limitations of P-graph is that these values are fixed and independent of the unit operations production rate and capacity. Once the model is solved, performance values based on the required capacity should be checked to confirm accurate representation of actual performance. It is important to note that energy content of steam and hot/cold water flows only account for the utility's useful energy. For example, the useful energy of HP steam is the energy available above the liquid saturation point at the given pressure. As steam expands in a turbine, its useful energy flow may increase from input to output accompanied by a downgrading of quality.

Table 4 presents the industrial energy and water prices and emission factors that have been applied in the model. Industrial energy prices for electricity, natural gas and biomass was extracted from Eurostat (2017) based on the EU-28 average. The location of the site relative to the biomass affects its price, which ranges from about 8 to 12 €/GJ with the midpoint selected for this study.

Table 1: Utility data and net demand for the industrial site and the district heating and cooling

Utility	EL	VHP	HP	MP	LP	HPHW	HW	CW	CHW
P (bar abs)		100	40	15	4	4			
T_{supply} / T_{return} (°C)		500	250	198	144	144 / 60	60 / 40	30 / 40	1 / 5
Q_{demand} (MW)	5	0	10	35	-3	0	3*	40	2*

Table 2: Performance ratios of major unit operations

	NG Boiler	NG CCGT	NG GE	Biomass Boiler	Geo-thermal	TVR	MVR	ORC	HPP	ACH	ECH
Fuel	-1	-1	-1	-1	-1						
EL		0.300	0.410					0.170	-0.286	-0.060	-0.333
VHP	0.621			0.570							
HP		0.122				-1					
MP		0.075			0.351	1.915	1.066				
LP		0.088	0.178		0.106	-0.872	-1			-1.111	
HPHW					0.149			-1			
Flue	0.029	0.150	0.050								
HW			0.218						1		
CW								-0.830	0.714	-2.111	-1.333
CHW										1	1
BFW (t/MW)	1.136	0.543	0.301	1.043	0.829						

Note: Positive values represent generation while negative values represent consumption

Table 3: Turbine stage performance ratios

	VHP-HP Stage	HP-MP Stage	MP-LP Stage	LP-HW Stage	LP-CW Stage	LP-CHW Stage
Steam in	-1	-1	-1	-1	-1	-1
Power	0.104	0.081	0.093	0.143	0.208	0.277
Steam out	1.059	1.060	1.030	1.062	0.997	0.997

Table 4: Industrial energy, GHG emissions and water prices and water footprint and emissions factors

	Electricity	Natural Gas	Biomass	Geothermal	Fresh water	GHG emissions
Consumption	81.4 €/MWh	6.0 €/GJ	10.0 €/GJ	2.7 €/GJ	0.2 €/t	5.0 €/t
Export	56.0 €/MWh					
Direct EF		55.2 kg/GJ		1.3 kg/GJ		
Indirect EF	279.5 kg/MWh	5.5 kg/GJ	0.8 kg/GJ	0.2 kg/GJ		
Indirect WF	24.35 t/MWh	0.11 t/GJ	70.00 t/GJ	0.05 t/GJ		

The applied linear TCC that is applied using discrete capacity step sizes for each unit operation are presented in Table 5. The cost data sources of are: IEA (2015) for CCGT; Pihl et al. (2010) for biomass boiler; Gebhardt et al. (2002) for HHP, ACH, and ECH; General Electric Power Generation (2017) for GE; US DOE (2016) for steam turbines; Piller GmbH (2016) for MVRs; Ghirardo et al. (2011) for ORC. This study estimates an i value of 4 %, which comprises 2 % for operations and 2 % for maintenance (Smith and Hawkins, 2004). In determining annual Total Cost, total capital investments are annualised using a discount rate of 7 % with an equipment lifetime of 30 y.

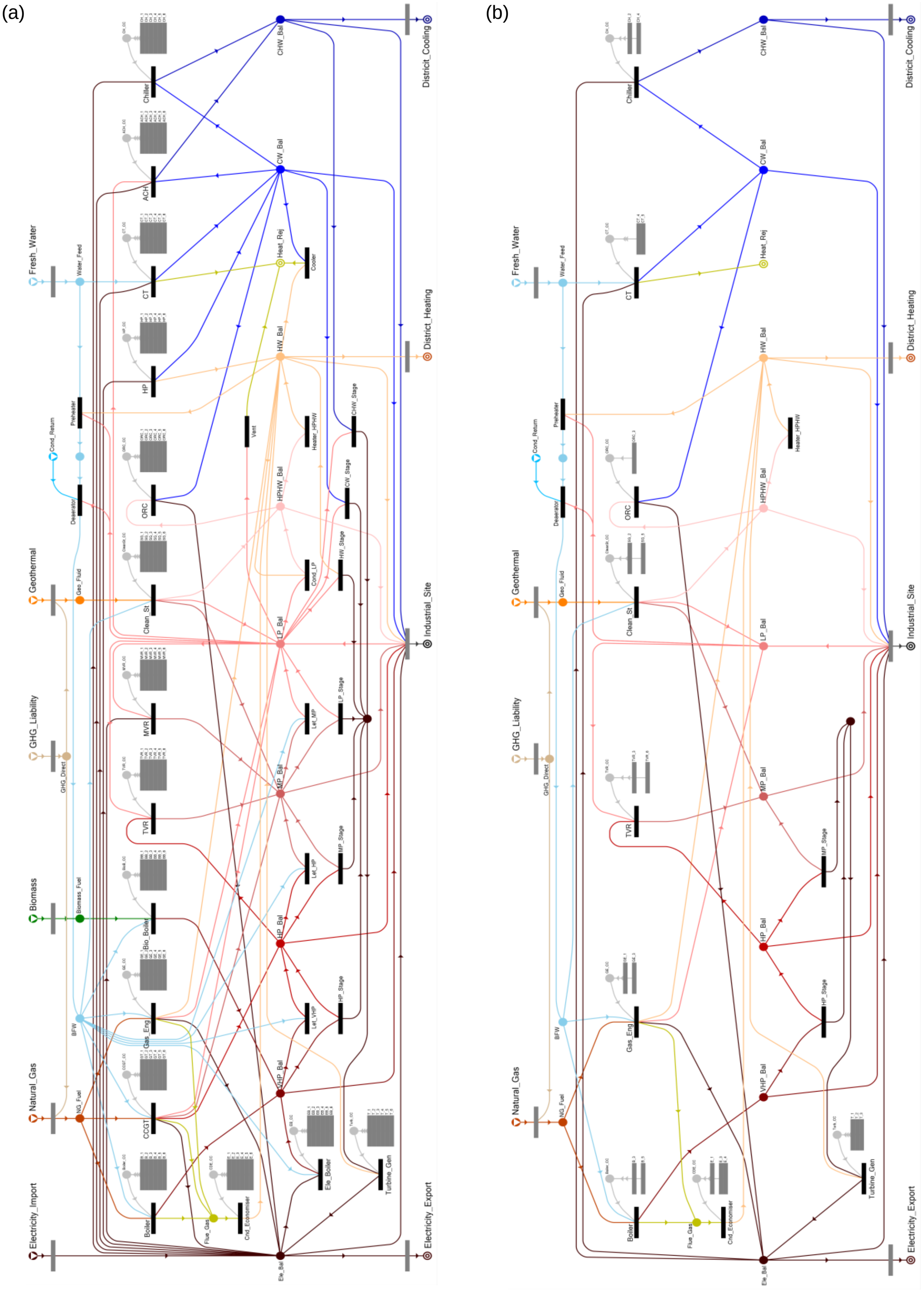

Figure 1: Total Site Utility Systems Planner Tool – (a) initial superstructure and (b) cost optimal solution.

Table 5: Capital cost function coefficients and size basis

	NG Boiler	NG CCGT	NG GE	Biomass Boiler	Geo-thermal	TVR	MVR	ORC	HPP	ACH	ECH
a (€/MW)	150,000	441,000	266,146	378,560	75,000	7,500	68,400	1,414,727	131,817	17,117	184,617
b (€)	-	-	107,850	3,400,662	-		263,250	499,416	46,766	133,017	46,766
Basis	Fuel	Fuel	Power	Fuel	Fuel	LP in	LP in	Power	HW	CHW	CHW
Unit step	2 MW	2 MW	0.5 MW	2 MW	2 MW	0.2 MW	0.2 MW	0.2 MW	0.2 MW	0.2 MW	0.2 MW

The USP tool was applied to minimise the Total Annualised Cost of the considered case study. The TAC includes contributions from fuel use, capital investment for major unit operation components, fresh water consumption, and on-site GHG emissions (from burning fuels). For the given performance and price data, Figure 1b presents the optimal design solution of the utility system given the performance and cost data inputs. For the optimal solution, the Total Cost of the complete utility system is 14.90 M €/y.

As overall fuel inputs, Natural Gas (NG) contributes 42.2 MW while geothermal supplies 35.0 MW, which was its set upper limit. NG fuel fires a regular boiler (86.5 % of NG) and a Gas Engine (13.5 % of NG). A steam turbine expanding VHP steam from the boiler generates 3.1 MW$_e$, while the Gas Engine generates 2.5 MW$_e$ and Organic Rankine Cycle another 0.8 MW$_e$. Of this, 5.0 MW$_e$ is supplied to the industrial site, 1.1 MW$_e$ is consumed within the utility system by electric chiller (0.6 MW$_e$) and cooling tower (0.5 MW$_e$), while the remainder is exported to the electricity grid (0.4 MW$_e$).

A novel part of the solution is the Thermal Vapour Recompression unit, which upgrades 6.1 MW of LP steam to MP steam using HP steam as the motive force, and the condensing economiser, which extracts 1.3 MW of HW from the two flue gas stacks from the boiler and Gas Engine. Given the Industrial Site Pinch sits between the MP and LP steam levels, it seems unusual to recover HW in a condensing economiser in a temperature range that has excess heat from the industrial site. However, district energy demands, combined with the energy demand of the BFW deaerator and application of Thermal Vapour Recompression and Organic Rankine Cycle operations, creates a lower LIES Pinch compared to the process demands of the Industrial Site. The Thermal Vapour Recompression process forms an open cycle heat pump where excess LP steam is upgraded to the MP steam level and supplies the BFW preheater and deaerator. District heating is another heat demand that requires HW. These additional, non-process energy demands, and utility operations modify the optimal utility system solution to warrant the installation of a condensing economiser to generate HW below the Industrial Site Pinch. This novel result reinforces the need to simultaneously select and optimise a utility system that includes non-conventional Combined Heat and Power operations, e.g. Organic Rankine Cycle and Thermal Vapour Recompression.

To quantify the environmental performance of the utility system, GHG and Water Footprints have been estimated by the USP following the methods of Wiedmann et al. (2006) for GHG Footprint and Mekonnen et al. (2015) for Water Footprint. Only direct on-site GHG emissions and fresh water consumption are considered as direct costs to the site. The remainder of the GHG and Water Footprints are indirectly accounted through the energy and capital markets, where applicable. For this case study, the optimal solution has a GHG Footprint of 85,540 t/y, of which 90.8 % is emitted on the Industrial Site, and a Water Footprint of 908,700 t/y, of which 77.3 % is on-site fresh water consumption. Future work will investigate a range of prices for GHG and Water Footprints, including both direct and indirect emissions, to understand the impact of possible increases of emissions prices on the optimal solution.

4. Conclusions

This study successfully developed a new Utility Systems Planner (USP) tool using P-graph to support Total Site Heat Integration. A representative industrial site case study with district heating and cooling is optimised to identify the best design of utility system. In this case, 42.2 MW of natural gas and 35.0 MW of geothermal heat are needed to satisfy total demands of 5.0 MW of electricity, 48.0 MW of heating, and 45.0 MW of cooling. The optimal solution contained a boiler, reciprocating gas engine, condensing economiser, steam turbine, thermal vapour recompression, organic Rankine cycle, cooling tower, and electric chiller. The new tool provides a platform for launching further research including site-specific application, multi-period optimisation, and sensitivity analysis of energy prices and unity operation performance.

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