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The water–energy nexus in manufacturing systems: Framework and systematic improvement approach

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ABSTRACT

Factories consist of production equipment, technical building services (TBS) and building shell, which are connected through interdependent energy and resource flows. The relationship of water and energy flows (water–energy nexus) is an important example—it couples energy and water demands in manufacturing (e.g. cooling, heating, cleaning) with TBS such as boilers, cooling systems or water treatment. While being intensively discussed in context of e.g. industrial ecology, there is no systematic methodological support to improve the water–energy nexus towards sustainability in manufacturing. Therefore, the paper provides a framework and methodology for systematic improvement, which is applied within a case study.

1. Introduction

As research and industrial practice has proved over the last years, reducing energy and resource demand is a topic of strong interest [1]. The focus of work rather lies on improving different energy and resource flows in an isolated manner. However, those flows are dynamically interconnected in factories [2]. Studies underline that system related measures bear high improvement potentials of about 20–50% [4].

The relation of water and energy – the so-called water–energy nexus (WEN) – is a typical example for a systemic connection of two flows (Fig. 1). First coined by Gleick in the 1990s [5], the term describes the inseparable relationship where “one of the two resources can only be provided, acquired or utilized by means of the other causing a reinforcing speed-up of resource demand for water and energy” [6,7]. Water is inevitable for energy generation and conversion, e.g. for mineral extraction, fuel production and electricity generation (“water for energy”) [8]. Vice versa, water cannot be treated or distributed without the usage of energy (“energy for water”). Thus, growing water and/or energy demand worldwide leads to self-energizing effects on both resources and an increasing relevance of the topic.

Thus, energy serves as process input leading to the cumulative value of *embodied energy* (*EE*) describing the total inserted amount of energy. Because of that, water adopts different states in terms of the current thermal, kinetic, potential and chemical *energy content* (*EC*) over the time.

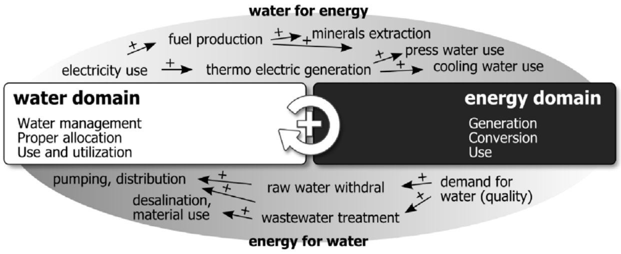

Fig. 1. Relationship between the water and energy domain. [7].

The WEN is often considered in context of larger macro-economic systems and industrial ecology, e.g. national or regional energy and water supply in connection with the natural system surroundings. In comparison to that, the number of approaches addressing the issue of WEN in context of (discrete) manufacturing is very limited; although the concept can be well transferred. Within factory boundaries, water for energy is needed for cooling and heating purposes, steam generation, cleaning, as well as directly as process water [9]. Like in larger systems, energy for water is used for water extraction, wastewater treatment and recycling as well as all distribution tasks [8]. As a consequence, questions like the environmental and economic feasibility of recycling wastewater several times (while investing a lot of energy for pumps) or the appropriate design and control of cooling/heating devices need an integrated perspective on energy and water alike. Due to the lack of appropriate methods and tools those interdependencies cannot be addressed yet.

Against this background, this paper presents a framework and related methodology to assess and systematically improve WEN related fields of actions in factories. It bases on a standardized and therewith transferable system description, a combined analysis with both EE and EC for the evaluation and prioritizing of fields of action as well as a method for scenario analysis.

2. State of research

2.1. Literature overview

Within the domain of macro-economic flows and their connection to the natural environment many case studies for regions or cities exist (e.g. Refs. [10,11]). In addition, there are methodological publications aiming e.g. at strategies for water supply in combination with pumping strategies or the coupling of smart power and water grids for a simultaneous, economic

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dispatch of both resources [12]. Furthermore, available work addresses water demands as part of Life Cycle Assessment (LCA) case studies, e.g. for water supply systems also with respect to energy [13] or automobiles [14]. More methodological contributions in the area of LCA introduce terms like water footprint, virtual water [15] or consider regional impacts [16].

With respect to the water–energy nexus in manufacturing or factories several authors consider energy flows (overview e.g. in Ref. [1]) while some address water flows [17–19] but typically not in an integrated manner. There are some graphical and mathematical approaches in context of pinch analyses [20,21]. However, those methods are aiming at continuous applications in process industry (e.g. chemical, food, pharmaceutical), which neglect specific circumstances in discrete manufacturing industry (e.g. metal machining, automotive, electronic). Thiede et al. and Mousavi et al. model and simulate manufacturing systems in terms of both energy and water and can be seen as first methodological contributions in this research direction [7,22].

2.2. Research gap

While on macro-economic level diverse approaches are available, there are just a few considering the factory perspective. Even more, the focus lies on isolated considerations of either energy or water flows so far. Although approaches to model water–energy flows in an integrate manner exist, a methodological step before that is needed. Since WEN aspects are complex, decision support for prioritizing fields of action is necessary. Transferable and systematic analysis methods covering WEN in discrete manufacturing are missing. Those methods should standardize assessment of specific factory situations and bridge the gap between disciplines like production, process or energy engineers.

3. Concept

3.1. Embodied energy and energy content of water

The concept distinguishes between EE and EC of water and the module specific energy demand (ED). The EE of water describes the total required energy to transport, heat, cool, filter or treat water including the actual ED to do so and can therefore be perceived as its *ecological backpack* (similar to [23] definitions for products). The EC however represents the currently present form and magnitude of energy in the water. The forms of EC in water can either directly result from the induced ED leading to certain physical properties and states of the water (e.g., velocity of water flow, temperature of water etc.) or indirectly through conversion losses. Thus, regardless of its generation, EC can be understood as a time-dependent subset of the overall EE. This implies that the EC may vary within as well as across different factory areas or segments. To analyze the water–energy nexus in factories, both aspects (EE and EC of water) are important.

3.2. WEN system framework for manufacturing

Fig. 2 graphically shows an abstracted and generalized framework for a water–energy system of a factory. The framework integrates several typical system elements and cycles and further subdivides them into different modules (I–V). Those modules differ concerning their intended function; pipes (I) for instance chiefly represent connecting elements to transport water via pumps (II) between production processes and several associated TBS technologies for heating (III), cooling (IV) or wastewater treatment (V). Furthermore, various immanent external factors such as environmental and seasonal conditions involving changing temperatures and humidity influence the water–energy operations of a factory. This is because e.g. temperature and humidity changes either support or impede the cooling capability for instance through evaporation processes of a system (as e.g. shown by Merkel's equation later) influencing water losses and associated energy demands, respectively.

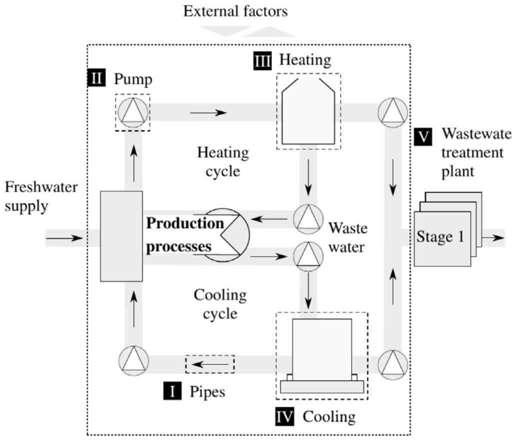

Fig. 2. Framework for a water–energy system of a factory.

The assessment of each element can be pursued based on their share of EE or its EC. To better comprehend the relationship between EE and EC per module, Fig. 3 illustrates qualitatively both aspects per module. The arrows indicate the dominating EC in each module. In addition to that, several influencing factors on the ED are emphasized. Those listed factors range from thermal conductivity, pipe length, time, temperatures, and height difference over to mass flows, velocities, power levels, efficiency rates, pressure differences, shares and temperatures of fresh and condensed water over to specific enthalpies, relative humidity, fan speed and volume flow. The ED is as an important share of the accumulating EE. Besides the ED, the EE also comprises the time-dependent share of EC, which can be subdivided into its thermal, kinetic, potential and chemical parts. Those parts may or may not be present or relevant for each module, as generally expressed by Eq. (1) for EE and EC. Each module is explained hereafter.

$$EE = ED + EC,\; EC = \alpha_1 \cdot E_{therm} + \alpha_2 \cdot E_{kin} + \alpha_3 \cdot E_{pot} + \alpha_4 \cdot E_{chem}, \\ with \quad \alpha_1, \ldots, \alpha_4 \in \{0, 1\}$$

Pipes (I) reflect connections between different system elements carrying heated or cooled water. Since no external energy is directly induced into the pipes, there is no directly associated share of ED. However, the additional energy required to make up for heating or cooling in case of thermal losses can be considered via an imputed energy demand. EC can vary due to the water pressure or velocity of the carried water as well as the height differences (s_s) of the pipe's system in form of either kinetic or potential energy. Temperature differences between the carried water inside the pipes (T_{in}) and the ambient air (T_{out}) may further lead to a significant share of thermal energy, as described by Eq. (1). Thermal losses reduce the thermal energy depending on thermal conductivity of pipes λ, see Eq. (2).

$$d\dot{Q}_w = \dot{m}_w \cdot c_w \cdot dT_w \tag{1}$$

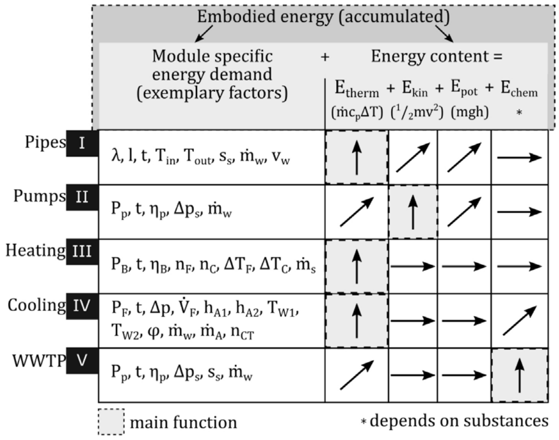

Fig. 3. Relations between ED, EC and EE per module.