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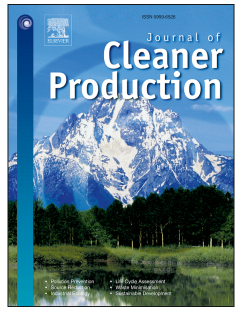

An exergy based approach to resource accounting for factories

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An exergy based approach to resource accounting for factories

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Abstract:

Resource accounting is widely practiced to identify opportunities for improving the sustainability of industrial systems. This paper presents a conceptual method for resource accounting in factories that is based on the fundamentals of thermodynamics. The approach uses exergy analysis and treats the factory as an integrated energy system comprising a building, its technical building services and manufacturing processes. The method is illustrated with a case study of an automotive cylinder head manufacturing line in which the resource efficiency of this part of the factory is analysed for different energy system options relating to heating ventilation and air conditioning. Firstly, the baseline is compared with the use of a solar photovoltaic array to generate electricity, and then a heat recovery unit is considered. Finally, both of these options are used together, and here it was found that the non-renewable exergy supply and exergy destruction are reduced by 51.6% and 49.2% respectively. Also, it was found that a conventional energy analysis would overestimate the resource savings from reducing the hot water supplied to the heating system, since energy analysis cannot account for energy quality. Since exergy analysis accounts for both energy quality and quantity it produces a different result. The scientific value of this paper is that it presents an exergy-based approach for factory resource accounting, which is illustrated through application to a real factory. The exergy-based approach is shown to be a valuable complement to energy analysis, which could lead to a more resource efficient system design than one based on energy analysis alone.

1. Introduction

There is both increasing global competition for scarce natural resources and increasing pressure on industries to waste fewer of them. Research into industrial sustainability is one response to these trends and there is a range of approaches to this subject (Gutowski, 2011). One approach to industrial sustainability is ‘resource efficient manufacturing’ which implies improving a manufacturing system thus producing the same product using fewer natural resources. To calculate a factory’s resource efficiency, it is necessary to account for all the resources flowing through its manufacturing systems, including materials and various forms of energy. When considering the energy flows, the most common approach is based on the first law of thermodynamics, which leads to the concept of an energy balance. This can be considered an established method of resource accounting (Bakshi et al., 2011), with the equivalent technique for material flows being the mass balance.

Henningsson et al. (2004) use mass and energy balances to calculate the financial savings that from improving resource efficiency in the UK food industry. Duflou et al. (2012) review methods used to improve resource efficiency in discrete part manufacturing including more of the industrial system than merely the factory, showing that a more holistic approach allows identifying greater opportunities for resource reuse, so that the analysis impacts more on waste reduction and resource efficiency. Similarly, Evans et al. (2009) suggest that a ‘whole systems thinking' approach is well suited to the current challenges of industrial sustainability. An example of whole systems thinking is the approach taken by Ball et al. (2012) in which the concept of resource flows within manufacturing is extended to include the resources used in the factory building too. They argue that an analysis of both the factory building (and its building services) and the manufacturing processes within it can identify opportunities for improving resource efficiency that might otherwise be missed. Resource optimization tools in manufacturing commonly focus on discrete events (such as plant breakdown events, order arrivals or process completions), whereas analysis of building energy systems focus on continuous energy flows. Since factories comprise both buildings and process plant, optimization tools that combine the two show great potential for resource savings (Oates et al., 2011; Herrmann and Thiede, 2009). Despeisse et al. (2012a) present a conceptual model that takes a whole system perspective on factory analysis, illustrating this with a case study (Despeisse et al., 2012b), similar work being carried out by Chen et al. (2014).

Studies based on mass and energy balances such as these exclude any notion of resource consumption since we know that during mass and energy transformations, both matter and energy are always conserved. Such techniques may quantify wasted resources but they cannot distinguish between the quality (or usefulness) of primary flows and those flows that we may label 'waste'. The notion of waste itself is problematic since the waste from one factory may sometimes be regarded as the feedstock for another, a key insight of industrial symbiosis. Unlike mass and energy, exergy (a thermodynamic quantity based on the 2nd law of thermodynamics) is consumed during transformations and can therefore be used to account for the quality as well as the quantity of mass and energy flows. Exergy destruction can rightly be regarded as a form of waste.

The exergy of a thermodynamic system is defined as "The maximum theoretical useful work (shaft work or electrical work) obtainable as the system is brought into complete thermodynamic equilibrium with the thermodynamic environment while the system interacts with this environment only" (Tsatsaronis, 2007). It is a property of both the system and the environment when both are considered as part of a composite system (Bakshi et al., 2011). Exergy can be calculated for both energy and mass flows, representing variation of a flow from the equilibrium environment. Resources that are at the equilibrium state are considered to have no useful potential. Therefore, exergy can be used to account for mass and energy flows of varying quality levels using common units to quantify their usefulness. This gives exergy analysis an advantage over the use of mass and energy balances when analysing natural resource flows. As a result, the method is quite mature in the field of environmental science, a short summary of relevant exergy research follows.

Wall and Gong (2001) list the different types of exergy that exist in nature and show how the concept of exergy can be used to measure human impact on the environment, leading to the development of exergy-based environmental indicators. Szargut et al. (2002) also use an exergy based indicator to measure the impact of manufacturing on the environment as an 'ecological cost' that is based on the cumulative consumption of non-renewable exergy. Here, the distinction between renewable and non-renewable exergy consumption is important, the latter being seen as a proxy for resource depletion. Gößling-Reisemann (2008) also measures the depletion of the earth's natural resources by the consumption of non-renewable exergy. Connelly and Koshland (2001) use exergy to measure resource consumption and an evolutionary analogy to assess industrial system sustainability. They define industrial sustainability according to two key principles: increasing the proportion of exergy from renewable sources, and reducing the exergy destroyed by the industrial system.

Rosen (2009) show theoretically how exergy analysis can be used to quantify the impact of technology on the environment. Exergy analysis is used by Dewulf and Van Langenhove (2005) to develop environmental sustainability indicators to make quantitative comparisons of different technologies, using these indicators to compare solid waste treatment technologies. Exergy-based indicators have also been used in a decision support tool for power plants (Zvolinschi et al., 2007) and to analyse the impact upon sustainability of different designs of a gas turbine (Granowskii et al., 2008). A much studied large industrial system is the Kalundborg eco-industrial park in Denmark (Jacobsen, 2006) where resource efficiency is maximised by integrating the material and energy flows between the different organisations of the park. Valero et al. (2012) carried out the first exergy analysis of Kalundborg showing how exergy could be used as a indicator for resource efficiency in industrial symbiosis. A similar approach can be used to account for resources at a national scale, as shown by Chen et.al. (2006) who use exergy to measure the resource efficiency of China. Further applications of exergy analysis to industrial sustainability can be found in review articles, such as those by Boroum and Jazi et al. (2013) and Sciubba and Wall (2010). Together, these studies suggest that exergy can be used to measure industrial sustainability at any scale.

It is appropriate at this stage to consider the usefulness of exergy analysis to manufacturing, in particular its application to the material and energy flows within and between the processes and building services of a factory, to explore any possible benefits compared to the traditional approach of mass and energy balances. The next section describes a conceptual exergy analysis method followed by its application to an automotive cylinder head production line. The baseline system is compared with three energy technology retrofit options of increasing resource efficiency. Finally, the results are discussed to clarify the implications of the method for industrial decision makers.

2. A novel approach for resource accounting in a factory

This section presents a conceptual approach to resource accounting and a guide to the conservation of factory resources, the idea being that this could serve as a decision making tool for improved resource efficiency in factories. Figure 1 illustrates the conceptual approach, showing a manufacturing system in which all material, energy and waste flows are represented as exergy flows. Considering both energy and mass flows on a common unit basis will facilitate identification and quantification of possible reuse opportunities. The factory environment comprises three sub-systems; the technical building services (TBS), the manufacturing processes and the factory building.

The exchange of exergy to and from the building sub-system is facilitated and simplified by defining a single building air node that is used to implement the exergy balance. In Figure 1, it is assumed that the generic factory consists of a single thermal zone, however in practice; there may be multiple thermal zones with an equivalent number of zone air nodes. It should be noted that in an integrated system, the focus is on the performance of the whole system rather than its individual sub-systems. If synergies between sub-systems are to be developed, then the reduction of overall factory resource consumption should be viewed as the primary goal. If individual sub-systems are to be analysed, then their interactions with other systems of the factory need to be taken into account so that accurate results are generated.

Figure 1 - The exergy-based approach for manufacturing system analysis

The features of this approach are listed as follows,

- A generic manufacturing facility is modelled as an integrated system based on exergy flows;
- The bi-directional arrows between the sub-systems suggest possible reuse of exergy flows;
- The possibility of exergy reuse within the processes themselves is highlighted;

- A possible interchange of exergy between the sub-systems promotes a reduction in both exergy supplied and exergy wasted;
- Exergy destruction occurs within each sub-system of the factory. This indicates thermodynamic losses during resource transformations and represents loss of value;
- The supply exergy has both renewable and non-renewable components. This distinction is essential, since industrial sustainability depends on both increasing the proportion of renewable exergy supply and reducing exergy losses from the factory;
- At a larger scale, the factory can be considered one element of an industrial symbiosis network. In such a case, changes at an individual factory can be analysed for impacts on the resource efficiency of the whole network;

Despite its possible benefits, the analytical approach described has some drawbacks. Combining mass and energy flows into a common exergy flow adds to analysis complexity, illustrated by the case study in section 3. The effort needed to tackle the added complexity has to be justified. Also, a complete holistic analysis would require data on all sub-systems of the factory. These are major challenges to the implementation of this approach in practice. In addition there are also theoretical inconsistencies in exergy calculations. For example, exergy analysis makes no distinction between flows that leave the factory that are beneficial and those that are harmful to the environment. Since both types of flow represent variations from the equilibrium state (Gaudreau et al., 2009), toxic waste flows will have positive exergy values. This represents a contradiction as useful value would be assigned to such flows. Furthermore, quantifying the chemical exergy of non-work producing substances such as minerals presents a challenge. A study by Delgado (2008) compares theoretically and experimentally obtained values of chemical exergy for minerals. A weak correlation between the two sets of results exposed this problem is exergy calculations. The issue of unresolved shortcomings in the theoretical basis of exergy analysis is also highlighted by Ao et al. (2008). While these issues of practice and theory detract from exergy analysis, significant advantages over energy analysis remain in its ability to quantify natural resource consumption and facilitate improvement decisions, as illustrated in the next section.

3. Case study

The conceptual model described in the previous section was applied to an engine cylinder head manufacturing line. The production processes mainly involved metal cutting and washing processes. The heating, ventilation and air conditioning (HVAC) system is an example of TBS that ensures comfortable working conditions inside the factory building. This study quantifies the HVAC system's non-renewable exergy supply and the exergy destruction. Furthermore, the impact of heat reuse and the addition of photovoltaic generation are analysed. The following 5 general steps were applied:

1. Collect data about the factory and associated systems and to define the system boundary. This can be an industrial park (multiple sites), a single factory or a part of one. This is to be decided in view of the scope of the particular case at hand. The factory data includes building dimensions, space arrangement, construction data, lighting etc. Systems data may include the type of systems and parameters such as air/water flow rates, temperature regime, operation and control etc.

   Since the conceptual model views the factory as an integrated system, both the production and building data needs to be acquired. This data are usually collected through site visits, talking to factory managers and plant engineers or specialised data acquisition equipment.
2. Based on the outputs of step 1 (collected data), the energy model of the case study is to be created, the output of which is the energy demand profile of baseline scenario.
3. Improvement options that might lead to reduced resource consumption are identified.

   Inputs to this step are the data from step 1 and systems data about the identified alternative options. The outputs of this step are the energy demand profiles of the alternative options.

4. Exergy modelling of the baseline and identified improvement options.

   Inputs to this step are data from step 1, and energy profiles generated in steps 2 and 3. This results in the exergy profiles of baseline and alternative options.

   It should be noted here that exergy modelling of flows may entail calculation of the different forms of exergy such thermal, mechanical or chemical exergy. Especially when taking a holistic approach, resource flows may include modelling of chemically complex flows such as patented chemicals or effluent water. However for the case study presented in this paper, only thermal exergy calculations were required, minimising complexity.
5. Finally, the results from steps 3 and 4 are compared, leading to the ranking of improvement options while considering both quantity and quality of resource flows.

Following these general steps, the analysis itself is now described. The system boundary for this case study encapsulates a part of the factory that housed the engine cylinder head production line (step 1); additionally the control volumes for each option are outlined in Figure 2. In this analysis, changes to the HVAC system are considered. Since this system is influenced by the production line and the building space, an accurate analysis requires a holistic approach. Figure 2 depicts the manufacturing system comprising three sub-systems: the HVAC as part of the TBS, the production line and the building. The resource efficiency is to be improved by considering three energy system options as shown in the figure. The baseline option considers the existing HVAC system with neither heat recovery nor renewable exergy supply. Option 1 incorporates a PV array, option 2 includes a heat recovery unit (HRU) and option 3 includes both the PV array and the HRU. The electrical exergy supplied by the PV that is surplus to the HVAC demand is used by the production line as shown in the figure. The HVAC system can be divided in two major subsystems:

- The dedicated outdoor air system (DOAS)
- A range of unit heaters (UH)

The DOAS consists of an air handling unit (AHU) with supply and return fans, main heating coils (HC), a heat recovery unit subsystem (HRU) and an air distribution network. The system operates with 100% outdoor air, which is distributed to the factory via 32 supply columns each delivering around 1060 l/s (1.06 m^3/s) of a fresh air. In total 122,000 m^3/h (33.89 m^3/s) of fresh air is delivered to the factory. The main heating coils are controlled by the supply air temperature sensor, set to 17°C.The heat recovery effectiveness was set to a realistic 75%. Additionally, the UH subsystem is composed of 15 unit heaters, each with a heating coil and fan. A UH fan re-circulates room air and is switched off when heating is not required. Each UH coil is controlled by a thermostat set to 21°C during occupancy. The set point during unoccupied periods (setback temperature) was unknown and was treated as a variable during calibration of the simulation model. The temperature profile for the hot water circuit, which delivers hot water from a heat source to heating coils (both in UH and AHU) was created using site data.

The factory is approximately 100m long and 56m wide, with average ceiling height of 9.05m. Double-glazed windows are installed on west, south and east facades and cover approximately 54.6m^2, 47.2m^2 and 39.8 m^2 of wall area respectively. The external wall is made of two layers of metal cladding (outer and inner) with a 100mm insulation and concrete block layers. Construction data concerning the ground floor and roof have been selected according to the typical construction practice for this age (early 1980s) and building location. Table 1 shows the U-values of the most important construction elements and their composition.

Figure 2 - The exergy based conceptual model for automotive factory analysis

72.5kW of artificial lighting is used for approximately 19.2 hours per day. The electricity consumption profile of the production lines has been derived from the measured data which was then used to determine the internal gains from production equipment necessary for the HVAC modelling. It is assumed that only 30% of heat from machining is dissipated as heat to surrounding air, while the rest is removed by other measures including the coolant system of the machining line.

Table 1 - Construction information used to model the factory building

A computer model of the HVAC system was created using EnergyPlus (2012) and a simulation was performed to quantify the effects of changes to this system upon resource demand (step 2) . In the factory, only the overall electrical energy and heating energy usage were recorded and used to calibrate the baseline model. Data for the building construction, lighting and production were acquired and input into the software model, and the factory building energy model was created using the Legacy OpenStudio (2013) plugin.

Finally, a local weather file was used to drive the building energy model. To calibrate the model, two input variables were chosen, the setback temperature set point and the air infiltration rate. A range of values were assigned to each of these two variables. The calibration was setup in jEPlus (2013), a Java based EnergyPlus shell created to manage and run large and complex parametric simulations. The results from parametric simulations were used to calculate the root mean square error (RMSE) between the simulated heating demand and the real demand as measured by the factory's building management system (BMS). Values for the setback temperature set point and the air infiltration rate from the scenario with the lowest RMSE value of 90kW (which corresponded to the coefficient of determination of 0.62) were used for simulating the technology options considered. From the analysis of the baseline model, improvement options were identified which are described in detail in sections 3.2 – 3.4 (step 3).

The building exergy analysis is based on the 'Low Ex' concept (Schmidt, 2004), for building exergy management which focuses on matching the energy quality of supply and demand to reduce exergy losses , hence reducing natural resource consumption (step 4). As shown in Figure 3, the supplied building exergy is calculated in seven stages, starting from the primary energy transformation. Since the analysis approach presented here is confined to the factory, only the last three stages of the Low Ex approach are considered. The analysis of the HVAC system and the factory building in this study can therefore be considered the last three stages of the Low Ex approach (Khattak et al., 2014). The mass flow rates and temperatures calculated by the EnergyPlus hourly simulation are used to calculate the exergy flows. There are three types of flow involved in the factory for which exergy is calculated:

The electricity flow is pure work; therefore electrical energy and exergy are equal,

$$\dot{E}_{electrical} = \dot{Ex}_{elec} \tag{1}$$

The air involved is assumed to be an ideal gas. The exergy of air flows is therefore calculated as,

$$\dot{Ex}_{air} = \dot{m}_{air} c_{air} \left[(T - T_0) - T_0 ln \left(\frac{T}{T_0} \right) \right] \tag{2}$$

Where $\dot{m}_{air}$ $[kg/s]$ is the mass flow rate of the air; c_{air} $[kJ/kgK]$ is the specific heat capacity of air and T $[K]$ and T_0 $[K]$ are the air and outside temperatures respectively.

Finally, the water involved is assumed to be incompressible, the exergy being calculated as,

$$\dot{Ex}_{wa} = \dot{m}_{wa} c_{wa} \left[(T - T_0) - T_0 ln \left(\frac{T}{T_0} \right) \right] \tag{3}$$

The symbols $\dot{m}_{wa}$ $[kg/s]$ and c_{wa} $[kJ/kgK]$ are the mass flow rate and specific heat capacity of the water respectively.

These three exergy equations are sufficient to analyse all flows in the factory. Table 2 provides a sample calculation for the air and water flows through the unit heaters for 8 hours of production in January. The data show that as the streams flow, exergy from the water is transferred to the air. After the generation of exergy profiles for the relevant flows, the energy and exergy based results are compared and discussed in sections 4 – 5 (step 5).

Table 2 - Sample calculations for air and water flows through the unit heaters

Figure 3 – Stages of energy flow transformations analysed in the LowEx approach (Hepbasli, 2012)

3.1 Baseline scenario

The baseline scenario against which improvement options will be compared considers the HVAC system without any heat recovery or renewable exergy supply. Since sustainability is linked to the consumption of non-renewable resources, the non-renewable exergy supplied is of concern. The rate of exergy supplied to the HVAC system and the rate of destruction of non-renewable exergy are calculated using the following equations:

$$\dot{Ex}_{supply} = \Delta\dot{Ex}_{wa} + \dot{Ex}_{elec} \quad (4)$$

$$\dot{Ex}_{dest} = \Delta\dot{Ex}_{wa} + \dot{Ex}_{in-air} + \dot{Ex}_{elec} - \dot{Ex}_{out-air} \quad (5)$$

The exergy rate delivered to the HVAC system from both the hot water flow and electricity are represented by $\Delta\dot{Ex}_{wa}$ $[kW]$ and $\dot{Ex}_{elec}$ $[kW]$ respectively. The supply cold air from outside the factory is at outside weather temperature, and therefore has zero exergy. The term $\dot{Ex}_{in-air}$ $[kW]$ is the supply air exergy rate to the unit heaters from within the factory space. Heat from the hot water is imparted to the inflowing air streams therefore delivering heated air to the building space ($\dot{Ex}_{out,air}$ $[kW]$).

3.2 Option 1 – With renewable exergy supplied from the PV array

In this scenario, renewable exergy is supplied to the HVAC system as electrical energy from a PV array ($\dot{Ex}_{PV,HVAC}$ $[kW]$). Since electricity is work (by definition), the non-renewable exergy supplied and exergy destroyed are calculated using the following equations:

$$\dot{Ex}_{supply} = \Delta\dot{Ex}_{wa} + \dot{Ex}_{elec} - \dot{Ex}_{PV,HVAC} \quad (6)$$

$$\dot{Ex}_{dest} = \Delta\dot{Ex}_{wa} + \dot{Ex}_{in-air} + \dot{Ex}_{elec} - \dot{Ex}_{PV,HVAC} - \dot{Ex}_{out-air} \quad (7)$$

3.3 Option 2 – With heat recovery

This option considers reuse of heat from the factory building space. Air from the building space is extracted by the HVAC air extraction system and used to preheat incoming cold air from the outside in a heat recovery unit (HRU). The mass and energy flow data are used to establish the exergy balance. The exergy supply rate and exergy destruction rate are calculated using the equations below:

$$\dot{Ex}_{supply} = \Delta\dot{Ex}_{wa} + \dot{Ex}_{elec} \quad (8)$$

$$\dot{Ex}_{dest} = \Delta\dot{Ex}_{wa} + \dot{Ex}_{elec} + \dot{Ex}_{in-air} + \dot{Ex}_{recov} - \dot{Ex}_{out-air} \quad (9)$$

The rate of exergy delivery to the HVAC system from both the hot water flow and electrical supply are represented by $\Delta\dot{Ex}_{wa}$ $[kW]$ and $\dot{Ex}_{elec}$ $[kW]$ respectively. To calculate the exergy destruction rate, the exergy delivered to the HVAC system from heat recovery ($\dot{Ex}_{recov}$ $[kW]$) must be quantified. Even though the internal gains from the production and building space are not direct inputs to the HVAC system, heat from these sub-systems is imparted to the TBS sub-system (in this case the HVAC system) through the heat recovery process. It was therefore necessary to quantify these gains, which was done using the simulation approach described earlier.

3.4 Option 3 – With heat recovery and solar power

The final option incorporates both the PV array and the HRU into the factory energy system. The size of the roof PV plant was determined by conducting a multi-objective optimisation study with two objectives; to maximise total annual PV plant electricity generation and minimise payback period. Parameters that were varied in the optimisation study were (i) PV panels slope angle, (ii) PV panel size orientation (horizontal or vertical), (iii) number of PV arrays and (iv) distance between PV arrays. The selected optimal solution has less than 10 years payback period based on an assumed investment cost of 1,200 Euros per kW of installed power. This calculation was based on data from the UK Department of Energy and Climate Change (DECC, 2012), and the factory electricity cost of 0.1 Euro per kWh. Since one objective is a reduction in destroyed exergy, a match is sought between the energy quality of supply and demand. For this reason the PV supply should fulfil only electrical demand and not heat demand (for example). The non-renewable exergy supply is therefore given as:

$$\dot{Ex}_{supply} = \Delta\dot{Ex}_{wa} + \left(\dot{Ex}_{elec} - \dot{Ex}_{PV,HVAC}\right) \quad (10)$$

In order to quantify the destruction of non-renewable exergy, the exergy balance for the HVAC system is established. The basic exergy balance for any system is given as:

$$\dot{Ex}_{in} = \dot{Ex}_{out} + \dot{Ex}_{dest} \tag{11}$$

Where $\dot{Ex}_{in}$ $[kW]$ and $\dot{Ex}_{out}$ $[kW]$ is the non-renewable exergy entering and leaving the system respectively. Figure 4 shows the exergy flows through the HVAC system in option 3. The reuse of exergy forms a circular loop as shown in the diagram. The figure shows two sources of thermal exergy to heat the incoming outside air - warm air from the factory space and heat from water flowing through the system. Additionally, the factory space air is heated by the HVAC system itself and internal gains from within the factory building. The factory workforce, artificial lighting and production equipment are the sources of internal gains, but since the contribution of the workforce is negligible, it is neglected. Since a part of the supply to the production machines and lighting is from the PV array, a portion of the thermal exergy in the factory air is thus supplied from a renewable source. This is also true for the heat recovered as it is also extracted from factory air. Let φ represent this proportion of renewable sourced thermal exergy in the factory air where,

$$\varphi = \frac{\dot{Ex}_{PV}}{\dot{Ex}_{total\ elec}} \times \frac{\dot{Ex}_{gains}}{\Delta\dot{Ex}_{wa} + \dot{Ex}_{gains}} \tag{12}$$

In order to separate out the renewable sourced exergy in the outgoing flow of warm air, let σ represent the proportion of the air exergy in the total that enters the HVAC system. It is given as,

$$\sigma = \frac{\dot{Ex}_{in-air} + \dot{Ex}_{recov}}{\dot{Ex}_{wa} + \dot{Ex}_{in-air} + \dot{Ex}_{recov}} \tag{13}$$

It follows that the fraction of renewable sourced exergy in the total that enters the HVAC system is given by the product $\varphi\sigma$. The exergy balance for non-renewable exergy flow through the HVAC system with heat recovery and solar power supply is given as follows.

$$\dot{Ex}_{supply} + (1-\varphi)\dot{Ex}_{in-air} + (1-\varphi)\dot{Ex}_{recov} = \dot{Ex}_{out-air}(1-\varphi\sigma) + \dot{Ex}_{dest} \tag{14}$$

It should be noted here that there is no physical distinction between renewable and non-renewable sourced exergy destruction. However, this parameter is required in order to quantify the losses of non-renewable exergy from the system.

Figure 4 - Flows through the HVAC system in option 3

4. Results:

Based on hourly values, the exergy supply rate for the three cases is shown in Figure **5**. It can be seen that the non-renewable exergy supply progressively reduces as one considers manufacturing system options from the baseline to option 3. For the baseline, the non-renewable exergy supplied is 852MWh/year which reduces to 646 MWh/year for the option with PV only and 628 MWh/year for the option with heat recovery only. Finally, the system with heat recovery and solar power requires the least amount which is 412 MWh of non-renewable exergy per year.

Figure 5 – Non-renewable exergy supply comparison

A similar pattern of reduction was also observed for non-renewable exergy destruction. For the baseline, it was 711 MWh/year which reduced to 526MWh/year for the option with solar power only and 851 MWh/year for the option with heat recovery only. Finally, the system with heat recovery and solar power had the lowest non-renewable exergy destruction of 361MWh/year.

When looking at weekly trends, for a short period around July and August, the PV array generates more electricity than is required for production and the factory lighting and HVAC system. Figure 6 shows the PV generated power and the total electric power demand of the factory averaged over a week. The surplus solar exergy using weekly values amounts to 82 MWh/year. However, if hourly values are considered, the PV array provides a surplus electricity of 185 MWh through the year. This is because that solar power is highly variable and using average values significantly affects the accuracy of the results.

Figure 6 - PV supply and total electricity demand of the factory

For all three options, the yearly non-renewable energy and non-renewable exergy supplies are tabulated in Table 3 along with the non-renewable exergy destruction, showing percentage reductions in both.

Table 3 - Results summary table

The percentage reduction is important when selecting the most resource efficient technology option for the HVAC system. Therefore, Figure 7 graphically presents the absolute values as well as percentage reductions from the baseline for each technology option. The energy supply is reduced by 7% from the baseline when only PV supply is employed. A much bigger reduction of 55% of baseline energy results from the heat recovery option. For this reason, in option three where both the PV supply and heat recovery are employed, there is 62.3% reduction from the baseline.

The exergy supply comparison gives very different results from that derived from energy analysis. The exergy supplied reduces by 24% and 26% respectively for the PV array and heat recovery options. This means that based on the exergy approach, both these technology options have similar benefits with respect to resource efficiency. Consequently, for the third option when both the PV and heat recovery are employed, there is a total reduction in exergy supply of 52%.

Figure 7 – Comparison of reductions in energy and exergy supply

5. Discussion:

The novel conceptual approach was illustrated through a case study. The non-renewable exergy supply and exergy destruction were the parameters selected to quantify the resource efficiency of the system. The issues encountered in deploying the approach in practice and the results are now discussed.

Compared to an energy analysis, the exergy analysis required no extra data for the HVAC system. Figure 2 however shows that data relating to systems external to the HVAC system (in this case production machinery and lighting) are required. In addition, an artificial distinction has to be made between renewable and non-renewable exergy, for the flows leaving the systems. This is demonstrated in option 3 where the heat delivered by the HVAC is separated into renewable and non-renewable portions. Table 3 provides a summary of the results for the three technology options considered. The destruction of exergy from non-renewable sources is reduced by 49.2% of the baseline using option 3, whereas the non-renewable exergy supply is reduced by 51.6%.

Compared to results based on energy analysis, option 3 represents a reduction of non-renewable energy supply by 62.3% of the baseline, indicating more significant resource savings compared to the results of exergy analysis. This can be attributed to the fact that energy analysis does not distinguish between reductions of thermal energy and electrical energy. The two energy streams have different work potential, usefulness and consequently value to society. Energy analysis therefore exaggerates resource efficiency results. This shortcoming is further exposed when comparing the technology options for reducing non-renewable energy supply. In Figure 7, it is clear that according to the energy analysis, the reduction in non-renewable energy supplied is much smaller using the PV array than that achieved using the heat recovery unit. It should be noted that the energy approach considers a kilowatt of thermal energy in water at 60^{o}C to be equivalent to a kilowatt of electrical energy. However, the useful work potential of electrical energy is greater than that of hot water with the same energy content so a comparison between the two technologies on the basis of energy savings is inadequate for resource efficiency purposes. Such a comparison might suggest to decision makers that employing a heat recovery unit only is the most effective technology option. The exergy approach however yields different results, as Figure 7 show that both the PV and heat recovery unit are equally effective in improving resource efficiency. The results from the exergy approach suggest that incorporating both the PV and heat recovery may be the best option.

Figure **5** shows the non-renewable exergy supply throughout the year. The profile is based on hourly values that are averaged over a week. It can be seen that the effect of heat recovery is more significant in winter (as one would expect). The reuse of heat from factory air is a particularly effective use of low grade thermal energy. By recovering the heat in the factory air to preheat very cold incoming air from outside, a low energy quality demand is fulfilled by a low energy quality supply. In other words, a low exergy demand is being met by a low exergy supply. This matching of energy quality between supply and demand reduces exergy destruction. Considering that the destruction of non-renewable exergy ranges from 83.5% to 92.5% of that supplied, energy quality matching can be seen to have a major impact on resource efficiency. On a similar note, the surplus electricity generated by the PV (185MWh/year) should only be used to meet demand for electrical energy. If it is used to fulfil demand for low quality energy (for example, heat) within the factory, the accompanying increased exergy destruction would significantly reduce resource efficiency. Therefore, the conceptual approach presented suggests exporting the surplus PV supply once all electrical demand within the factory is met.

Finally, option 3 is not the last word in resource efficiency. Further actions might be explored using the suggested approach, both inside or outside the factory. For example, the HVAC resource consumption could be further reduced via an exergy interaction with the production line. An example would be reusing surplus heat in the waste water from the washing processes to preheat the incoming outside air. Taking an integrated approach to factory analysis thus allows one to see further opportunities for improvement. Additionally, the use of the 2nd law in the approach provides a strong base for resource accounting. Both these factors combined demonstrate how this approach to resource efficiency can be a useful decision making tool for industrial sustainability.

6. Conclusion:

Existing literature shows that exergy analysis has clear benefits for resource accounting of industrial processes. Additionally, there has been a recent focus on considering the factory as an integrated energy system since it results in a complete analysis while identifying greater resource reuse opportunities. Considering the benefits of an integrated approach and the use of exergy to quantify resource consumption, an exergy based analysis that views the factory as an integrated system has many benefits, although it had not been demonstrated prior to this study. This paper addresses this knowledge gap by presenting a novel conceptual approach for factory resource efficiency analysis based on exergy, and models the factory as an integrated system. A case study has been used to demonstrate the application of the approach in practice. Three examples of factory energy system modifications have illustrated how a real factory might operate with half of the natural resource consumption compared to the baseline. Both the non-renewable exergy supply and exergy destruction can be reduced by approximately 50% whereas the non-renewable energy supply can be reduced by 63.2%. Alternatively using a conventional energy analysis would show that a PV array is relatively ineffective in reducing resource consumption compared to an HVAC heat recovery unit. The energy demand would be reduced by only 7% from the baseline using the PV array compared to a 55% reduction using the heat recovery unit. This would lead to a likely decision to employ the heat recovery unit only. The results from the exergy approach reveal that both the PV array and the heat recovery unit are equally effective at reducing natural resource consumption. The scientific value of this is that the use of exergy analysis can complement energy analysis and lead to better system design decisions if the aim of the exercise is to reduce the consumption of natural resources instead of simply to reduce energy use alone. The differences between the results from the energy and exergy analyses are because conventional energy balances are based on the 1st law of thermodynamics and therefore do not take into account the *quality* of resource flows. Since exergy analysis does consider the quality of resource flows, it yields results, which allow system designers to reduce natural resource consumption leading to more sustainable (i.e. resource efficient) industrial systems. These findings are applicable to all energy using industrial systems, particularly those in which energy is carried in the form of heated fluids as well as electricity.

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References:

Ao, Y., Gunnewiek, L., Rosen, M.A., 2008. Critical review of exergy-based indicators for the environmental impact of emissions. International Journal of Green Energy 5, 87-104.

Bakshi, B.R., Gutowski, T.G.P., Sekulić, D.P., 2011. Thermodynamics and the Destruction of Resources. Cambridge University Press New York.

Ball, P., Despeisse, M., Evans, S., Greenough, R., Hope, S., Kerrigan, R., Oates, M., Quincey, R., 2012. Modelling buildings, facilities and manufacturing operations to reduce energy consumption, Production and Operations Management Society (POMS) international conference, Chicago, USA.

Boroum and Jazi, G., Rismanchi, B., Saidur, R., 2013. A review on exergy analysis of industrial sector. Renewable and Sustainable Energy Reviews 27, 198-203.

Chen, D., Thiede, S., Schudeleit, T., Herrmann, C., 2014. A holistic and rapid sustainability assessment tool for manufacturing SMEs. CIRP Annals-Manufacturing Technology.

Connelly, L., Koshland, C.P., 2001. Exergy and industrial ecology—Part 1: An exergy-based definition of consumption and a thermodynamic interpretation of ecosystem evolution. Exergy, an international journal 1, 146-165.

DECC, 2012. Solar PV cost update. (Department of Energy and Climate Change).

Delgado, A.V., 2008. Exergy evolution of the mineral capital on earth. Mechanical Engineering Ph. D. thesis, University of Zaragoza, Spain.

Despeisse, M., Ball, P.D., Evans, S., Levers, A., 2012a. Industrial ecology at factory level–a conceptual model. Journal of Cleaner Production 31, 30-39.

Despeisse, M., Oates, M.R., Ball, P.D., 2012b. Sustainable manufacturing tactics and cross-functional factory modelling. Journal of Cleaner Production.

Dewulf, J., Van Langenhove, H., 2005. Integrating industrial ecology principles into a set of environmental sustainability indicators for technology assessment. Resources, Conservation and Recycling 43, 419-432.

Duflou, J.R., Sutherland, J.W., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, S., Hauschild, M., Kellens, K., 2012. Towards energy and resource efficient manufacturing: A processes and systems approach. CIRP Annals-Manufacturing Technology 61, 587-609.

EnergyPlus, 2012. Energy Simulation Software Version 8.1 [Online]. US department of energy.

Evans, S., Gregory, M., Ryan, C., Bergendahl, M.N., Tan, A., 2009. Towards a sustainable industrial system: With recommendations for education, research, industry and policy. University of Cambridge, Institute for Manufacturing.

Gaudreau, K., Fraser, R.A., Murphy, S., 2009. The tenuous use of exergy as a measure of resource value or waste impact. Sustainability 1, 1444-1463.

Gong, M., Wall, G., 2001. On exergy and sustainable development—Part 2: Indicators and methods. Exergy, an international journal 1, 217-233.

Gößling-Reisemann, S., 2008. What is resource consumption and how can it be measured? Journal of Industrial Ecology 12, 10-25.

Granovskii, M., Dincer, I., Rosen, M.A., 2008. Exergy and industrial ecology: an application to an integrated energy system. International Journal of Exergy 5, 52-63.

Gutowski, T.G., 2011. Manufacturing and the Science of Sustainability, Glocalized Solutions for Sustainability in Manufacturing. Springer, pp. 32-39.

Henningsson, S., Hyde, K., Smith, A., Campbell, M., 2004. The value of resource efficiency in the food industry: a waste minimisation project in East Anglia, UK. Journal of Cleaner Production 12, 505-512.

Hepbasli, A., 2012. Low exergy (LowEx) heating and cooling systems for sustainable buildings and societies. Renewable and Sustainable Energy Reviews 16, 73-104.

Herrmann, C., Thiede, S., 2009. Process chain simulation to foster energy efficiency in manufacturing. CIRP Journal of Manufacturing Science and Technology 1, 221-229.

Jacobsen, N.B., 2006. Industrial symbiosis in Kalundborg, Denmark: a quantitative assessment of economic and environmental aspects. Journal of Industrial Ecology 10, 239-255.

jEPlus, 2013. jEPlus – An open source EnergyPlus shell for parametric studies

Khattak, S., Greenough, R., Brown, N., 2014. Analysing the use of waste factory heat through exergy analysis. European Council for an Energy Efficient Economy.

Oates, M.R., Wright, A., Greenough, R., Shao, L., 2011. A new modelling approach which combines energy flows in manufacturing with those in a factory building, Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, pp. 223-230.

OpenStudio, 2013. Legacy OpenStudio Plug-in for SketchUp.

Rosen, M.A., 2009. Enhancing ecological and environmental understanding with exergy: concepts and methods, Proceedings of the 4th IASME/WSEAS Int. Conference on Water Resources, Hydraulics & Hydrology (WHH'09) pp, pp. 94-103.

Schmidt, D., 2004. Design of low exergy buildings-method and a pre-design tool. The International Journal of Low Energy and Sustainable Buildings 3, 1-47.

Sciubba, E., Wall, G., 2010. A brief commented history of exergy from the beginnings to 2004. International Journal of Thermodynamics 10, 1-26.

Szargut, J., Ziębik, A., Stanek, W., 2002. Depletion of the non-renewable natural exergy resources as a measure of the ecological cost. Energy Conversion and Management 43, 1149-1163.

Tsatsaronis, G., 2007. Definitions and nomenclature in exergy analysis and exergoeconomics. Energy 32, 249-253.

Valero, A., Usón, S., Costa, J., 2012. Exergy analysis of the industrial symbiosis model in Kalundborg. Proceedings of ECOS.

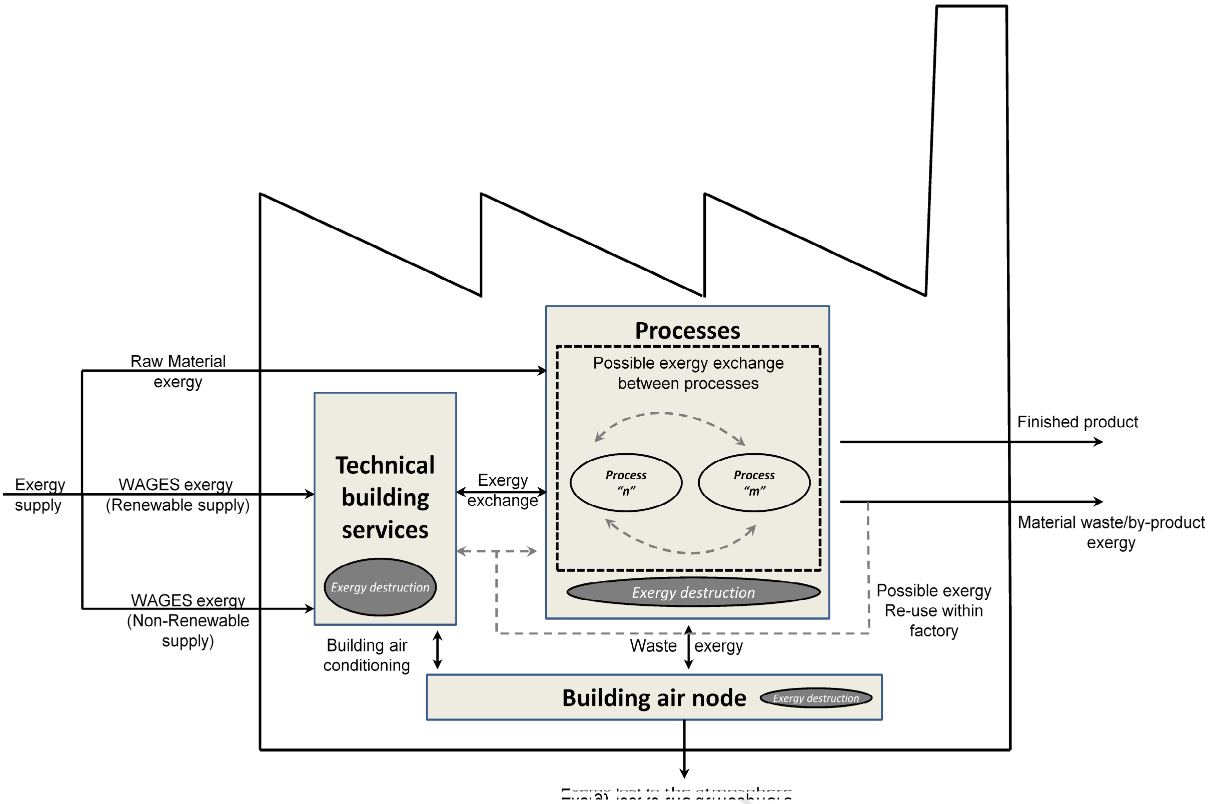
Wall, G., Gong, M., 2001. On exergy and sustainable development—Part 1: Conditions and concepts. Exergy, an International Journal 1, 128-145.

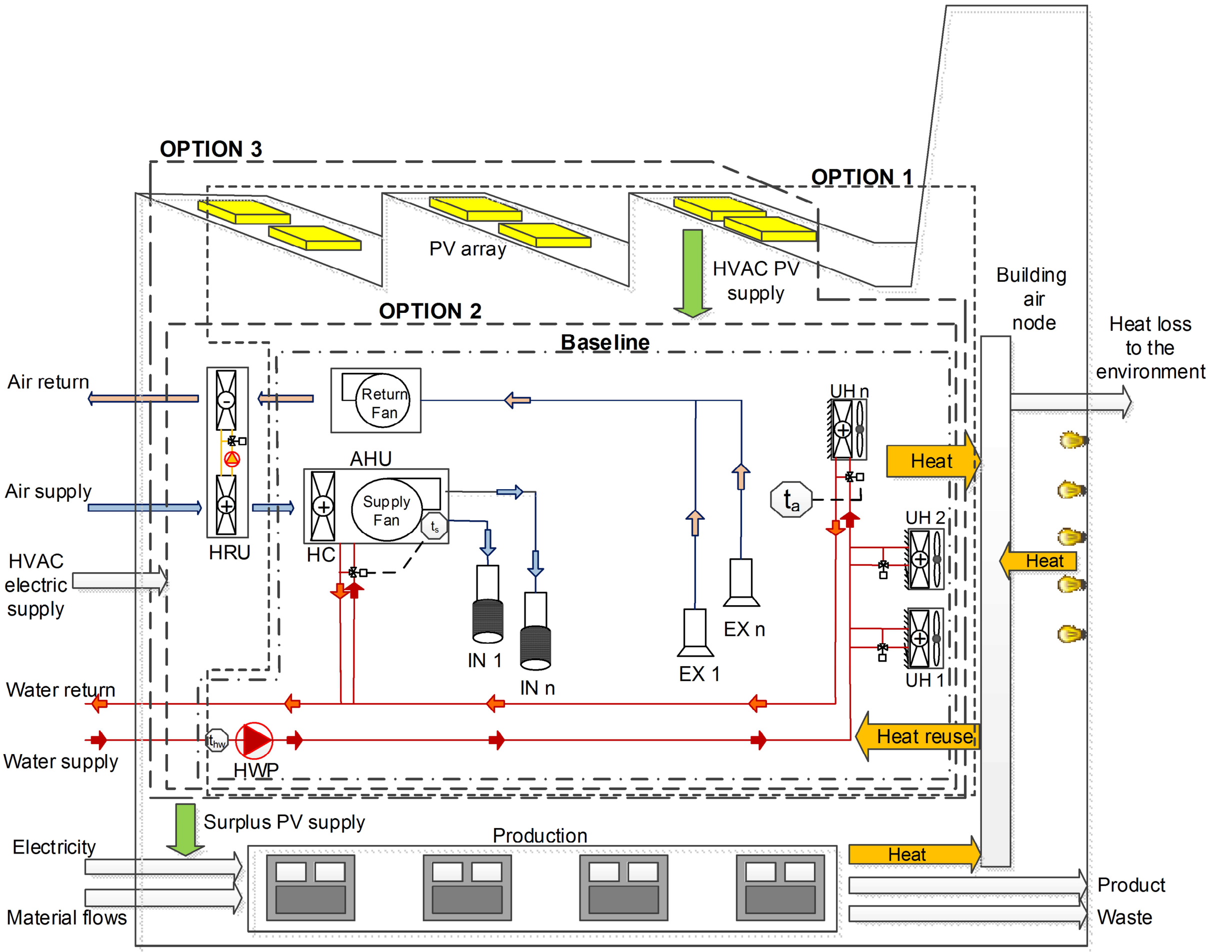
Zvolinschi, A., Kjelstrup, S., Bolland, O., Kooi, H.J., 2007. Exergy sustainability indicators as a tool in industrial ecology. Journal of Industrial Ecology 11, 85-98.

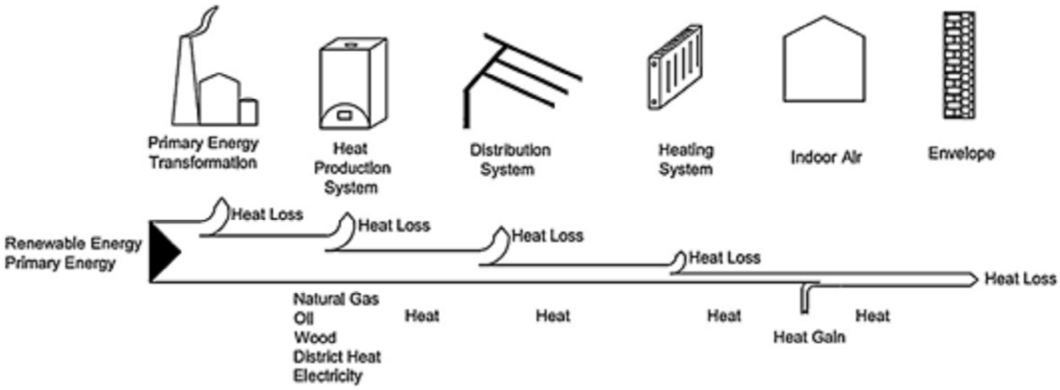
	Slab-on-ground Floor	**Flat roof (no ceiling)**	**External wall**	**Glazing**
U-value [W/m^2K]	2.2	0.3	0.4	3.1
Outside layer	Floor insulation	19mm asphalt	White-painted steel	6mm clear glass
Layer 2	150mm concrete	13mm fibreboard	100mm concrete block	6mm air cavity
Layer 3	N/A	100mm insulation	100mm insulation	6mm clear glass
Layer 4	N/A	100mm concrete (light)	White-painted steel	

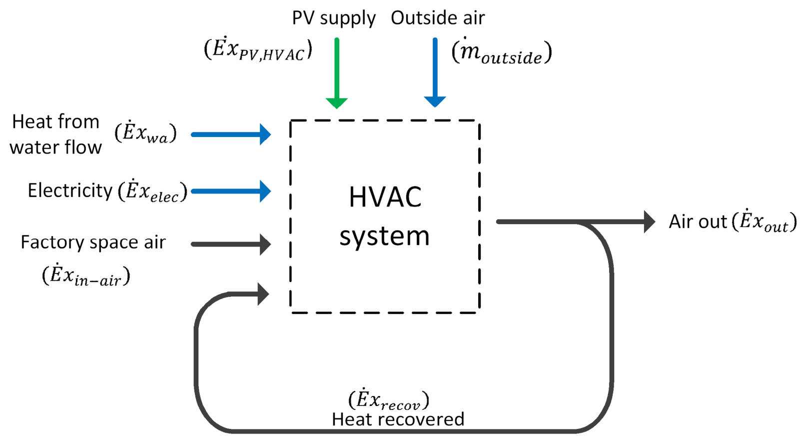
Air						
Time	**Flow rate**	**Supply air Temp.**	**Exhaust air Temp.**	**Supply air Exergy rate**	**Exhaust air exergy rate**	**Air exergy gain rate**
(Hours)	kg/s	^oC	^oC	kW	kW	kW
1	0.00	14.41	14.41	0.00	0.00	0
2	0.00	14.33	14.33	0.00	0.00	0
3	19.48	17.35	22.72	4.95	10.23	5.28
4	40.31	20.00	26.51	16.48	32.98	16.5
5	40.31	20.00	26.33	16.35	32.29	15.94
6	40.31	20.00	26.31	16.70	32.71	16.01
7	40.31	20.00	26.23	16.44	32.11	15.67
8	40.31	20.00	26.11	16.19	31.41	15.22
Water						
Time	**Flow rate**	**Supply water Temp.**	**Return water Temp.**	**Supply water exergy rate**	**Return water exergy rate**	**Water exergy loss rate**
(Hours)	kg/s	^oC	^oC	kW	kW	kW
1	0.00	52.16	52.16	0.00	0.00	0
2	0.00	52.16	52.16	0.00	0.00	0
3	5.87	50.35	43.85	81.15	60.24	20.91
4	3.51	48.75	31.78	46.62	18.28	28.34
5	3.36	48.84	31.60	44.61	17.18	27.43
6	3.33	48.89	31.58	44.67	17.21	27.46
7	3.26	48.91	31.49	43.55	16.61	26.94
8	3.22	48.63	31.34	42.23	16.07	26.16

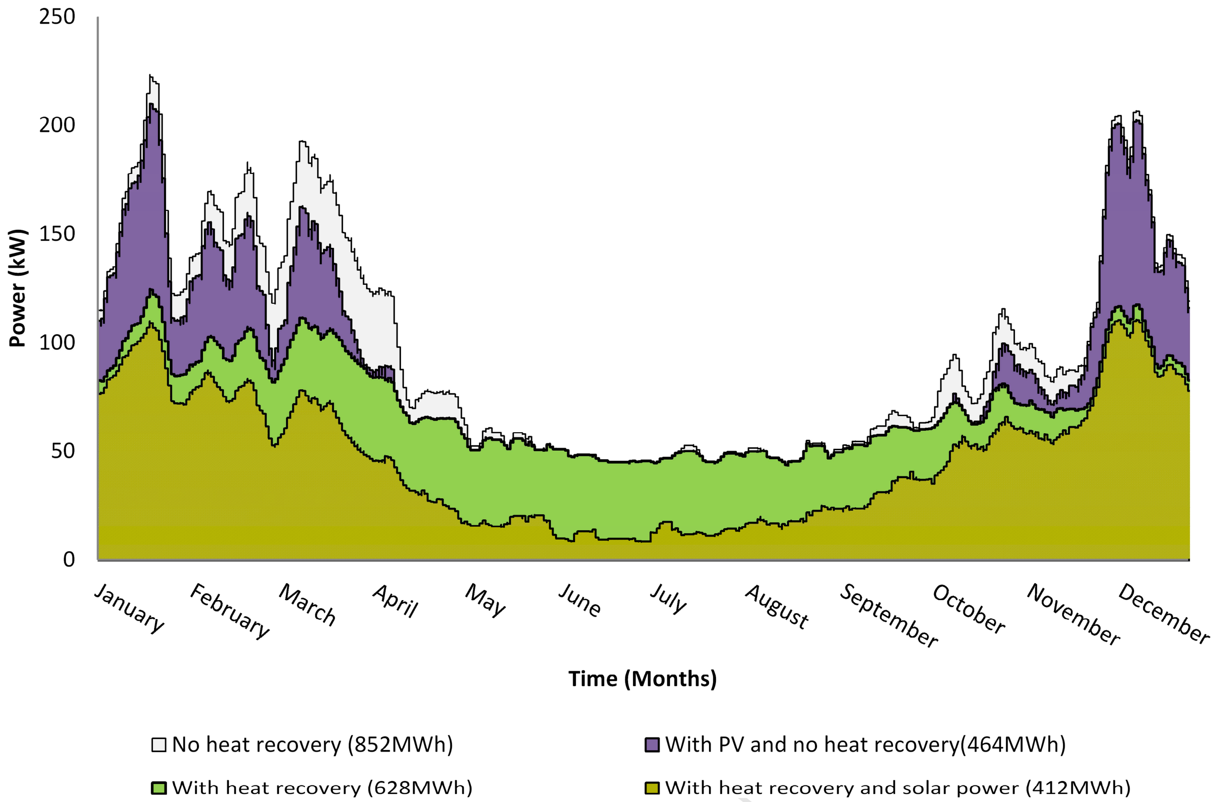
	Non-renewable energy supply (MWh/year)	Non-renewable exergy supply (MWh/year)	Non-renewable exergy destruction (MWh/year)
Baseline system	2962	852	711
Option 1 – PV only	2756	646	526
Option 2 – Heat recovery only	1333	628	581
Option 3 – Heat recovery & PV	1118	412	361
Reduction from Baseline in Option 1	206 (6.9%)	206 (24.2%)	185 (26%)
Reduction from Baseline in Option 2	1634 (55%)	224 (26.2%)	130 (18.2%)
Reduction from Baseline in Option 3	1849 (62.3%)	440 (51.6%)	350 (49.2%)

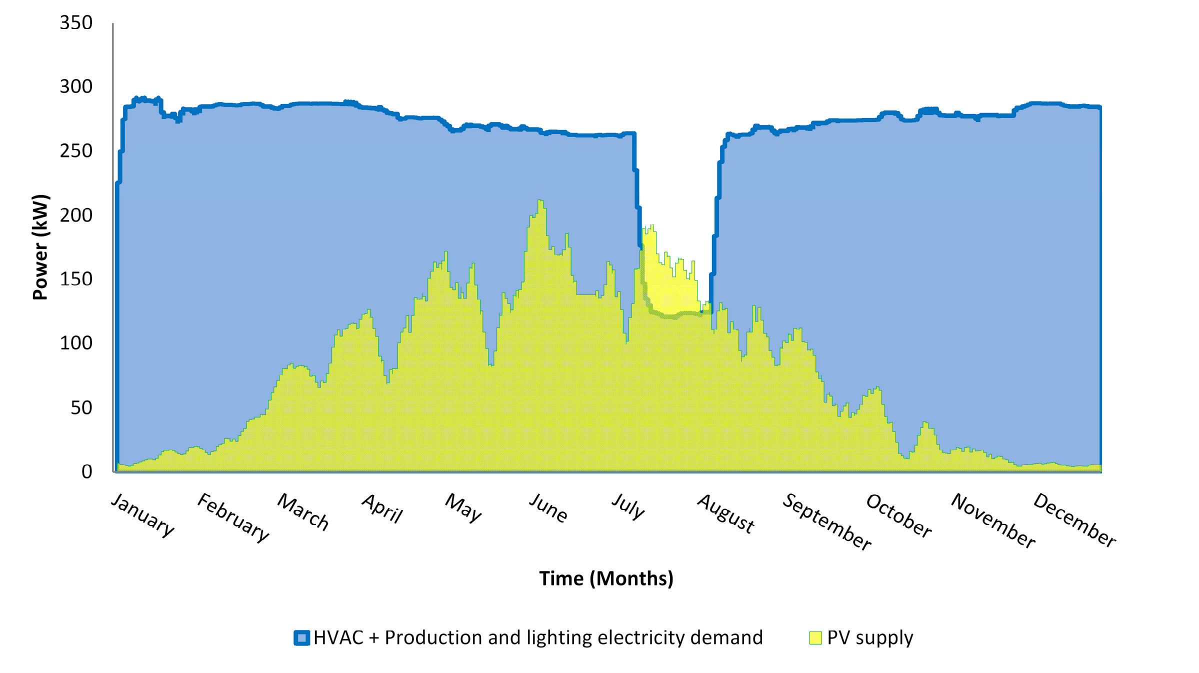

Processes
Possible exergy exchange between processes
Process "n"
Process "m"
Exergy destruction
Raw Material exergy
Exergy supply
WAGES exergy (Renewable supply)
WAGES exergy (Non-Renewable supply)
Technical building services
Exergy destruction
Exergy exchange
Finished product
Material waste/by-product exergy
Possible exergy Re-use within factory
Building air conditioning
Waste exergy
Building air node
Exergy destruction

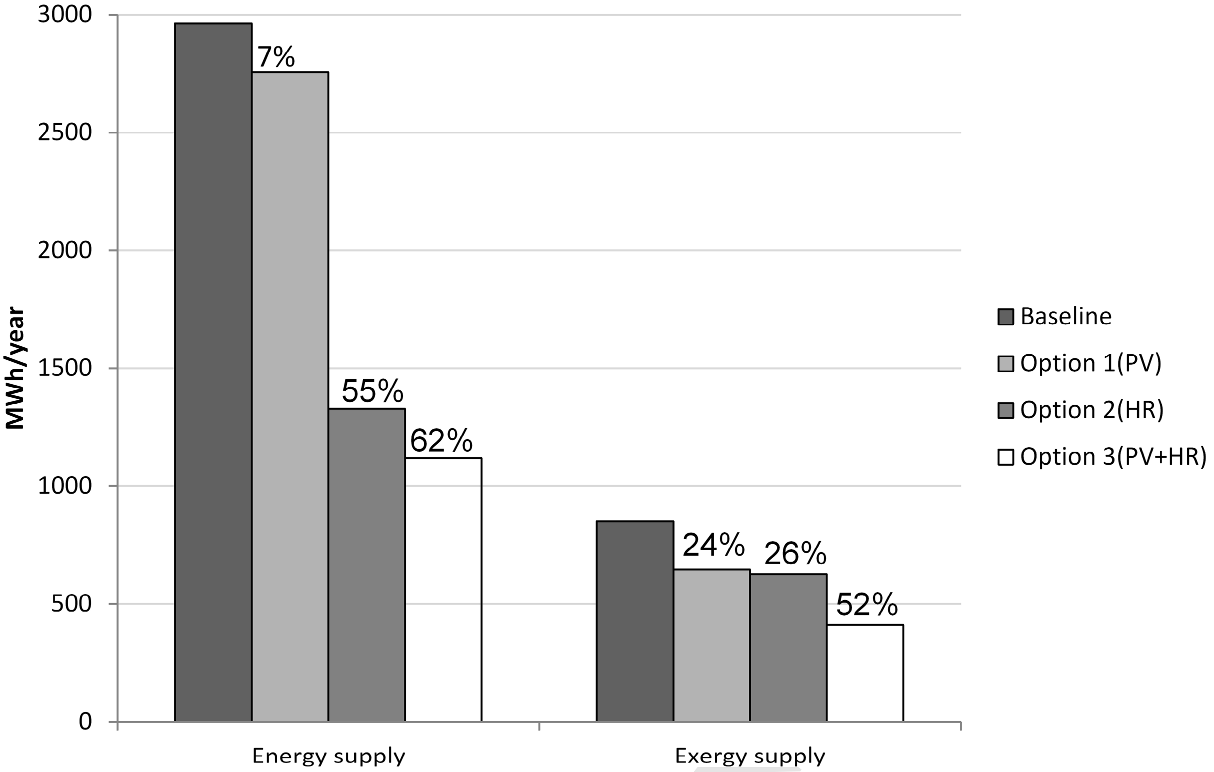

OPTION 3
OPTION 1
PV array
HVAC PV
supply
OPTION 2
Baseline
Building
air
node
Heat loss
to the
environment
Air return
Return
Fan
UH n
Air supply
AHU
Supply
Fan
Heat
HVAC
electric
supply
HRU
HC
UH 2
Heat
IN 1
IN n
EX n
EX 1
UH 1
Water return
Water supply
HWP
Heat reuse
Surplus PV supply
Production
Electricity
Heat
Product
Material flows
Waste


Primary Energy Transformation
Heat Production System
Distribution System
Heating System
Indoor Air
Envelope
Renewable Energy
Primary Energy
Heat Loss
Heat Loss
Heat Loss
Heat Loss
Heat Loss
Natural Gas
Oil
Wood
District Heat
Electricity
Heat
Heat
Heat
Heat Gain
Heat


PV supply
$(\dot{E}x_{PV,HVAC})$
Outside air
$(\dot{m}_{outside})$
Heat from water flow
$(\dot{E}x_{wa})$
Electricity $(\dot{E}x_{elec})$
Factory space air
$(\dot{E}x_{in-air})$
HVAC system
Air out $(\dot{E}x_{out})$
$(\dot{E}x_{recov})$
Heat recovered


250
200
150
100
50
0
Power (kW)
January
February
March
April
May
June
July
August
September
October
November
December
Time (Months)
No heat recovery (852MWh)
With PV and no heat recovery(464MWh)
With heat recovery (628MWh)
With heat recovery and solar power (412MWh)


350
300
250
200
150
100
50
0
Power (kW)
January
February
March
April
May
June
July
August
September
October
November
December
Time (Months)
HVAC + Production and lighting electricity demand
PV supply


3000
2500
2000
1500
1000
500
0
MWh/year
7%
55%
62%
24%
26%
52%
Energy supply
Exergy supply
Baseline
Option 1(PV)
Option 2(HR)
Option 3(PV+HR)

Highlights:

- A novel exergy-based approach to resource accounting in factories is presented
- The approach is explained using a case study of a cylinder head machining line
- An energy system re-design is presented with half the baseline resource consumption
- The tendency of energy analysis to overestimate resource efficiency is explained
- The paper explains how exergy analysis can drive resource efficiency improvements

Nomenclature	
c_{air}	Specific heat capacity of air
c_{water}	Specific heat capacity of water
$\dot{E}_{electrical}$	Electrical energy flow rate
$\dot{E}x_{in}$	Total exergy flow rate into the system
$\dot{E}x_{out}$	Total exergy flow rate out of the system
$\dot{E}x_{supply}$	Non-renewable exergy supply rate
$\Delta\dot{E}x_{wa}$	Water flow exergy supply rate
$\dot{E}x_{elec}$	Electricity supply rate
$\dot{E}x_{dest}$	Non-renewable exergy destruction rate
$\dot{E}x_{in-air}$	Factory space supply air flow rate
$\dot{E}x_{out-air}$	Hot air supply rate delivered by the HVAC system
$\dot{E}x_{recov}$	Exergy recovery rate
$\dot{E}x_{PV,HVAC}$	Photovoltaic power supply to HVAC system
$\dot{E}x_{total\ elec}$	Total electricity demand rate of the factory
$\dot{E}x_{gains}$	Rate of exergy gains to the HVAC system from factory components
$\dot{m}_{air}$	Mass flow rate of air
$\dot{m}_{outside}$	Mass flow rate of supply air
$\dot{m}_{wa}$	Mass flow rate of water
T	Temperature of air or water stream
T_0	Weather temperature
Acronyms	
AHU	Air handling unit
BMS	Building management system
DOAS	Dedicated outdoor air system
HRU	Heat recovery unit
HVAC	Heating ventilating and air conditioning system
IE	Industrial ecology
TBS	Technical building services
UH	Unit heaters
WAGES	Water, air, gas, electricity and steam.