Optimal linking of heat flows based on the discrete Fourier transform

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Abstract:

Two strategies must be implemented to achieve existing climate change targets: renewable energies must replace fossil fuels, and primary energy consumption must be reduced to ease demand on limited renewable energy production. These two strategies must be applied to all economic sectors, including industry.

Classic industrial optimization methods like Pinch analysis are mainly designed for continuous demand and supply profiles. However, since a lot of industrial processes are not continuous, Pinch analysis isn't always applicable. Therefore, this work presents a new methodology based on the discrete Fourier transform. The methodology determines the flexibility demand for different combinations of energy sources and energy demands. Flexibility demand occurs at times where energy demand is greater than the amount of available produced energy. A flexibility option (e.g. energy storage), which is smaller than the required flexibility demand can cause power shortages – that is, instances where demand cannot be fully covered. Depending on the application, small shortages might be acceptable, for example if a backup system is available. In fact, allowing small shortages can help to decrease storage sizes and increase full utilization of the flexibility option. This can therefore improve economic efficiency.

The case study shown in this work uses a methodology based on the discrete Fourier transform in order to find best way of covering a given time-resolved heat demand with different available waste heat sources. This methodology is also used to determine a full and reduced storage size, which respectively covers all and most of the difference between waste heat potential and demand. Compared to the full storage size, the size could be reduced by 46 %, which would cause shortages of just 9 % of the total energy demand. Moreover, this reduction of storage size increases the number of the average utilization cycles from 4.3 to 6.9 cycles per week.

Keywords: discrete Fourier transform, storage sizing, flexibility demand, renewable energy sources, optimization, industry

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1 Introduction and Motivation

In order to achieve the greenhouse gas savings required to meet the Paris Agreement [1], two main strategies must be implemented: fossil fuels must be replaced by renewable energy sources, and total primary energy consumption must be significantly reduced. It is therefore important to ensure minimal conversion losses, highly efficient final energy use, and cross-sectoral and cascaded energy utilization because renewable energy sources are limited. [2–4]

In the industrial sector, one of the major future challenges is the transition from current fossil fuel based energy supply towards renewable energy sources. When making this transition, it is necessary to use technologies with a high exergy efficiency so that total primary energy consumption is also reduced [5]. Current optimization and energy efficiency methods like Pinch analysis focus mainly on continuous processes supplied by controllable non-volatile energy-carriers. Since a lot of industrial processes are not continuous, new tools and methods are required to plan and optimize future industrial energy systems. Therefore, this paper presents a methodology based on the discrete Fourier transform (DFT). This methodology optimizes industrial energy systems with non-continuous processes and volatile renewable sources.

2 Method

2.1 Power profiles

In general, a power profile can be considered as a time series of power demand or power generation. Every power profile is assigned to one single energy carrier (e.g. electricity, hot water, or steam) and is, depending on the energy carrier, defined by different parameters (e.g. mass flow, temperature, pressure, and steam quality).

In the following, this paper focus on heat flows. The power of a heat flow primarily depends on the temperature $T_{A,t}$, or enthalpy $h_{A,t}$ and the mass flow $\dot{m}_{A,t}$. Both parameters can vary over time ((eq. (1)).

$$P_{A,t} = \dot{m}_{A,t} \cdot c_{p,A} \cdot (T_{A,t} - T_0) = \dot{m}_{A,t} \cdot (h_{A,t} - h_0) \quad (1)$$

$P_{A,t}$ … Heat power profile *A* at the time step *t* in W

$\dot{m}_{A,t}$ … Mass flow of profile *A* at the time step *t* in kg/s

$c_{p,A}$ … Specific heat capacity of profile *A* in J/(kg*K)

$T_{A,t}$ … Temperature of profile *A* at the time step *t* in °C

T_0 … Ambient temperature in °C

$h_{A,t}$ … Enthalpy of profile *A* at the time step *t* in J/kg

h_0 … Enthalpy of profile *A* at ambient conditions in J/kg

In order to cover the need of a time-varying demand profile, another non-dispatchable generation profile (e.g. from renewables or from a waste heat source) can be used. Therefore, the required transformer unit (e.g. heat exchanger) must be available and the temperature of the source must be higher than the temperature of the energy demanding process plus conversion losses. However, active transformer units like heat pumps enable the heat transfer from a lower to a higher temperature level. Such active conversion units have also an additional operating power demand. In this work, only energy flows from the higher to a lower temperature level are considered. Therefore, no active transformer units are included.

In the next section, the basics of the discrete Fourier transform are discussed. Afterwards, in section 2.3, the application of the discrete Fourier transform to power profiles is described.

2.2 Discrete Fourier transform [6, 7]

The discrete Fourier transform enables the transformation of any time-discrete signal from the time domain into the frequency domain. An entire representation of the signal in the frequency domain requires both the amplitudes and the phases of every signal component (Figure 1).

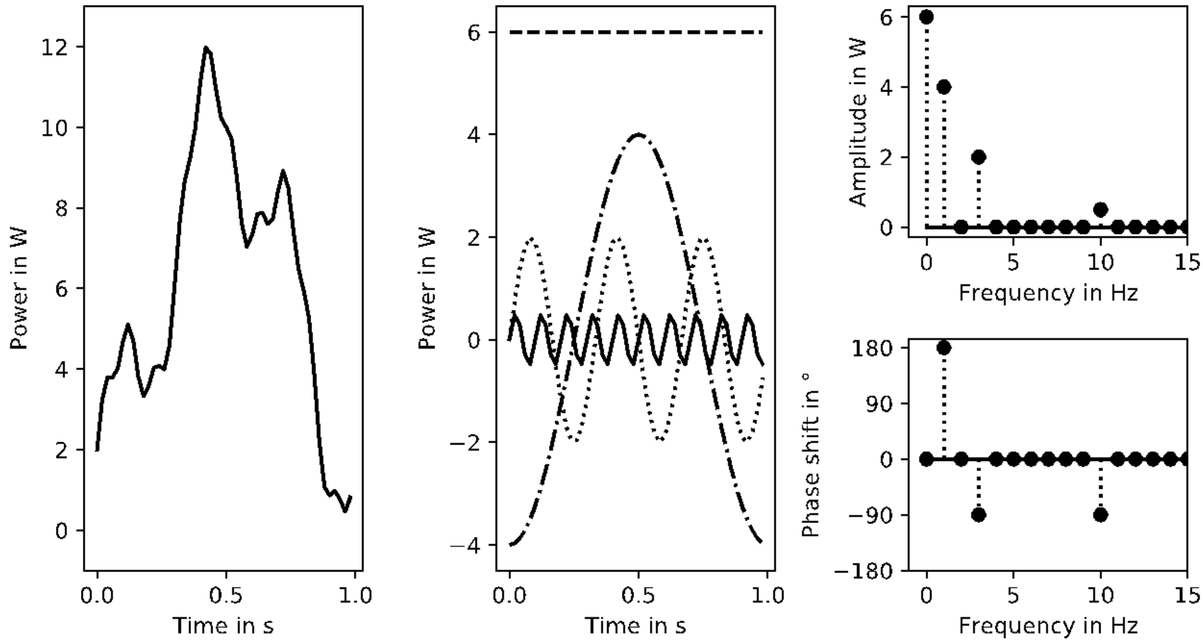

Figure 1: Principle of the DFT. Total signal (left), which can be described by a superposition of different oscillations (center) as well as the representation of the same signal in the frequency domain (right).

The importance of a particular frequency can be determined by the size of the corresponding amplitude. This means that frequencies with higher amplitudes have higher impact on the total signal than frequencies with lower amplitudes (Figure 1). Besides the amplitudes, the phase shifts must also be taken into account. This is necessary because the phase shift determines whether and when constructive or destructive interference of signal components occurs. In the following section, the DFT will be used to determine a flexibility demand.

2.3 Comparison of two transformed power profiles and evaluation of the actual flexibility demand

If generation does not cover the demand in every time step, flexibility options are necessary. To determine the flexibility demand, a combination of the demand profile and the generation profile must be evaluated in frequency domain. Therefore, we transfer the demand profile, the generation profile, and the residual load profile into the frequency domain by using the DFT. The residual load of every time step is equal to the demand minus the non-dispatchable generation (eq. (2)).

$$P_{Res,t} = P_{Load,t} - P_{ND\_Sup,t} \tag{2}$$

$P_{Res,t}$ … Total residual load at the time step *t* in W

$P_{Load,t}$ … Total power demand at the time step *t* in W

$P_{ND\_Sup,t}$ … Total non-dispatchable power supply, such as renewable generation, waste heat potential or others at the time step t in W

Important: in the following, this work is based on a comparison of one generation profile (waste heat profile) with one demand profile.

After transforming the whole residual load from time domain to the frequency domain, the flexibility demand is determined from the inverse transformation (the transformation back to the time domain) of only selected residual load frequencies. Therefore, it is essential to select the appropriate frequencies. While the inverse transformation of all frequency components is used to determine the total flexibility demand, a selected set of frequencies can be used to determine a reduced flexibility demand. However, in contrast to the total flexibility demand, a reduced flexibility demand always leads to shortages. Shortages are situations, where the demand cannot be covered by the generation nor by the flexibility option. Depending on the application, different strategies to deal with these shortages can be applied. For example, a backup system (e.g. a process steam heat exchanger) may be implemented to ensure the coverage of the demand at any time. Similarly, if downtime is tolerated, shortages are no longer an issue. In this work, shortages are acceptable and the inverse transformation of the three frequencies with the highest amplitudes of the residual load are used to determine the reduced flexibility demand.

The inverse transformation of a set of selected frequency components generates a new, time-resolved flexibility demand profile $P_{FD,t}$. The flexibility demand profile is equal to the total residual load, if all frequencies components are considered. This profile will be progressively cumulated. The difference between the minimum and the maximum value of this cumulated flexibility demand vector $E_{FD,k}$ is equal to the total flexibility demand per frequency set (eq. (3) and (4)).

$$E_{FD,k} = \sum_{t=1}^{k} P_{FD,t} \cdot \Delta t \tag{3}$$

$P_{FD,t}$ … Flexibility demand profile at the time step *t* in W

$E_{FD,k}$ … Mathematical from the *first* to the k^{th} time step cumulated flexibility demand profile in kWh

Δt … Time between two time steps in s

$$E_{cal\_FD} = \text{abs}[\max(E_{FD,k}) - \min(E_{FD,k})] \text{ with } k \in [0, \text{t}_{\max}] \quad (4)$$

E_{cal_FD} … Calculated flexibility demand in kWh

This flexibility demand can be covered in various ways, for example by energy storages or demand response. In this work, the identified flexibility demand will be covered by a thermal energy storage. The maximum energy content of the thermal energy storage is equal to the previously determined flexibility demand.

In the next section, a validation methodology is discussed. This methodology allows a comparison of different thermal energy storage sizes, based on key indicators

2.4 Validation of the thermal energy storage size

It is possible to consider various combinations of frequency components. Therefore, different flexibility demands, and consequently storage sizes, will result when considering different selections of frequency components. In order to rate and compare different storages sizes, key indicators can be used. The validation methodology in this work offers two key indicators. The first key indicator represents the total energetic shortage, while the second key indicator depends on storage utilization. Two different approaches are used to determine these two key indicators.

The first approach is a storage simulation tool. This tool uses an initially specified energy storage to best possibly compensate the residual load profile. To do this, each time step of the residual load profile is analyzed sequentially. For each time step, a negative or positive residual load respectively charges or discharges the energy storage. If the storage is already full and negative residual load occurs (i.e. power excess), the current residual load gets discarded. This also results if the storage is empty and a positive residual load occurs (i.e. power shortage). All power excesses and shortages are recorded. The simulation assumes, that the profiles are repeated each week without any changes. Therefore, the tool iterates until the transient oscillation of the state of charge becomes stable. In the context of this simulation, a stable state is reached, when the storage has the same state of charge at the beginning of the week and at the end of the week. After the simulation, the records of the stable state are analysed. The total energetic shortage of one week is the value of the first key indicator.

The second approach is based on analyzing the number of utilization cycles. The storage is divided into 5 kWh energy bands, where the first band represents the first five kWh, the second band represents the 6^{th} to the 10^{th} kWh, and so on. For each band, the number of times the storage is charged and discharged is recorded. This number of cycles defines the storage utilization per band. A small number of cycles in a band indicates an oversized storage. The value of the second key indicator is equal to the average number of utilization cycles over all bands.

3 Case study

3.1 Model description

In this case study, we apply the above methodology to the energy supply of a production process in the food industry. In this production process example, there are three ovens, one cooker, and two dryers. While the ovens are directly supplied by natural gas, the dryers and the cooker need process steam. In addition, the space heating of the production facility is also covered by process steam which is generated by a gas-fired combined heat and power (CHP) unit as well as by a gas boiler. The gas boiler is only used when the process steam production via the CHP unit cannot cover the whole processes' steam demand (Figure 2).

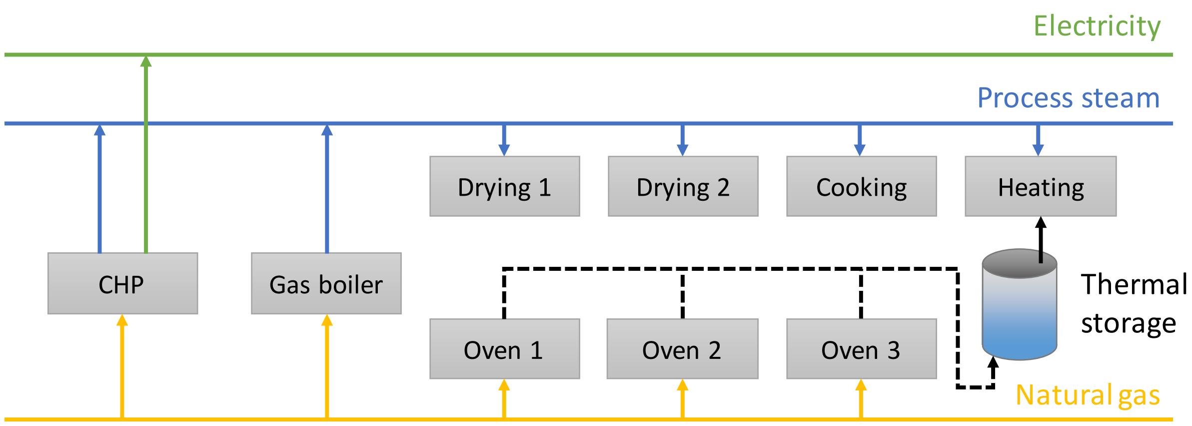

Figure 2: Model overview

In order to increase the primary energy efficiency of the whole production, the waste heat from one of the three ovens should be used. Utilization of waste heat enables a reduction in the total process steam consumption and thus saves gas. Due to the low temperature levels, the waste heat of the ovens can only be used to cover the space heating demand. To keep investment costs low, only one of the three ovens is equipped with a waste heat recovery system. Since the heat demand profile and the waste heat profiles of the three ovens are fluctuating, a thermal energy storage is necessary. The waste heat potential of each oven and the heat demand are specified at one constant temperature level (Table 1) but the mass flow, and thus power, varies over time (Figure 3 and Figure 4).

Three different configurations are compared in this case study (Table 2). These configurations differ with regards to storage availability and the possibility of power shortages. In configuration B and C, storages are available. Shortages are only acceptable in configurations A and C. In the next section, a recommended waste heat source, storage size, and the occurring shortages are determined for each configuration.

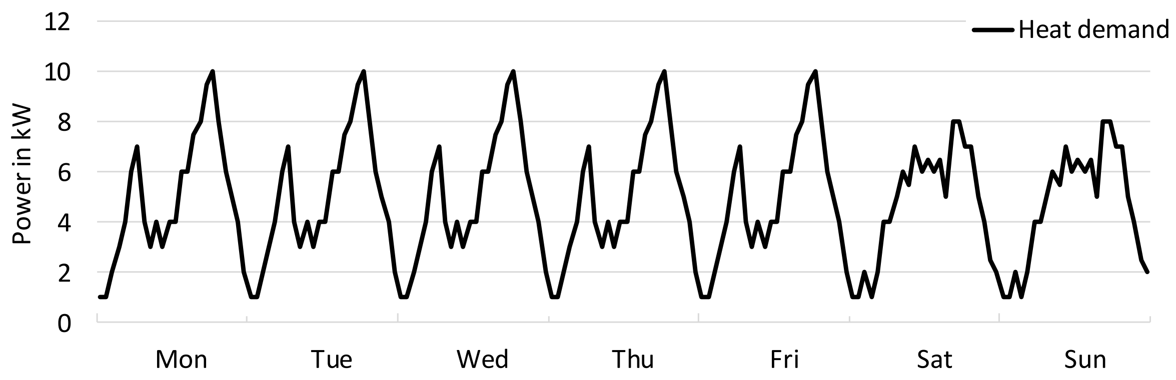

Figure 3: Visualization of the weekly power pattern of heat demand profile.

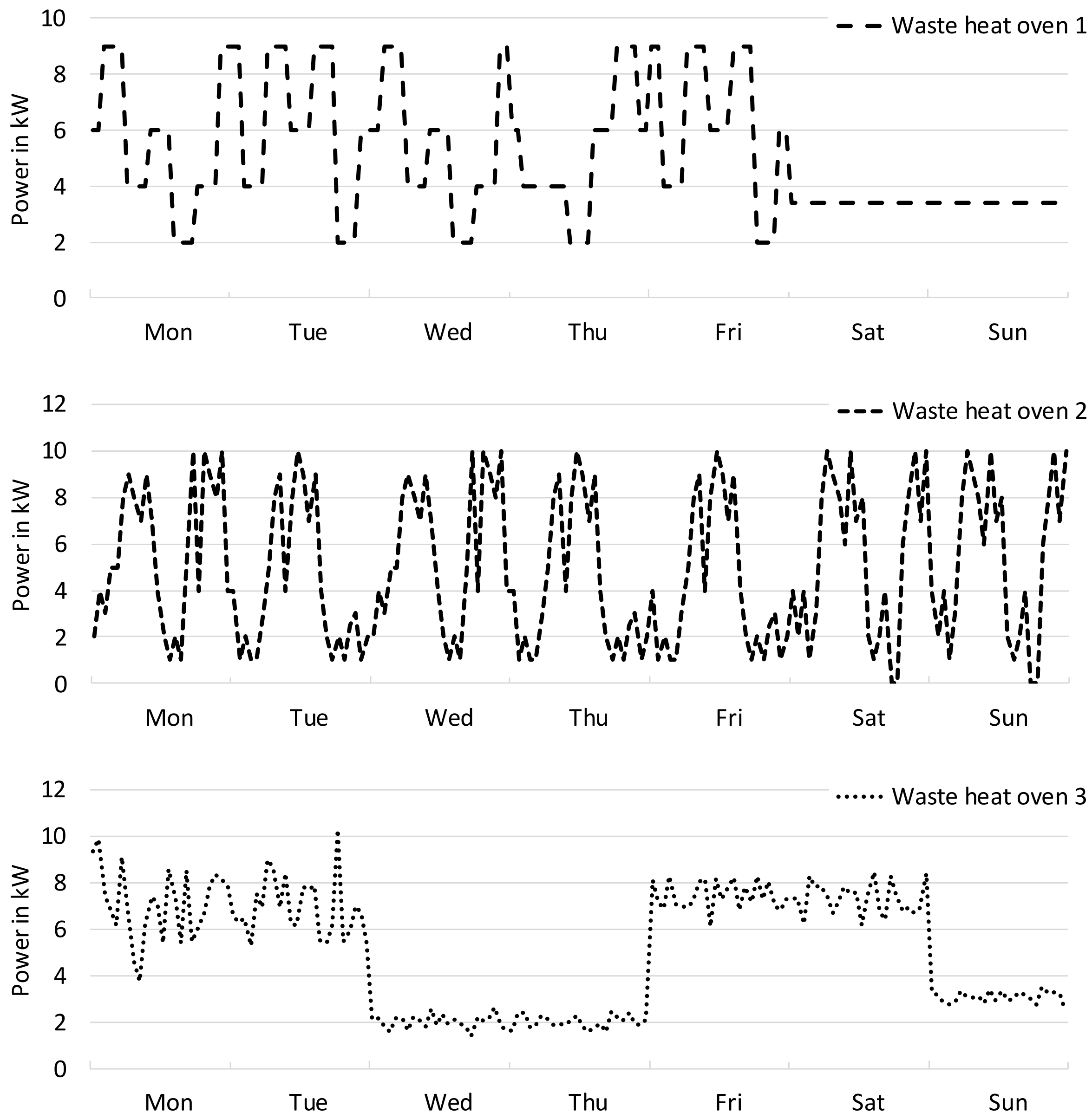

Figure 4: Visualization of the weekly power pattern of the different waste heat profiles.

Table 1: Specification of selected operation units

Name	*Temperature in °C*	*Energy supply potential per week in kWh*	*Energy demand per week in kWh*
Waste heat oven 1	120	847	-
Waste heat oven 2	95	833	-
Waste heat oven 3	135	859	-
Heating demand	80	-	814

Table 2: Overview of the three different configurations of the case study

	Storage available	*Power shortages tolerable*
Configuration A	No	Yes
Configuration B	Yes	No
Configuration C	Yes	Yes

3.2 Results

3.2.1 Discrete Fourier transform of the profiles

The characteristic frequency components of the different profiles can be identified from the amplitude spectrum. The heat demand has two dominant amplitudes with a frequency of 7 and 14 cycles per week. The same frequencies are also dominant in the profile of waste heat from oven 2. Waste heat from oven 3 has three dominant frequencies (1, 2 and 5 cycles per week) while waste heat from oven 1 has no dominant frequency (Figure 5).

The dominant frequencies of the residual loads in the amplitude spectrums are the combination of the dominant frequencies of the corresponding waste heat profile and of the heat demand (Figure 6). In the following section, the best waste heat source, the storage size (if available) and possible occurring shortages are determined for each of the three configurations. In all cases, the storage size is equal to the determined total or reduced flexibility demand.

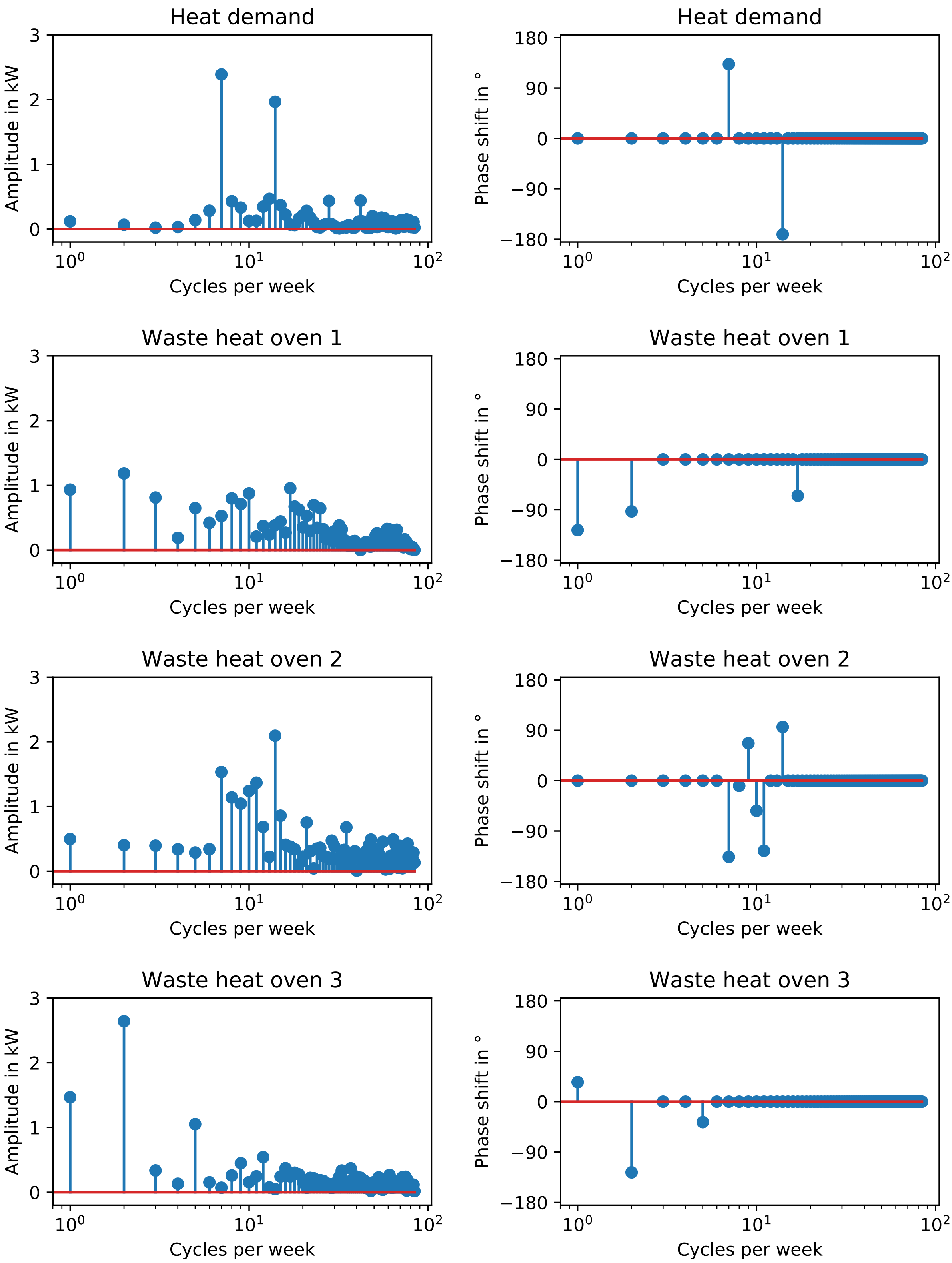

Figure 5: Amplitudes and phase shifts of all profiles. For clarity, the phase shift diagrams only show components with an amplitude of 0.9 kW or higher.

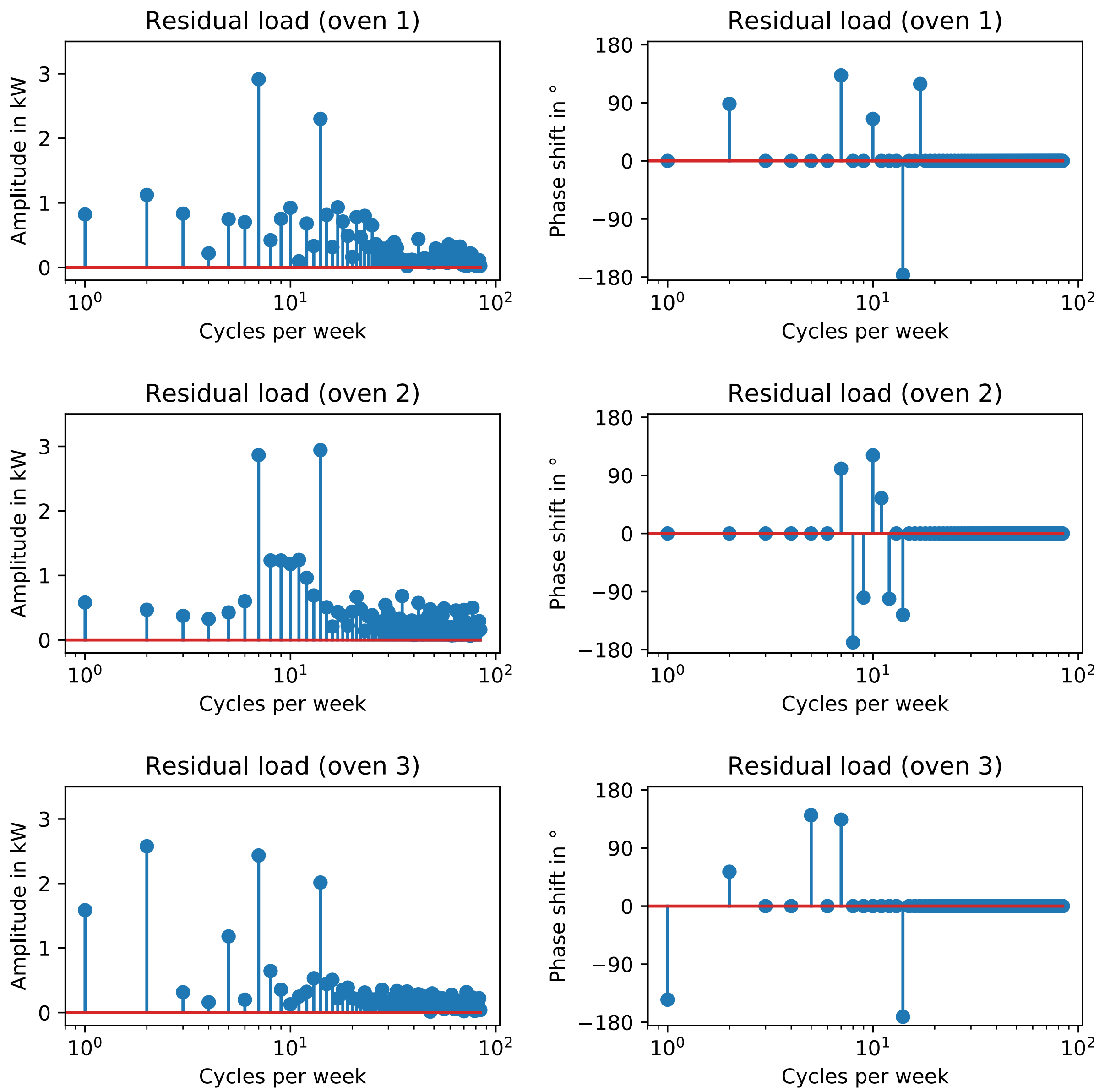

Figure 6: Amplitudes and phase shifts of all three residual load profiles. A residual load profile is the heat demand profile minus the waste heat profile of the mentioned oven. For clarity, the phase shift diagrams only show components with an amplitude of 0.9 kW or higher.

3.2.2 Configuration A

There are no storages available in this configuration. Therefore, power shortages will occur. Consequently, the best waste heat source for this configuration is the one that causes the least shortages.

The total energetic shortage of the space heat demand can be calculated by the mathematical sum of the positive residual load multiplied by the time between two time steps. These shortages must be covered by process steam. The smallest shortage can be achieved by using the waste heat from oven 3. This waste heat source can cover 591 of 814 kWh/week, thus the shortage is 223 kWh/week. In comparison, the use of oven 1 leads to a shortage of

232 kWh/week, while oven 2 causes a shortage of 272 kWh/week (Table 3). Therefore, oven 3 is the recommended waste heat source for this configuration.

Table 3: Energetic shortage without an energy storage (configuration A)

Waste heat source	*Oven 1*	*Oven 2*	*Oven 3*
Heat demand in kWh/week	814	814	814
Energetic coverage in kWh/week	582	542	591
Energetic shortage in kWh/week	232	272	223

3.2.3 Configuration B

The storage size in this configuration must be large enough so that no shortages occur. Therefore, the best storage size is the smallest possible size that can compensate the entire residual load. This can be achieved by considering all frequency components when determining the flexibility demand. Therefore, the flexibility demand profile is equal to the residual load. Based on the sizing methodology (section 2.3), the following storages sizes can be calculated (Table 4):

Table 4: Thermal energy storage sizes which compensate the whole residual load (configuration B)

Considered frequencies in 1/week	*Storage size in kWh*		
	Oven 1	*Oven 2*	*Oven 3*
all (0 to 84)	110	63	142

After the sizing process, the different sizes must be validated in order to compare results (section 2.4). The criteria for this configuration stipulate that shortages must not occur. Therefore, the value of the first validation key indicator, which describes the total shortage, is zero for all three waste heat sources. However, the other validation approach is important. This approach deals with the storage utilization. All statistical utilization results of the different waste heat sources are shown in Table 5. The second key indicator is the mean value for each oven in this table.

Table 5: Results of the storage utilization (configuration B)

Waste heat source	*Oven 1*	*Oven 2*	*Oven 3*
Number of bands *	22	13	28
Mean **	2.2	4.3	1.5
Standard deviation **	1.5	2.1	0.6
Minimal **	0	1	1
Maximal **	4	8	3

* the number of bands is the rounded value of the storage size divided by 5 kWh (band size).
** number of cycles over all 5 kWh bands

The storage size for using the waste heat from oven 1 (case 110 kWh storage size, all frequencies considered) is bigger than actually necessary for this application. This effect is represented by the minimal number of zero cycles per week in the corresponding column in Table 5. A minimal number of zero cycles per week indicates, that at least one energy band is never used. This is caused by the method explained in section 2.3. A flexibility option, which has exactly the same size as the calculated flexibility demand, is able to compensate the whole residual load. Such a storage size is able prevent all shortages and all excesses. However, if the sum of all excesses is higher than the sum of all shortages, but the goal is only to avoid shortages, then the calculated flexibility is demand will be too big. This is why this storage is larger than necessary.

The setup that uses waste heat from oven 2 requires the lowest storage size. In addition, this setup has the highest mean value of storage utilization. This is why oven 2 is the recommended waste heat source for this configuration.

3.2.4 Configuration C

This configuration is similar to configuration B. The difference is that shortages are allowed in this configuration whereas they were prohibited in configuration B. This change enables a reduction of the storage size, compared to configuration B.

Based on the storage sizing methodology (section 2.3), only the three most dominant frequency components of the residual load were used to determine the reduced flexibility demand. Therefore, the components with 2, 7 and 14 cycles per week were used for the waste heat from ovens 1 and 3, while for the waste heat from oven 2, the components with 7, 11 and 14 cycles per week were used. The resulting reduced storage size is shown in Table 6. These storage sizes are significantly smaller than the sizes from configuration B (Table 5).

Table 6: Thermal energy storage sizes for selected frequency components (configuration C)

Considered frequencies in 1/week	*Storage size in kWh*		
	Oven 1	*Oven 2*	*Oven 3*
2, 7, 14	52	-	89
7, 11, 14	-	34	-

It is important to validate the storage sizes so that the different configurations are comparable. The first key indicator (the energetic shortages for the different waste heat sources) is determined by applying the storage simulation tool (section 2.4). The results of the energetic shortages are shown in Table 7.

Table 7: Energetic shortages for selected frequency components (configuration C)

Considered frequencies in 1/week	*Total energetic shortages in kWh/week*			*Total energetic shortages in %*		
	Oven 1	*Oven 2*	*Oven 3*	*Oven 1*	*Oven 2*	*Oven 3*
2, 7, 14	55	-	106	7	-	13
7, 11, 14	-	74	-	-	9	-

The second key indicator is based on the number of storage utilization cycles per week. All results of the second validation approach are shown in Table 8. Compared to Table 5, smaller storages have more cycles per week. The higher the number of cycles, the larger the energy throughput, compared to the storage size. Accordingly, in most cases, small storages can be operated more economically than bigger storages.

Table 8: Results of the storage utilization (configuration C)

	Oven 1	*Oven 2*	*Oven 3*
Number of bands *	10	7	18
Mean **	3.8	6.9	1.9
Standard deviation **	1.2	1.6	0.9
Minimal **	2	4	1
Maximal **	6	9	4

* the number of bands is the rounded value of storage size over 5 kWh per band.
** number of cycles over all 5 kWh bands

4 Summary

In this case study, we were looking for the best combination of one waste heat source and one given heat demand. It is important to note that the heat demand need not exclusively be covered by waste heat. In exceptional cases, it can also be covered by process steam.

Configuration A: Without adding a thermal energy storage, the best option would be to use the waste heat from oven 3, since it can cover 591 of 814 kWh/week total energy demand. Thus, 223 kWh/week must be covered by process steam.

Configuration B: A storage size which can compensate the whole residual load can be calculated by considering the whole frequency spectrum. Using the waste heat from oven 2 would be the best option since the energy storage size would be just 63 kWh. The combination of oven 2 and this storage size ensures that no shortages occur.

Configuration C: Considering only selected frequency components of the residual load for storage sizing results in a decreased storage size, compared to configuration B. A storage size of 34 kWh results when oven 2 is used as the waste heat source and only the three most dominant frequency components of the residual load are taken into account. This setup causes 74 kWh/week (9 %) shortages, which has to be covered by process steam. However, the storage has a high utilization with nearly seven cycles per week. This, in combination with the smaller storage size, results in an economically efficient storage.

Methodology in general: The methodology shown in this work has large potential. One of its biggest advantages is its simplicity, which allows a reduced flexibility demand to be determined when small shortages are tolerable. The acceptability of power shortages depends on the particular application. When using a storage to cover this reduced flexibility demand, the storage has a good utilization with a high number of cycles. This increases economic efficiency. Additionally, this methodology is very fast and needs only little computational time.

However, it is not necessarily obvious which frequencies from the DFT should be considered. In this work, the residual load profiles of ovens 1 and 2 have profiles with only two dominant frequency components, and a few others which have all nearly the same height (Figure 6). Moreover, in configuration C, only the three most dominant frequencies were considered. This is not necessarily the optimal number of frequencies to use. Therefore, further research is necessary in order to improve this methodology (section 5).

5 Outlook

In future, the methodology shown in this work will be further developed and focus on:

- developing a clever algorithm to select the best frequency components for a reduced flexibility demand;
- extending the methodology to consider multi-energy systems, such as CHP units or power-to-gas systems; and
- comprehensively validating results based on a mathematical optimizer.

6 Acknowledgement

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