An optimisation approach for spatial allocation of energy sources to district heating networks

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Abstract. District heating networks (DHN) combined with low-carbon heat sources are a promising way to reduce greenhouse gas emissions from heating. However, few works have addressed the problem of allocating localised thermal energy supplies to DHN heating demands considering the spatial proximity constraint of transporting heat energy. The work improves an existing spatiotemporal analysis method by introducing an adapted form of Hitchcock transportation problem and linear programming to solve the optimal allocation problem in network of supplies and demands. The new method is compared with the original method and is found to improve the accuracy of estimating the allocable industrial excess heat supply in a Swiss case study. The method could be applied to diverse thermal sources, such as industrial excess heat, geothermal, lakes and rivers, etc.

1. Introduction
Decarbonising heating of buildings is highlighted by European Union (EU) as a requirement to deliver its greenhouse gas emission reduction goal [1]. District heating networks (DHN) combined with low-carbon energy generation has proved to help emission reduction, improve system efficiency and energy security [2]. Although many studies have been published on mapping renewable and waste energy potential to supply DHN [3–5], few works have addressed the problem of allocating heat supplies to DHN heat demands considering the spatial proximity constraint of transporting heat energy.

Furthermore, in situations where energy supplies are shared by several DHN energy demands, it is necessary to consider an allocation method that maximise the total useable potential. Chambers et al. [6] developed a spatiotemporal analysis method to evaluate the potential for supplying DHN by industrial excess heat (IEH). They use a spatial clustering method to link and cluster heat supplies and demands. However, a key limitation of this work is that there is no attempt to determine the allocation of supplies to demands within each cluster of nearby sources and demands. Instead, they simply calculated the net energy balance per cluster. This results in the overestimation of the allocable heat energy. This work applies a new method to estimate the maximum allocable heat potentials in networks of supplies and demands and compares the result with that of the previous work. A method is developed that adapts a transport optimization algorithm to the case of district heat network energy distribution.

2. Methods and input data

2.1. Case study and input data
To demonstrate the performance of the new optimal allocation method, we conducted a comparison between the results of it and the original net heat balance method on the same case study – potential of
IEH supply for DHN in Switzerland [6]. The input data for the case study includes datasets on IEH supply, DHN potential areas with predicted heat demand in the study area, as described in Table 1. For simplicity, only the reduced heat demand scenario ‘SwissRes’ (the energy saving scenario based on ‘SwissRes’ residential building retrofit model) and low temperature district heating networks (LTDH) are considered in this study.

Table 1. Summary of input data

| Datasets                  | Description                                                                 | Sources |
|---------------------------|------------------------------------------------------------------------------|---------|
| IEH supply                | IEH supply from industrial processes and waste incineration                  | [7]     |
| Heat demand scenario 'SwissRes' | Total demand per building for heating and hot water on a yearly basis in energy saving scenario based on ‘SwissRes’ | [8,9]   |
| District network potential regions | GIS polygons of areas for potential low temperature district heating for heat demand scenario ‘SwissRes’ | [10]    |

The total IEH supply in Switzerland is estimated to be 11.8 TWh/year. It is assumed to be constant over the year. The total heating demand of the ‘SwissRes’ scenarios is 54 TWh/year, of which 12.2 TWh/year could potentially be supplied by DHN. Figure 1 shows the monthly variation in total DHN demand, as well as total IEH supplies. IEH supplies and DHN areas are spread spatially, as shown in the example in Figure 2. Viable connections need to be identified when utilizing IEH for DHN, subject to spatial proximity constraints.

Figure 1. Monthly profiles of industrial excess heat supply and district heating demand in Switzerland

Figure 2. An example area with industrial excess heat supplies and district heating networks
2.2. Data preparation
The data pre-processing is adapted from an existing spatial clustering method, and is described in detail in the corresponding work [6]. All possible connections between IEH supplies and DHN demands are firstly filtered by spatial constraints of 5km distance using geographic information system (GIS) tools. Then these connections are further filtered by threshold heat transporting density of 1.8 MWh.y/m. Finally, the set of IEH supplies and DHN demands are clustered into distinct intra-connected components according to viable connections using graph theory.

2.3. Optimal allocation methods
The optimal allocation method applied in this work solves the problem of maximizing allocable heating energy within each cluster subject to connectivity constraints. The problem is framed as a variant of Hitchcock transportation problem [11]. The adaptation is made by enabling unbalanced total supplies and demands, as well as modifying the objective function to maximise the allocation of heat energy. Finally, the optimization problem is solved using linear programming.

The objective function is maximizing the total allocable energy:

\[
\max \sum_i \sum_j \eta_{ij} e_{ij}
\]  

(1)

Where \( i \) indicates the index of IEH supply, \( j \) indicates the index of DHN demand. \( \eta_{ij} \) is the distributing efficiency of the connection between IEH supply \( i \) and DHN demand \( j \), which equals 0.9 (accounting for 10% heat loss) when the connection is viable and equals 0 otherwise. \( e_{ij} \) is the decision variable which indicates the allocable heat demand in this connection.

The decision variable \( e_{ij} \) are constrained by the capacity of supplies and demands:

\[
\sum_j e_{ij} \leq s_i
\]  

(2)

Where \( s_i \) is the capacity of IEH supply \( i \).

\[
\sum_i \eta_{ij} e_{ij} \leq d_j
\]  

(3)

Where \( s_i \) is the capacity of DHN demand \( j \).

2.4. Storage system
Without seasonal storage system, the use of IEH to supply DHN is subject to temporal balance of supply and demand. The matching of supply and demand is therefore done on a monthly basis. The yearly total useable IEH is the sum of twelve months.

When seasonal storage is considered, surplus IEH supply in the months when heat demand is low could be stored and used in other months when IEH supply is insufficient. In this study, heat losses of the storage system are ignored. Usable IEH potential is assessed by solving the allocation problem on a yearly basis. The extra usable IEH potential compared with sum of monthly useable potential without storage is achieve by seasonal storage, and thus termed as storable IEH supply. Following the original method, the utilization of storable IEH is assumed to be distributed proportional to monthly energy deficit.

3. Results
A comparison between the results of usable IEH supply of the new method and the original one is carried out by applying them on the same Swiss case study. The results are summarized in Table 2.
Table 2. Comparison of results of the new optimal allocation method and the old method

|                  | IEH supply (TWh/y) | DHN demand (TWh/y) | Useable IEH supply without seasonal storage (TWh/y) | Useable IEH supply with seasonal storage (TWh/y) |
|------------------|--------------------|--------------------|--------------------------------------------------|------------------------------------------------|
| Original net heat balance method | 11.8              | 12.2               | 7.1                                              | 8.7                                            |
| New optimal allocation method    | 5.2               | 6.0                | 5.2                                              | 6.0                                            |

Figure 3 presents the estimated useable IEH supply without considering seasonal storage. The original method estimated in total 7.1 TWh/year useable IEH supply, corresponds to 58% of total DHN heat demands. The new method instead estimated in total 5.2 TWh/year useable IEH supply, decreased 27% compared with the original method.

Figure 4. A virtual example of one cluster. The circle indicates supply and demand nodes. The bar indicates their capacity.

The original net heat balance method does not solve the problem of optimal allocation with each cluster and therefore cause overestimated useable IEH supply. The implicit assumption of the original net heat balance method is that heat energy can move freely within the cluster. In reality, heat can only
be transported through direct connection, but not sequence of connections, since it would result in heat transmission lines that are longer than the transmission limit threshold used in the original filtering. This is illustrated in the virtual cluster presented in Figure 4. S1 (Source #1) is connected to D1 (Demand #1) and D2, S2 is connected to D1. Although S2 and D1 are in the same cluster, heat energy is not able to distribute from S2 to D1. Ignoring the spatial constraint within the cluster, the original method overestimates the useable supply to be 5 units, while the new method gives accurate estimate of 3 unit.

In the Swiss case study, we found large clusters that contain numerous supply nodes and demand nodes (up to 4059 nodes) and spread in huge areas. It is essential to use the optimal allocation method to solve the allocation problem within each cluster, in order to fully assess the impact of spatial constraint.

In the case when seasonal storage is considered, the surplus IEH in summer when the heat demand is low could be saved and used in winter when supply is in shortage. The original method finds 1.6 TWh/year storable IEH, contributing extra 22% of useable IEH. With the optimal allocation method, the storable IEH is 0.8 TWh/year, 15% of useable IEH without seasonal storage.

![Figure 5](image.png)

Figure 5. The results of storable IEH estimated by the original and new methods, as well as useable IEH, IEH supply and DHN demand

4. Discussion
We found that the new allocation method improves the accuracy in estimating the maximum allocable energy in clusters with long sequences of links. It is essential to implement the new optimal allocation method which properly models spatial constraints. This method can be generalised to allocate other types of resources in networks of suppliers and users. In the field of energy, it is specifically suitable to evaluate the potential of spatially bounded energy sources, such as IEH, geothermal, free thermal energy from waterbodies, etc.

If there is no spatial constraint, 8.9 TWh/year IEH could be utilised after considering monthly balancing of IEH supply and DHN demands. The spatial constraint is a major limiting factor of using IEH, making large amount of IEH supply not accessible by DHN. It reduces the useable potential to 5.2 TWh/year. Season storage only offers extra 0.6 TWh/year of storable potential. By improving the efficiency and decreasing the cost of DHN, we could further ease the spatial constraint in utilising renewable and waste energies, and in the end support the transition to a decarbonized energy system.

5. Conclusion
This paper presents a method to calculate the maximum allocable resource within network of supplies and demands. The method improves an existing spatiotemporal analysis method by introducing an adapted form of Hitchcock transportation problem and linear programming to solve the optimal allocation problem. The effectiveness of the new method is demonstrated by applying both the new and the original method on a case study of IEH potential to supply DHN in Switzerland. The new method is found to improve the accuracy of estimating IEH potential. The method could be applied to diverse thermal sources, such as industrial excess heat, geothermal, lakes and rivers, etc.
Under spatial and temporal constraints, 5.2 TWh/year out of 11.8 TWh/year IEH supply is found to be usable to supply DHNs. Seasonal storage could contribute another 0.8 TWh/year storable IEH by lifting the temporal constraint.

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