A New Evaluation Framework to Assess the Prosumer Efficiency in Thermal Source District Heating Networks

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Abstract

Thermal Source Network (TSN) district heating systems are a sustainable solution for integrating renewable energy and waste heat sources in the urban heating sector. These networks typically employ heat pump-based prosumers on the supply side. On the demand side, a heat pump substation at each consumer upgrades the heat received from the district heating network to the suitable temperature for a given building. However, there is a gap in the literature for an evaluation metric for assessing the efficiency of the prosumers in TSN networks. This paper proposes a new evaluation framework, the Prosumer Performance Index (PPI), to evaluate low-grade heat prosumers' efficiency in a TSN system from the aspects of energy, economics, and environment. This framework facilitates district heating owners' decision-making using low-grade waste heat in TSN networks. The simulation results demonstrate the variation of PPI over a year for four different scenarios of the central heat pump plant's supply temperature setpoints. Overall, by promoting energy efficiency, economic viability, and environmental sustainability, the PPI contributes to advancing sustainable urban heating solutions in alignment with global climate objectives.

1. Introduction

The heating and cooling sector transition is an important step in Europe's proposed energy transition goal (Zhang et al., 2022). In this context, developing sustainable district heating technologies can be pivotal in achieving the EU's ambitious climate goals (Revesz et al., 2020).

For a district heating system, a lower temperature allows the integration of renewable energy into the network and the use of low-grade waste heat sources, increasing the efficiency of the heat network (Guelpa et al., 2023).

District heating systems consist of a central heat-generating plant that supplies heat to a group of buildings or a district by circulating a heat-carrying fluid through a system of interconnected pipes. Over the past few decades, district heating systems have evolved, leading to a trend of decreasing temperature and increasing sustainability. This trend can be observed by looking at the shift from the first generation (pressurised steam of 150 °C) to the fourth generation (hot water of less than 80 °C) (Dang et al., 2024).

A subclass of the 4th generation district heating systems is the "Thermal Source Network (TSN)". In these systems, the water temperature ranges from 5 °C to 35 °C (Wirtz et al., 2020). Therefore, each building connected to the network must be fitted with a "substation" that is equipped with water-source heat pumps to raise the supply water temperature to the necessary levels for space heating and domestic hot water. In the literature, these TSN systems are often referred to as "fifth-generation district heating". However, in 2024, the IEA DHC Executive Committee (IEA DHC, 2024) recommended that the term "5th generation district heating" should not be used as it could be mistakenly perceived as an upgrade over 4th generation district heating. Instead, the executive committee suggested that pipe networks that are primarily used as a source for heating and cooling through decentralised heat pumps should be labelled as "thermal source networks" (TSN). These TSNs should be considered as a subclass of 4th generation district heating.

The term 'prosumer' is frequently used in the literature as a critical component of TSNs. It can be referred to any component of the system that plays both

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roles of energy consumer and energy producer. In the context of this research, "prosumers" are the central heat pump plants in a TSN that "consume" energy from the electricity grid and "produce" heat for the thermal grid.

Due to their low temperature, TSNs offer a key potential for harvesting Low-Grade Waste Heat (LGWH) such as data centres, metro stations, and sewage systems (Volkova et al., 2022). One of the key opportunities TSN technology provides is the shift from a monopolistic energy market to a market with multiple active prosumers (Angelidis et al., 2023). However, the lack of a clear evaluation metric for prosumers can threaten the future operation of decentralised TSNs.

A few studies have analysed the performance of TSNs based on various KPIs. For example, (Li et al., 2023) compared the techno-economic performance of TSN, individual air-source heat pump heating, and individual gas-fired heating. This analysis was conducted with five KPIs: levelised cost, upfront cost, peak load, exergy, and carbon emissions. This study provided a tool for policymakers to decide between technology options. However, they did not analyse the performance of different prosumers that propose to supply heat using the same technology within a TSN.

It is observed from the literature that there is a significant research gap for a comprehensive evaluation framework that considers the performance of prosumers from the three aspects of energy, economics, and environmental impacts.

The aim of this paper is to fill this gap by defining and formulating proper evaluation metrics and implementing them in a dynamic model of a TSN system. This multi-criteria metric is called the Prosumer Performance Index (PPI). Simulations are carried out for a hypothetical case study located in Dublin. The PPI metrics are calculated for different network supply temperature scenarios.

The novelty of this work lies in introducing a new set of metrics, specifically designed to evaluate the energy, economic, and environmental performance of prosumers in a TSN. Unlike traditional metrics such as the Coefficient of Performance (COP) and Levelized Cost of Heat (LCOH), the PPI metrics incorporate specific TSN parameters like pumping energy consumption and the income generated from selling heat by the prosumer. This comprehensive approach provides a more accurate and detailed assessment of prosumer efficiency within TSN systems, addressing gaps in the existing literature.

The structure of this paper is as follows:

Section 2 introduces the formulation of the PPI framework and a dynamic simulation of a TSN by applying the PPI metrics. The analysis results of the prosumers' energy, economic, and environmental performance in the case-study TSN model within the PPI framework are provided and discussed in Section 3. The discussion also provides limitations and challenges of applying the PPI framework in actual TSN networks. Finally, conclusions and future work are outlined in Section 4.

2. Materials and Methods

The methodology presented in this paper focuses on developing and applying the Prosumer Performance Index (PPI) framework. This framework offers a novel, generalisable approach to evaluate prosumers in TSN systems. By formulating the PPI framework, the research addresses the gap in the literature by providing a comprehensive approach to assess prosumer efficiency considering energy, economic, and environmental aspects. This dynamic simulation model enables the analysis of PPI metrics under varying conditions and different scenarios for the prosumer plant's setpoint temperature. An overarching diagram of this methodology is illustrated in Fig. 1. The methodology showcases an innovative and generalisable approach to evaluating prosumer performance in the TSN system. This method applies to any TSN system.

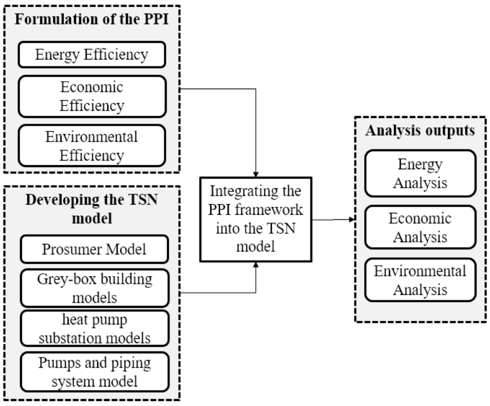

Fig. 1 – Overarching methodology diagram of developing and applying the PPI framework

2.1 Prosumer Performance Index

The Prosumer Performance Index (PPI) is a multi-criteria evaluation framework that aims to assess the performance of a heat prosumer in a TSN system based on their energy efficiency, economic efficiency, and environmental efficiency. The PPI metric for each of these three domains is formulated in the next sections.

The TSN system contains a prosumer that consumes power from the grid to produce the heat from a low-grade heat source through a heat pump. The network consumes power from the grid to distribute the heat carrying water in the district. Finally, at each building, a heat pump substation consumes power from the grid to upgrades this heat to the desirable temperature and deliver it to the building. This trade-off is illustrated in Fig. 2.

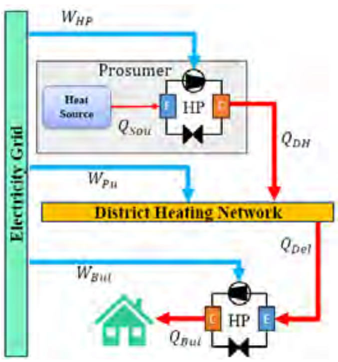

Fig. 2 – Diagram of the TSN system with central prosumer and heat pump substations

2.1.1 Energy Analysis Model

The PPI metric for the energy efficiency of prosumers is formulated as:

$$PPI_{Energy} = \frac{\sum_{n=1}^{n=N} Q_{Bui}}{W_{HP} + W_{Pu} + \sum_{n=1}^{n=N} W_{Bui}} \quad (1)$$

Where N is the number of buildings, $\sum_{n=1}^{n=N} Q_{Bui}$ is the total heat demand of all buildings connected to the TSN, W_{HP} is the central heat pump's compressor power consumption, W_{Pu} is the circulating pump's power consumption, and $\sum_{n=1}^{n=N} W_{Bui}$ is the total sum of all substations' heat pump power consumptions.

2.1.2 Economic Analysis Model

The PPI metric for economic efficiency is calculated as:

$$PPI_{Economic} = \frac{\dot{c}_{heat} \times (\sum_{n=1}^{n=N} Q_{Del})}{\frac{TIC \times r}{1-(1+r)^{T}} + C_{O\&M} + \dot{c}_{elec} \times (W_{HP} + W_{pu})} \quad (2)$$

Where TIC is the total investment costs paid in a lump sum (€),T is the number of years, $C_{O\&M}$ is the fixed Operation & Maintenance Cost (excluding power bills), $\dot{c}_{heat}$is the heat price for TSN consumers, $\dot{c}_{elec}$is the electricity price for the central heat pump, and $\sum_{n=1}^{n=N} Q_{Del}$ is the total sum of delivered heat to the evaporator side of all substations.

It should be noted that since the stakeholder for economic PPI analysis is the district heating owner and it is assumed that the substations are installed and maintained by the consumers, the boundaries for the definition of $PPI_{Economic}$ does not include the capital and operational costs related to the substation.

2.1.3 Environmental Analysis Model

The equivalent carbon emissions for the TSN's electricity are quantified using the emission factors:

$$EM = EF \times \left(W_{HP} + W_{pu} + \sum_{n=1}^{n=N} W_{bui} \right) \quad (3)$$

Where EF is the emission factor for electricity (gCO_2/kWh), which is obtained from the (Sustainable Energy Authority of Ireland (SEAI), 2022).

The PPI metric for environmental efficiency is calculated as follows:

$$PPI_{Environmental} = \frac{\sum_{n=1}^{n=N} Q_{Bui}}{EM} \quad (4)$$

It can be observed from the equation that higher heat production for lower emissions leads to higher ratio of $PPI_{Environmental}$ which is desirable.

2.2 TSN System and Supply-Side Model

2.2.1 Modelica-based Network Model

Modelica language offers high flexibility in reusing and extending component models. This makes it a suitable modelling tool for modelling the various configurations in the TSN systems that also include various components from thermodynamics, fluid mechanics, and control domains (Abugabbara et al., 2020). Being a flexible object-oriented, equation-based modelling language for physical systems, Modelica has already been successfully used in the dynamic thermal modelling of TSNs (Bünning et al., 2018). Compared to other tools such as EnergyPlus (Crawley et al., 2001), Modelica offers advantages for dynamic performance evaluation and control testing in district heating simulations. Modelica libraries facilitate capturing dynamic changes during system startup and realistic controller behaviors. (Chen et al., 2022).

In this research, the TSN system was simulated on a desktop computer with an Intel(R) Core (TM) i7-1255U processor and 32 GB of RAM running under Windows 11 Pro 64-bit. Dymola version 2024 (Dassault Systèmes, 2024) was used as the Modelica simulation environment since it offers a user-friendly interface for model development and post-processing. To develop the TSN system, validated component models from the free open-source Modelica Buildings Library (Wetter et al., 2014) were used.

Simulations were performed for one year with one-hour intervals. Fig. 3 shows the diagram view of the developed model in the Dymola environment, which includes the building models, heat pump substations, pipe models, central heat pump plant and the low-grade waste heat source.

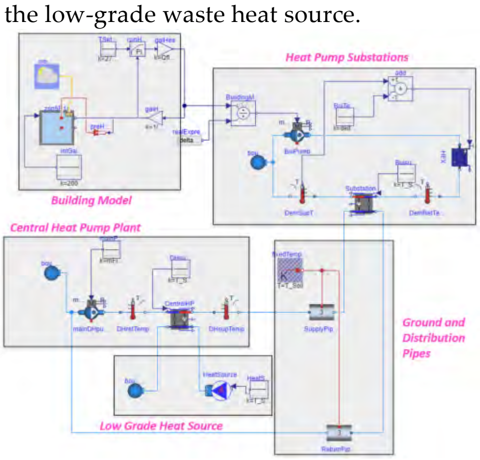

Fig. 3 – Diagram view of the TSN model in Dymola

2.2.2 Heat Pump Models

The Carnot refrigerant cycle was used to model both central and substation heat pumps. The Coefficient of Performance (COP) was scaled according to the Carnot efficiency, which is a basic approximation that is not influenced by the performance curves of any specific commercial heat pump product (Zarin Pass et al., 2018). This method eliminates the possibility of errors arising when extrapolating manufacturer performance data to low-lift operating conditions. The COP for a Carnot heat pump is calculated as:

$$COP_{HP} = \eta_{Carnot} \frac{T_{HP,Cond}}{T_{HP,Cond} - T_{HP,Evap}} \quad (5)$$

Where η_{Carnot} is a prescribed Carnot efficiency (assumed 0.3 here), $T_{HP,Cond}$ is the heat pump's condenser temperature and $T_{HP,Evap}$is the evaporator temperature. P_{Comp} is the compressor's power consumption and is calculated using equation:

$$COP_{HP} = \frac{\dot{Q}_h}{P_{Comp}} \quad (6)$$

Where $\dot{Q}_h$ is the supplied heat at the condenser side. The mass flow rate at the condenser and evaporator of the heat pumps are calculated by:

$$\dot{m}_{Cond} = \frac{\dot{Q}_h}{c_p \Delta T_{Cond}} \quad (7)$$

$$\dot{m}_{Evap} = \frac{\dot{Q}_h}{c_p \Delta T_{Evap}} \quad (8)$$

Where c_p is the specific heat capacity of water in J/kg·K, ΔT_{Cond} and ΔT_{Evap} are the temperature difference between the inlet and outlet of the condenser and evaporator respectively.

2.2.3 Pump Models

The circulation pump carries and circulates the water between the central heat pump's condenser and the substation heat pumps' evaporator sides. The power consumption of this circulating pump is calculated as:

$$W_{Pu} = \frac{\dot{V}_{Cond} \times \Delta P}{\eta_h \times \eta_m} \quad (9)$$

Where $\dot{V}_{Cond}$ is the volume flow rate in m^3/s, ΔP is the pump pressure rise in Pa, η_h and η_m are the hydraulic and motor efficiencies of the pump.

2.2.4 Demand Side Models

The demand side of the TSN model includes a heat pump substation and a building heat demand model. The heat pump substation includes a heat pump, a circulating pump, and a heat exchanger. This heat pump receives the TSN's heat in the evaporator side, upgrades it to the desired temperature level of the building, and delivers it to the circulating hot water through the condenser side. This hot water exchanges heat with a heat exchanger (which represents the building's terminal heating equipment) and provides the required heat demanded by the building.

3. Case Study

This research analyses a hypothetical TSN system proposed in a paper by for a cluster of 100 buildings located in Dublin, Ireland.

The simulation is carried out for Dublin (lat: 53.4°, long: 6.2°, altitude: 74 m), a Humid Continental climate in Ireland (The American Society of Heating, Refrigeration and Air-Conditioning Engineers, 2020). The weather data file for Dublin was downloaded from the EnergyPlus™ website. The input design parameters for the district heating network are summarised in Table 1.

A simplified grey-box building model is used to calculate the TSN model's heat demand for this network's demand side. This model is based on the ISO 13790 Standard (International Organization for Standardization, 2008) and written in the Modelica language and validated by (Maccarini et al., 2021). The behaviour of buildings' thermal properties is described by a model resembling an electric network consisting of five resistances and one capacitance. They used four cases of the (ANSI/ASHRAE Standard 140, 2007) validate the model. The model demonstrated good accuracy in general, and the validation results were within the acceptable ranges. This research uses case 600 from those four cases as a case-study. Fig. 4 shows the geometry of this model.

Table 1 – Case study design input parameters

Parameter	**Value**	**Unit**
Building indoor setpoints	20	°C
Substation supply temperature	70	°C
Ground temperature	6	°C
Carnot efficiency	30	%
Pump hydraulic and motor efficiencies	70	%
Evaporator temperature difference of the heat pump	-10	K
Condenser temperature difference of the heat pump	10	K

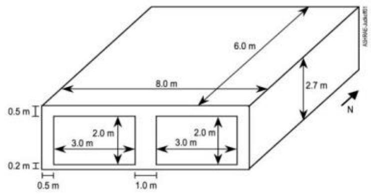

Fig. 4 – Dimensions of the test model based on ANSI/ASHRAE Standard 140 Case 600

4. Results and Discussion

In this section, the PPI values for the energy, economic, and environmental domains are calculated based on four scenarios for the central heat plant's setpoint temperature. This temperature is considered 15 °C, 20 °C, 25 °C, and 30 °C for the scenarios 1 to 4 respectively. These values are selected from the temperature range of TSN systems as reviewed by (Buffa et al., 2019). The model is simulated for each scenario to compare the scenarios, and the resultant PPI values for each domain are plotted in Fig. 5 to compare prosumers' efficiency in each scenario.

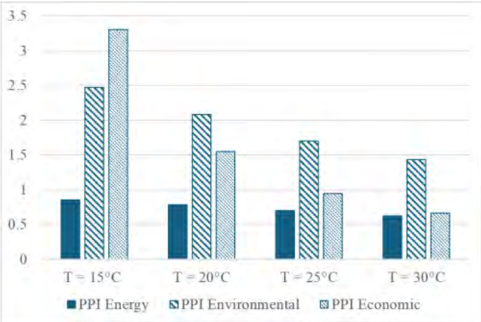

Fig. 5 – Annual PPI values for the modelled case study with four scenarios for the network setpoint temperatures

4.1 Energy Analysis Results

It can be observed in Fig. 5 that lower setpoint temperatures lead to higher prosumer efficiency because reducing this setpoint leads to lower temperature difference between the heat source and heat sink in the central heat pump, which results in less energy consumption by the compressor (W_{HP}). Over the whole year, scenario 1 (best case) has an annual PPI_{Energy} of 0.85, and for scenarios 2 to 4, it equals 0.78, 0.70 and 0.62, respectively.

4.2 Economic Analysis Results

The economic analysis was done by assuming a discount of 8% (Saffari et al., 2023), an electricity price of € 0.21/kWh (Saffari et al., 2023), and a hypothetical heat price of € 0.15/kWh. The capital and operation costs were obtained from SEAI's 2023 cost database. The system's lifetime for economic analysis was assumed to be 25 years.

Fig. 5 shows the $PPI_{Economic}$ for each scenario for a full year. The results demonstrate that a lower set point temperature leads to a better economic efficiency of the prosumer. The arithmetic mean values of $PPI_{Economic}$ for scenarios 1 to 4 are 3.3, 1.55, 0.94 and 0.66, respectively.

4.3 Environmental Analysis Results

An emission factor of 332 gCO2/kWh was used to calculate the environmental impacts based on SEAI's database. As illustrated in Fig. 5 for the four scenarios, the $PPI_{Environmental}$ ranges from 2.47 in the best case (scenario 1) to 1.43 in scenario 4.

4.4 Discussion

This paper formulated and calculated a theoretical evaluation framework metric for a hypothetical case study of a TSN located in Dublin using detailed dynamic models in Modelica. The motivation for proposing this metric was to develop an evaluation framework that fits the structure of TSN energy systems more specifically compared to other evaluation metrics, such as Coefficient of Performance (COP) and Levelized Cost of Heat (LCOH).

From an energy perspective, traditionally, the COP has been a commonly used metric to measure energy efficiency in heat pump-based DH supply systems (Tomc et al., 2024).The main limitation of using COP for evaluating prosumers in a TSN is that it only considers the heat pump's thermal performance and not the pumping energy consumption of the network. From an economic perspective, the LCOH is a widely used metric for estimating the lifetime heat production costs of a DH system (Saini et al., 2023). However, the LCOH accounts for production costs and does not consider the financial profit from selling the heat based on each prosumer's proposed heat price. As a result, the insights gained from the LCOH might be limited.

The goal of developing the PPI framework is to evaluate prosumers from various aspects. An interesting subject for future research is applying this evaluation framework in TSN networks with multiple prosumers. Each prosumer has a different share of heat supply in the same network, and the prosumers can be compared with each other in the PPI framework.

The formulation proposed in this research can be applied to any TSN system with heat-pump-based prosumers in any location. However, there are important limitations in the application of the PPI framework that should be considered. First, the PPI framework is a new metric and has never been used in other studies, making the validation of this metric challenging. Second, for the same reason, the calibration of the values calculated in the PPI framework is also problematic due to the lack of previous works and real-world implementation. Finally, being a newly proposed metric, it is difficult to communicate with various stakeholders using this metric, because stakeholders are typically familiar with traditional metrics such as LCOH, COP, and equivalent CO2 emissions, so they may not readily understand the values of PPI evaluation. These limitations pose key challenges for the application of PPI compared to other metrics.

Despite these challenges, the development of the PPI framework provides a novel approach to the multi-dimensional evaluation of prosumers within TSN systems. This work contributes to the theoretical foundation necessary for comprehensive performance evaluation in district heating networks and will be a useful reference for future studies in this area.

5. Conclusion

This paper has introduced a novel evaluation framework, the Prosumer Performance Index (PPI), designed to address the gap in assessing the efficiency of prosumers in Thermal Source Network (TSN) district heating systems. Through the development of the PPI, this research provides a valuable tool for district heating owners to assess prosumers' energy, economic, and environmental efficiency within TSN networks. By considering these multiple criteria, decision-makers can make informed choices regarding the utilization of low-grade waste heat and the optimization of TSN operations.

The simulation results presented in this paper demonstrate the variability of the PPI across different scenarios, highlighting the impact of network supply temperature setpoints on prosumer efficiency. The PPI framework aids TSN stakeholders in evaluating prosumer efficiency from various perspectives (energy, economic, and environmental), thereby facilitating better decision-making from the initial contracting with prosumers to the operational management phase.

However, there are important limitations to the PPI framework that should be considered. The validation of this new metric is challenging due to its novel nature and the lack of previous studies. Calibration of the PPI values is also problematic because of the absence of real-world implementation. Additionally, communicating the significance of PPI values to stakeholders, who are more familiar with traditional metrics like LCOH, COP, and equivalent CO2 emissions, poses a challenge.

Further research and validation of the PPI framework across diverse TSN networks with different heat generation technologies will be essential. The PPI framework can also serve as a foundation for implementing innovative control mechanisms and designing scenarios for developing TSN systems.

In conclusion, while the PPI framework represents a significant theoretical advancement in evaluating prosumer efficiency, its practical application requires further investigation and validation. Nonetheless, the PPI framework contributes to the theoretical groundwork necessary for advancing sustainable urban heating solutions in alignment with global climate objectives.

Acknowledgement

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Nomenclature

Symbols

TSN	Thermal Source Network
DH	District Heating
PPI	Prosumer Performance Index
COP	Coefficient of Performance
LCOH	Levelized Cost of Heat
KPI	Key Performance Indicators
TIC	Total Investment Costs
SEAI	Sustainable Energy Authority of Ireland
EM	Equivalent Carbon Emissions
EF	Emission Factor (gCO2/kWh)
P	Power (W)
W	Electricity Consumption (kWh)
ΔT	Temperature difference (K)
ΔP	Pressure drops (Pa)
$\dot{V}$	Volume flow rate (m^3/s)
$\dot{m}$	Mass flow rate (kg/s)
$\dot{Q}$	Heat flow rate (W)
η	Efficiency

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