Received: 12 October 2020 | Revised: 14 January 2021 | Accepted: 18 January 2021

IET Smart Grid

DOI: 10.1049/stg2.12020

The Institution of Engineering and Technology WILEY

ORIGINAL RESEARCH PAPER

Techno-economic-environmental analysis of a smart multi-energy grid utilising geothermal energy storage for meeting heat demand

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Funding information

Engineering and Physical Sciences Research Council (EPSRC), Grant/Award Number: EP/P01173/1

Abstract

This study presents an evaluation framework for the techno-economic-environmental (TEE) performance of the integrated multi-vector energy networks (IMVENs) including geothermal energy. Geothermal energy storage (GES) offers huge potential for both energy storage and supply and can play a critical role in decarbonising the heat load of smart multi-energy grids. The two most common types of GES, that is, high-temperature GES (HTGES) and low-temperature GES (LTGES), were modelled and integrated within the framework. This framework evaluates the impact of different low carbon energy sources including HTGES, LTGES, wind and Photovoltaics (PV) on the amount of energy imported from upstream, operational costs and emissions of IMVENs to meet the heat load of a region. The evaluation framework performs TEE performance analysis of any configuration of IMVEN representing future energy system pathways to provide a basis for well-informed design choices to decarbonise heat. The TEE evaluation framework was tested on a real-world case study, and several IMVEN configurations were designed and analysed. The results reveal that the most efficient, cost effective and least carbon-intensive configurations for meeting the heat load of the case study are the configurations benefitting from HTGES, from high penetration of heat pumps and from LTGES, respectively.

1 | INTRODUCTION

The UK Government has committed to a 'Net Zero' carbon economy by 2050 [1]. One major source of carbon emission is associated with heat demand from the domestic, commercial and industrial sectors. Providing for heat demand accounts for around one-third of UK carbon emissions [2]. To decarbonise the provision of heat, it is essential to increase the penetration of low carbon energy sources[1] (LCESs) in smart multi-energy grids (SMEGs), that is, integrated gas, electricity and district heating and cooling networks [3,4]. This, consequently, has an impact on the operation of SMEGs from the techno-economic-environment (TEE) point of view [5,6].

Unlike other types of LCESs, that is, wind and PV that are intermittent and supply electricity, geothermal energy storage[2] (GES) can provide a constant and more controllable heat supply. Hence, it offers huge potential for both energy storage and supply and can play a critical role in decarbonising heat load as well as offering baseload supply that can be difficult to achieve with other LCESs. The UK GES potential was assessed during the 1980s [7-9]. These works conclude that the UK GES has the modest potential for electricity production but is better suited to direct heat production. One geothermal heat network was developed as a result of this work, the Southampton well was drilled to a depth of 1.8 km and supplies around 2 MW of heat from a 72°C source. Many other nations have developed their

[1]The term LCES denotes any technology that provides energy either with zero carbon emissions, e.g. renewable energy sources (RESs) including wind and PV, or with low carbon emissions, e.g. heat pumps.

[2]In this study, GES is considered LCES since electricity is needed either to supply the pump for water circulation or to supply the possible heat pump to boost the mine water temperature although the heat source of GES is renewable.

GES [10,11] including china, which is the largest user of direct geothermal heat. However, the development of GES in the UK has been slow due to low cost gas and the high upfront capital costs associated with drilling deep geothermal wells. The UK Government plans to have a moratorium for new gas connections from 2025. The widespread declaration of climate emergencies across many local authorities and the renewable heat incentive which provides subsidies for the production of heat from low carbon sources have led to a renaissance for UK geothermal. More recent work on the geothermal potential of the UK's flooded abandoned mining infrastructure has revealed a subsurface resource in place of 2.2 billion GWh [12]. The impact of integrating this vast supply and storage potential on the operation and planning of SMEGs needs to be evaluated in terms of TEE aspects.

Here SMEGs and integrated multi-vector energy networks (IMVENs) are the same; however, SMEG describes more the operational characteristics of the energy system, whereas IMVEN describes more the structural characteristics of the energy system. The electrical smart grids can be seen as part of overall SMEGs [4]. This study emphasises this understanding of SMEGs and shows that the inclusion of flexible combined heat and power (CHP) and GES will enhance TEE performance of electrical smart grids.

1.1 | Aims and objectives

A framework is developed for the evaluation of TEE performance considering the integration of GES with IMVENs to meet the heat load at the distribution level. For this purpose, the two most common types of GES, that is, low-temperature GES (LTGES) and high-temperature GES (HTGES) have been modelled. The TEE impact of different generation levels of LCESs including LTGES, HTGES, wind and PV on IMVENs has been evaluated through several IMVEN configurations for meeting the heat load including single vector (gas network (GN), smart electricity network (SEN) or GES-driven district heating network (DHN)) and coupled vectors (all the combinations of GN, SEN or GES-driven DHN). Finally, the TEE performance of all these configurations has been compared, to: (i) evaluate the impact of the integration of networks on TEE performance compared to the separate energy networks for meeting the heat load; and (ii) evaluate the impact of different LCESs and integration of HTGES and LTGES with IMVEN on TEE performance of the networks. Based on the outcomes of this research, the potential benefits of the implementation of the TEE evaluation framework include: (i) comparing available and future scenarios for meeting the heat load to make an informed decision to support the most efficient[3], cost-effective and least carbon-intensive design choice[4] according to the availability of LCESs, including GES, in a region; (ii) using the TEE evaluation framework to design different components of the heat supply system including heat pump (HP) and CHP according to TEE objectives; (iii) enhancing the performance of the overall energy system (IMVEN) by implementing a smart control and management system over the framework; and (iv) developing business models to deploy the most suitable scenario for supplying heat to a region.

[3]'Most efficient' in this context denotes meeting the heat load with lowest amount of energy import from upstream networks.

[4]'Design choice' in this study refers to the configuration of heat supply system including all the components of that configuration.

1.2 | Literature review

The studies on TEE analysis of different future scenarios, including GES, for meeting the heat load of a region have been captured and considered in the literature review for this study. It should be noted that only the papers that have performed detailed network level operational analysis of IMVENs have been considered. This means that: (i) the papers on hub level analysis (e.g. [13]) have not been considered; (ii) the papers on operational analysis of a single network to meet the heat demand (e.g. [14-17]) have not been considered.

Among the papers without modelling GES [18-21]: (i) Technical [19] and techno-economic (TE) [18] analysis of several scenarios for different shares of integrated gas and electricity transmission networks (IGETNs) to meet the heat load have been investigated; (ii) Technical analysis of gas boiler (GB)- or CHP-driven DHN at the distribution level was studied in [20]; and (iii) TEE analysis of combinations of GB-, CHP- or HP-driven DHN for district heat loads and GB, HP or CHP to meet the rest of the heat loads (called 'local' heat load in their paper) has been investigated at distribution level [21].

The studies that have considered GES to perform TE [22] or TEE [23] analysis of different scenarios in IGETNs:(i) have not disclosed the details of the GES modelling. GES is only a small part of the heat supply to the energy system of their case study, which is modelled as a black box; and (ii) have not performed TEE analysis of the impact of integration of GES on IMVEN compared to IMVEN without GES.

Table 1 highlights the contributions of this article in relation to all the available literature on TEE analysis of different IMVEN configurations to meet the heat load.

1.3 | Research gaps

To conclude the literature review, the studies on TEE analysis of different IMVEN configurations to meet the heat load of a region: (i) have considered a simplified model of GES and have not disclosed the details of GES modelling since GES has been modelled only as a black box and small part of the heat supply system of their case study. In this case, these studies neglect the electricity requirements of the components of the geothermal system that is required to boost the hot water quality. This required electrical energy is not fixed and depends on the heat load and consequently it will impact the TEE performance of

TABLE 1 Contributions of this article compared to all the available literature on scenarios for meeting the heat load

Ref.	GES modelled?	Impact analysis of GES	Case study level [3] T	D	Single network [4]	Coupled networks [5]	Economic analysis?	Environmental analysis?
[18]	✗	✗	✓	-	✗	G/E	✓	✗
[19]	✗	✗	✓	-	✗	G/E	✗	✗
[20]	✗	✗	-	✓	H	✗	✗	✗
[21]	✗	✗	-	✓	G, E, H	G/H, E/H	✓	✓
[22]	✓ [1]	✗	✓	-	✗	G/E	✓	✗
[23]	✓ [1]	✗	✓	-	✗	G/E	✓	✓
This Study	✓ [2]	✓	-	✓	G, E, H	G/E, G/H, E/H	✓	✓

[1]No details disclosed. GES is only a small part of the heat supply to the energy system of their case study and is modelled as a black box.

[2]Both high- and low-temperature GESs have been modelled and integrated into the IMVEN TEE evaluation framework.

[3]T: Transmission level, D: distribution level.

[4]Single network to meet the heat load. G: gas network, E: electricity network, H: heat network.

[5]Combination(s) of integrated networks to meet the heat load.

IMVENs. Also, this detailed modelling of the geothermal system is needed as it enables to model and evaluate the impact of operational parameters of geothermal system on TEE performance of IMVEN during the geothermal feasibility study phase; (ii) have not investigated the impact of LCESs and integration of GES on TEE performance of IMVENs compared to IMVENs without GES and LCESs. It is essential to evaluate the impact of the integration of GES on TEE performance of IMVENs. Additionally, different LCESs availability in different regions might have an impact on the design choices specific to that region for integration of different networks to meet the heat load; (iii) have not performed TEE performance analysis of only one vector to meet the heat load, i.e. GN, SEN and GES-driven DHN. This is to show the TEE the benefits of integration of the networks; (iv) have not performed TEE analysis of all the combinations of integrated GN, SEN and GES-driven DHN to meet the heat load. As it can be seen later, each configuration can affect differently the TEE performance of IMVENs. The last two items need to be fulfilled to quantitatively compare and make an informed decision to support the most efficient, cost-effective and least carbon-intensive design choice for meeting the heat load of a region. These configurations include single vector and coupled vectors based on the availability of LCESs (GES, wind and PV) that are specific to the region.

1.4 | Research questions

This study advances the state-of-the-art of TEE performance analysis of IMVENs through several IMVEN configurations for meeting the heat load of a region through addressing the following research questions:

- How can GES be modelled and integrated into the framework of TEE evaluation of IMVEN?
- How to evaluate the impact of LTGES and HTGES on operation of IMVEN to meet the heat load from TEE point of view?
- What is the most cost-effective and least carbon-intensive combination of IMVEN in order to meet the heat load of a region?
- What is the impact of wind and PV generation levels on TEE performance of IMVENs to meet the heat load of a region?
- How wind and PV generation levels might impact the design choices for meeting the heat load from TEE point of view?

1.5 | Contributions

The contributions of the article are:

- A valid and generic TEE evaluation framework is developed, which can be applied to any distribution or transmission level case study with different IMVEN topology and load/generation profiles.
- Modelling and integration of LTGES and HTGES into the TEE evaluation framework of IMVEN operational analysis are fulfilled.
- TEE impact of LTGES and HTGES on operation of IMVEN to meet the heat load at the distribution level is evaluated.
- Impact of wind and PV levels on TEE performance of IMVENs with different design choices including LTGES and HTGES is investigated.
- TEE operational analysis of several configurations for meeting the heat load including single vector (GN, SEN or GES-driven DHN) and integrated vectors (all the coupled combinations of GN, SEN or GES-driven DHN) is carried out.

- All the configurations for meeting the heat load are compared from TEE point of view to study the most efficient, cost-effective and least carbon-intensive one.

1.6 | Organisation of the study

The rest of the study is structured as follows: Section 2 explains the algorithm of the developed TEE evaluation framework for IMVENs, the mathematical representation of all the components of the framework and the considered IMVEN configurations. The case study and the designed scenarios are presented in Section 3. The results obtained are explained and discussed in Section 4. Finally, conclusions and future work are presented in Section 5.

2 | THE PROPOSED IMVEN TEE EVALUATION FRAMEWORK

2.1 | Definition of TEE parameters

This section summarises the technical, economic and environmental parameters of the operation of IMVENs, which have been explained in detail in [4,24,25].

2.1.1 | Technical parameter

Technical parameter denotes the amount of energy supplied by the upstream networks. The lower the technical parameter, the less the energy supplied by the upstream networks. This technical evaluation enables the framework to evaluate the level of security of supply and self-sufficiency of the local distribution network from the upstream level.

2.1.2 | Economic parameter

Economic parameter represents the operational cost of IMVEN and is the cost of purchase of energy from the upstream networks. The economic evaluation quantifies the cost saving resulting from increased integration of distribution networks and more utilisation of local renewables at the distribution level.

2.1.3 | Environmental parameter

Environmental parameter is defined as the amount of CO_2 equivalent emitted due to final energy use and is directly related to the amount of energy imported from upstream networks. The environmental evaluation quantifies the reduction in carbon emissions as a result of more integration of distribution networks and more utilisation of local renewables at the distribution level.

Once the TEE parameters are determined, it is possible to evaluate the performance of IMVEN for meeting the heat load based on the amount of energy imported from upstream networks (technical evaluation), operational cost of IMVEN (economic evaluation) and CO_2 equivalent emission from IMVEN (environmental evaluation).

2.2 | Algorithm of the IMVEN TEE evaluation framework

Figure 1 shows the block diagram for the algorithm of the developed TEE evaluation framework for IMVEN operation. As can be seen, one of the inputs in the evaluation framework is the topology of the GN, SEN and DHN. This will enable considering different configurations of the IMVEN. The rest of the inputs include the heat and electricity load profiles, energy generation profiles from LCESs (HTGES, LTGES, wind and PV), coupling components (CCs) parameters (efficiency and connections) and unit parameters for economic and environmental (EE) analysis.

The TEE analysis is then performed in two steps: (i) the technical simulation engine performs the technical evaluation of the integrated networks through operational analysis of the networks to determine the amount of energy supplied by upstream networks (technical parameter) for meeting the heat and electricity loads. (ii) EE analysis is then performed based on the technical parameter calculated from step (i). Therefore, TEE parameters of the IMVEN operation are determined.

The outputs of the IMVEN evaluation framework are the technical, economic and environmental performance parameters of integrated operation of the IMVEN.

2.3 | Mathematical representation of the technical simulation engine

A technical simulation engine was developed for operational analysis and calculation of the technical parameters of IMVEN operation. The steady-state representation of AC power flow in the SEN, gas flow in the GN and hot water flow in the DHN was formed and solved using the Newton method. The networks were soft-linked through CCs to obtain an integrated networks model. The details of the equations used for the networks, the GES and CCs are presented in the following sections.

2.3.1 | Model of the SEN

The equations for the balance of active and reactive power flow at every bus of the SEN, except the slack bus, are formed as (1) and (2), respectively:

$$P_{G_i} - P_{L_i} - \sum_j |V_i||V_j|\left(G_{ij} sin\left(\delta_i - \delta_j\right) + B_{ij} cos\left(\delta_i - \delta_j\right)\right) = 0 \quad (1)$$

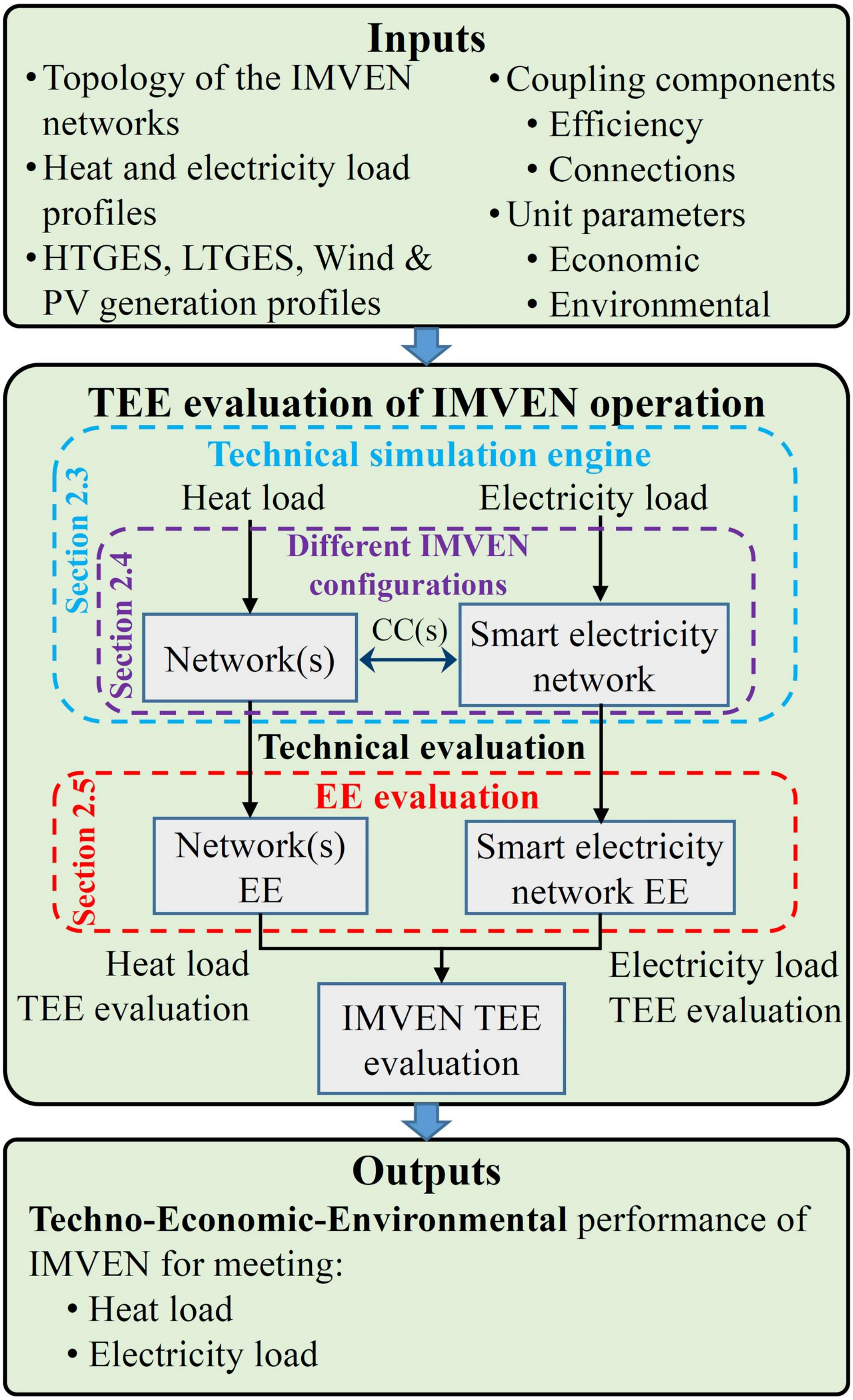

FIGURE 1 Algorithm of the developed TEE evaluation framework

$$Q_{G_i} - Q_{L_i} - \sum_j |V_i||V_j|\left(G_{ij}\sin\left(\delta_i - \delta_j\right) - B_{ij}\cos\left(\delta_i - \delta_j\right)\right) = 0 \quad (2)$$

where $P_{G_i}(MW)$ is the net active power generation, $P_{L_i}(MW)$ is the net active load at bus i, G_{ij} is the real part and B_{ij} is the imaginary part of the element in the bus admittance matrix corresponding to the ith row and jth column, $Q_{G_i}(MVAr)$ is the net reactive power generation and $Q_{L_i}(MVAr)$ is the net reactive load at bus i, $|V_i|$ and $|V_j|$ are voltage magnitudes, and δ_i and δ_j are voltage angles of the two ends of the branch $i\ j$.

There is PV generation at some of the buses of the network; however, the value of their power generation is known. Therefore, all the buses of the network are considered as PQ buses. Once the set of (1) and (2) for all the buses of the SEN is formed and solved using MATPOWER toolbox [26], the voltage magnitude and angle of all the buses as well as the power flows in all the branches of the network are determined. Therefore, the value of the energy imported from upstream through the slack bus can be calculated.

2.3.2 | Model of the gas network

The equation for gas flow balance at every node of the GN, except the source node, is formed as:

$$\sum_j \left(q_{j,\text{in},i} - q_{j,\text{out},i}\right) - q_{i,L} = 0 \quad (3)$$

where $q_{j,\text{in},i}(m^3/s)$ is the gas flow in the branches j entering node i, $q_{j,\text{out},i}(m^3/s)$ is the gas flow in the branches j leaving node i, and $q_{i,L}(m^3/s)$ is the gas load at node i. The gas load $q_{i,L}$ is calculated based on the heat load using (14).

The general flow equation was used for relating the gas flow in the branches to the pressure of the two end nodes [27]:

$$q_{ij} = \pi\sqrt{\frac{R_{\text{air}}}{8}}\ \frac{T_n}{p_n}\sqrt{\frac{\left(p_i^2 - p_j^2\right)D^5}{f\ S_{\text{mix}} L\ T\ Z_{\text{mix}}}} \quad (4)$$

where $q_{ij}(m^3/s)$ is the gas flow in the branch $i\ j$, $R_{\text{air}}(\approx 287.0\ \text{J/kg.K})$ the air constant, $T_n(K)$ the standard temperature, $p_n(pa)$ the standard pressure, $p_i(pa)$ and $p_j(pa)$ the pressures at two end nodes of the branch $i\ j$, $D(m)$ the branch diameter, f the friction factor, S_{mix} the specific gravity of the gas mixture, $L(m)$ the branch length, $T(K)$ the temperature of the gas and Z_{mix} the compressibility of the gas mixture. For the purpose of brevity, calculation of f, S_{mix} and Z_{mix} as well as the algorithm for calculation of gas flow of the branch using p_i and p_j is not duplicated here since they are explained in detail in [28].

Once the set of Equation (3) is formed and solved, the values of pressure of the nodes and flow of the branches are determined and hence the value of the gas flow from the source node taken from the upstream is obtained.

2.3.3 | Model of the DHN

The methodology explained in [29] for simulation of operation of DHNs is adopted and briefly presented in this study. The equation for the balance of fluid (hot water) flow rates at the nodes of the DHN is formed as follows:

$$\sum_j \dot{m}_{j,\text{in},i} - \dot{m}_{j,\text{out},i} - \dot{m}_{i,L} = 0 \quad (5)$$

where $\dot{m}_{j,\text{in},i}(\text{kg/s})$ and $\dot{m}_{j,\text{out},i}(\text{kg/s})$ are the flow rates of branches j entering and leaving node i, respectively, and $\dot{m}_{i,L}(kg/s)$ is the flow rate at node i to meet the heat load $P_{i,h}(W)$, which is calculated using:

$$P_{i,h} = c_p \dot{m}_{i,L}\left(T_{\text{s},i} - T_{\text{r},i}\right) \quad (6)$$

in which $T_{\text{s},i}(K)$ and $T_{\text{r},i}(K)$ are the supply and return temperature of the flow at the load, respectively, and c_p is the specific heat capacity of water ($\approx 4200\,\text{J}/_{\text{kg.K}}$). Also, the heat loss in the branches is considered as follows:

$$T_{\text{end}} = \left(T_{\text{start}} - T_a\right)e^{\frac{-\lambda L}{c_p \dot{m}}} \quad (7)$$

where $T_{\text{start}}(°\text{C})$ and $T_{\text{end}}(°\text{C})$ are the temperature of the flow at the start and end of the branch, respectively, $T_{\text{a}}(°\text{C})$ the ambient temperature, $\lambda(W/m.K)$ the thermal conductivity of the branch per unit meter and $L(m)$ the length of the branch. Also, in any mixing point, either in the supply network or the return network, the temperature of the mixture is calculated using:

$$T_{\text{mix}} = \frac{\sum_j \dot{m}_j T_j}{\sum_j \dot{m}_j} \quad (8)$$

in which $T_{\text{mix}}(°\text{C})$ is the temperature of the mixed flow and $T_j(°\text{C})$ is the temperature of the flow $\dot{m}_j(\text{kg/s})$ entering the mixing node. Once the set of above non-linear equations is solved the values of the flow of the branches and the source, supply temperature to the nodes and return temperature to the source are obtained. Then, the heat power required from the source to meet the heat load of the DHN is obtained using (6).

2.3.4 | Geothermal energy storage

The two most common types of GES, i.e. HTGES and LTGES, are modelled in this study. The schematic of these two types is depicted in Figure 2.

- *HTGES:* In HTGES, water with a temperature around 80°C is extracted from the underground and is transferred back to

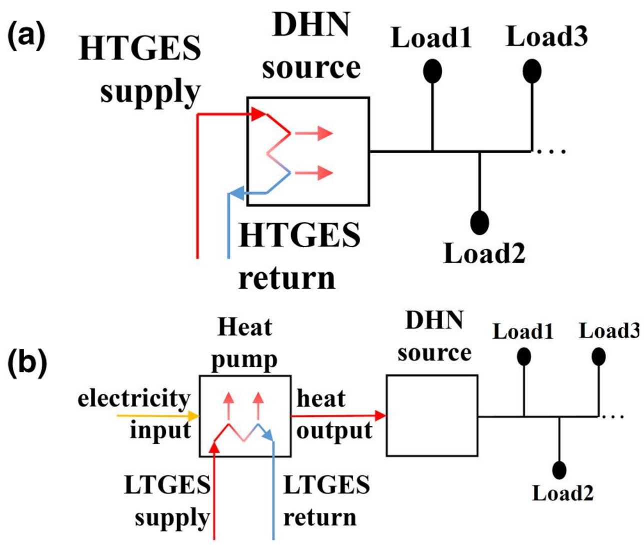

FIGURE 2 Modelled GES types: (a) high-temperature GES (HTGES) and (b) low-temperature GES (LTGES)

the underground reservoir once heat is extracted from it (Figure 2(a)). The high temperature of this water makes it suitable for direct use by the DHN source. In this case, the amount of heat input from HTGES to the DHN source is as follows:

$$P_{\mathrm{HTGES}} = \dot{m}_{\mathrm{HTGES}} c_p \left(T_{s,\mathrm{HTGES}} - T_{r,\mathrm{HTGES}}\right) \tag{9}$$

where $P_{\mathrm{HTGES}}(W)$ is the heat supply of HTGES to the DHN source, $\dot{m}_{\mathrm{HTGES}}(\mathrm{kg/s})$ the water flow rate of HTGES and $T_{s,\mathrm{HTGES}}(℃)$ and $T_{r,\mathrm{HTGES}}(℃)$ the supply and return temperature of HTGES, respectively.

- *LTGES:* In LTGES, the water is taken from a flooded mine with temperature around 15℃. The low temperature of this water is not sufficient to directly supply the DHN source. Therefore, a HP is used to boost the temperature of the water in the output circuit of the HP, following heat exchange with the water from LTGES, making it usable to supply the DHN source (Figure 2(b)). In this case, the electricity input to the HP can be calculated using the heat output and coefficient of performance of the HP as explained in Section 2.3.5.

In both cases of HTGES and LTGES, the electric load of the pump that is used to pump the water from the depth of underground and send it back to the same depth is determined through a look-up table.

2.3.5 | Heat pump

The heat output of a HP $P_{h,\mathrm{HP}}(W)$ is related to the electricity supplied to it $P_{e,\mathrm{HP}}(W)$ using:

$$P_{h,\mathrm{HP}} = P_{e,\mathrm{HP}} CoP_{\mathrm{HP}} \tag{10}$$

in which CoP_{HP} is the coefficient of performance of the HP.

2.3.6 | Combined heat and power

In this study CHP follows the heat load. Therefore, the gas flow supplied to the CHP $q_{g,\mathrm{cHP}}(m^3/s)$ is calculated using:

$$q_{g,\mathrm{cHP}} = P_{h,\mathrm{CHP}} \Big/ \left(GCV_{\mathrm{mix}} \eta_{\mathrm{th,cHP}}\right) \tag{11}$$

where $P_{h,\mathrm{CHP}}(\mathrm{kW})$ is the heat load, $GCV_{\mathrm{mix}}(\mathrm{kJ/m^3})$ is the gross calorific value of the gas mixture [30], and $\eta_{\mathrm{th,cHP}}$ is the thermal efficiency of the CHP. Also, the electric power generation of CHP $P_{e,\mathrm{CHP}}(\mathrm{kW})$ is as follows:

$$P_{e,\mathrm{CHP}} = P_{h,\mathrm{CHP}} \eta_{e,\mathrm{cHP}} / \eta_{\mathrm{th,cHP}} \tag{12}$$

in which $\eta_{e,\mathrm{cHP}}$ is the electrical efficiency of CHP.

2.3.7 | Electric heater

The electric consumption of electric heater (EH) $P_{e,\mathrm{EH}}(\mathrm{kW})$ is calculated using the heat load $P_{h,\mathrm{EH}}(\mathrm{kW})$ and EH efficiency (η_{EH}) as follows:

$$P_{e,\mathrm{EH}} = P_{h,\mathrm{EH}} / \eta_{\mathrm{EH}} \tag{13}$$

2.3.8 | Gas boiler

The gas flow consumption of GB $q_{\mathrm{GB}}(\mathrm{m^3/s})$ is calculated based on the heat load $P_{h,\mathrm{GB}}(\mathrm{kW})$ and GB efficiency (η_{GB}) using:

$$q_{\mathrm{GB}} = P_{h,\mathrm{GB}} / \left(GCV_{\mathrm{mix}} \eta_{GB}\right) \tag{14}$$

2.4 | The considered IMVEN configurations

Several configurations of IMVEN to meet the final heat load[5] have been considered. The configurations considered in

[5]'Final heat/electricity load' denotes the heat/electricity load of the final energy user in the rest of the paper.

addition to the networks participating in meeting the final heat load in each configuration are presented in Figure 3 and described in Table 2. As can be seen from the table, individual networks as well as all the possible combinations of the networks have been considered to compare the TEE performance of IMVENs for meeting the final heat load. These configurations and the calculation of the energy supplied from the upstream networks (technical parameter) to meet the heat load in each configuration are explained in this section.

2.4.1 | Configuration 1: all electric

The final heat load is met by the EHs. Hence, both the final electricity and heat loads are placed on the corresponding SEN bus. Once the amount of electricity imported from the upstream SEN, $E_{\mathrm{EN,up}}(MWh)$, is calculated, the technical parameters for heat load, $TP_h(MWh)$, and for electricity load, $TP_e(MWh)$, respectively, are calculated using:

$$TP_h = \frac{\sum_{i=1}^{N_L} P_{h,i}}{\sum_{i=1}^{N_L}\left(P_{h,i}+P_{e,i}\right)} E_{\mathrm{EN,up}} \tag{15}$$

$$TP_e = \frac{\sum_{i=1}^{N_L} P_{e,i}}{\sum_{i=1}^{N_L}\left(P_{h,i}+P_{e,i}\right)} E_{\mathrm{EN,up}} \tag{16}$$

in which N_L number of load points[6], $P_{h,i}(kW)$ the heat load of the load point i and $P_{e,i}(kW)$ the electricity load of the load point i.

2.4.2 | Configuration 2: all gas

The final heat load is met by the GBs. Therefore, $TP_h(MWh)$ will be equal to the energy of the gas imported from the upstream GN. On the other hand, $TP_e(MWh)$ will be equal to all the power supplied by the upstream SEN.

2.4.3 | Configurations 3a and 3b: Gas & electric (3a low penetration of HPs, 3b high penetration of HPs)

The final heat load is met by a combination of HPs and GBs based on the penetration level of HPs (HP_{pen} in percentage). It is assumed HP_{pen} is the same for all the load points. In this configuration, HP_{pen}-part of the final heat load is met by the HP and the rest is met by the GB (e.g. if $HP_{\mathrm{pen}} = 40\%$, then 40% of the heat load is met by HPs). Then, $TP_{h,\mathrm{EN}}$ due to HPs in the SEN will be calculated as explained in 2.4.1 and $TP_{h,\mathrm{GN}}$ due to GBs in the GN will be calculated as explained in Section 2.4.2. Finally:

$$TP_{h,total} = TP_{h,EN} + TP_{h,GN} \tag{17}$$

The penetration levels of HP for configurations 3a and 3b have been assumed to be 20% and 80%, respectively.

2.4.4 | Configurations 4a and 4b: GES (4a HTGES with EH at DHN source, 4b LTGES with EH at DHN source)

The final heat load is met by the HTGES and LTGES in configurations 4a and 4b, respectively. The assumptions include: (i) HTGES and LTGES supply a constant heat at all the time steps to the DHN source; (ii) The water pumps of the HTGES and LTGES and the HP associated with the LTGES are supplied by the SEN slack bus. This is the reason SEN is feeding HTGES and LTGES in Figure 3 although their heat source is renewable; (iii) if the supplied heat from either HTGES or LTGES is not sufficient to meet the total heat load then an EH at the DHN source will provide the rest of the required heat. Since the source of heat from HTGES and LTGES is renewable, the associated TP_h is assumed to be equal to zero. Hence, TP_h in these two configurations is the summation of the electric loads of the water pump of HTGES/LTGES and the EH at the DHN source. The TP_h of LTGES has another element corresponding to the electric consumption of the HP. The governing equations are as explained in Section 2.4.1.

2.4.5 | Configuration 5: CHP

The final heat load is met by a CHP that supplies both the SEN slack bus and the DHN source. It is assumed that it follows the heat load and is supplied by an upstream GN. TP_h(MWh) in this configuration is:

$$TP_h = E_{\mathrm{CHP\ output},h} + EL_{\mathrm{CHP},h} \tag{18}$$

where $E_{\mathrm{CHP\ output},h}$(MWh) is the heat energy supplied to the DHN source by the CHP and $EL_{\mathrm{CHP},h}$(MWh) is energy loss of the CHP associated with the heat output of it, which is:

$$EL_{\mathrm{CHP},h} = EL_{\mathrm{CHP,tot}}\eta_{th,\mathrm{cHP}} / \left(\eta_{th,\mathrm{cHP}} + \eta_{e,\mathrm{cHP}}\right) \tag{19}$$

where $EL_{\mathrm{CHP,tot}}$(MWh) is the total energy loss of the CHP. On the other hand, TP_e(MWh) is calculated using:

$$TP_e = E_{\mathrm{EN,up}} - E_{\mathrm{CHP\ output},e} + EL_{\mathrm{CHP},e} \tag{20}$$

[6]'Load point' refers to any of the nodes/buses that the final heat/electricity load is placed on the networks for TEE evaluation. These load points are denoted by the buses or load nodes in Figure 4.

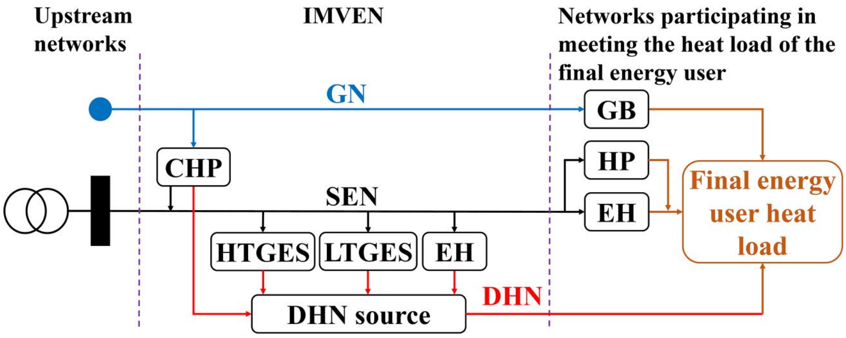

FIGURE 3 Schematic of all the possible configurations of IMVEN considered in this study

TABLE 2 The IMVEN configurations considered for meeting the heat load of the final energy user

No.	Description	Networks meeting the heat load
1	All electric (EH)	SEN
2	All gas (GB)	GN
3a	Gas & electric (low HP_{pen})	GN, SEN
3b	Gas & electric (high HP_{pen})	GN, SEN
4a	HTGES with EH at DHN source	DHN
4b	LTGES with EH at DHN source	DHN
5	CHP	DHN
6	LTGES and EH at final load	SEN, DHN
7	LTGES and GB at final load	GN, DHN

where $E_{\text{CHP output},e}(MWh)$ is the electrical energy output of the CHP and $EL_{\text{CHP},e}(MWh)$ the energy loss of the CHP corresponding to the electrical output of it, which is as follows:

$$EL_{\text{CHP},e} = EL_{\text{CHP,tot}}\eta_{e,\text{cHP}} / \left(\eta_{th,\text{cHP}} + \eta_{e,\text{cHP}}\right) \quad (21)$$

2.4.6 | Configuration 6: LTGES with EH at final load

The heat is supplied by LTGES through DHN source. If LTGES is not sufficient to meet all the heat load, then EHs at the final load points will meet the rest of the heat load. TP_h in this case is the summation of the electricity loads of the water pump and HP of the LTGES and the EHs at the final load points with the equations explained in 2.4.1.

2.4.7 | Configuration 7: LTGES with GB at final load

The LTGES supplies heat to the DHN source. If the total heat load is more than the heat supplied by LTGES, then the rest of the heat load will be met by GBs at the final load point. $TP_{h,\text{EN}}$ due to the electricity load of the water pump and the associated HP with the LTGES is calculated as explained in Section 2.4.1. $TP_{h,\text{GN}}$ as a result of the GBs is calculated as explained in Section 2.4.2. The total $TP_{h,\text{total}}$ is calculated using Equation (17).

2.5 | Economic and environmental evaluation

Once the technical parameters of operation of the IMVEN are calculated, the amount of energy supplied by the upstream gas and electricity networks are obtained. The next step is to calculate the economic and environmental performance parameters of the integrated networks, which is carried out by multiplying the values of the technical parameters by the corresponding unit cost and unit carbon emission factors to obtain the total operational cost and total carbon emission of the IMVEN, respectively. The values of unit cost and unit carbon emission factors are presented in Table 3. In case the heat load is met by both GN and SEN, then the economic or environmental parameter of both networks is added up to obtain the total economic or environmental parameter for meeting the electricity or heat load. As an example, the economic parameter of the IMVEN operation to meet the electricity load EcP_e(£)in configuration 5 (CHP) corresponding to Equation (20) is calculated as follows since SEN slack bus is fed by an upstream SEN and CHP is supplied by an upstream GN:

$$EcP_e = 28.1 \times E_{\text{EN,up}} - 9.5 \times \left(E_{\text{CHP output},e} - EL_{\text{CHP},e}\right) \quad (22)$$

In this study, constant values for the cost of operation of the gas and electricity networks are considered; however, it is possible to consider a profile for these operational costs since in reality the energy price, which forms part of the operational cost, may vary even during a single day.

3 | CASE STUDY

3.1 | Overview

The considered real-world case study is a small rural village in Scotland, which comprises 120 dwellings and circa 300 residents. The village benefits from a small wind farm and rooftop PVs. The data for wind and PV generation as well as the heat and electricity load (with 5-minute granularity) for a representative winter week (w/c 23 February 2015) were available and used to compare the TEE performance of the considered IMVEN configurations for meeting the heat load of the village.

3.2 | IMVEN considered

Figure 4 shows the schematic of the gas (GN), smart electricity (SEN) and district heating (DHN) networks of the village. The village was divided into six zones, each of which comprises domestic and non-domestic loads. Each of these zones corresponds to each individual final heat or electricity load point discussed in Section 2.4. The total electricity or heat load of each zone was considered as a lumped load of the zone. Also, for each zone a node/bus was considered and the lumped electricity or heat load of the zone was placed on the corresponding node/bus. It is assumed that the wind farm is connected to the SEN slack bus.

TABLE 3 Unit factors for calculation of the cost of operation and carbon emission

Parameter	GN	SEN
Operational cost (£/MWh)	9.5 [32]	28.1 [32]
Carbon emission (kgCO_2eq/MWh)	232.0 [33]	173.0 [34]

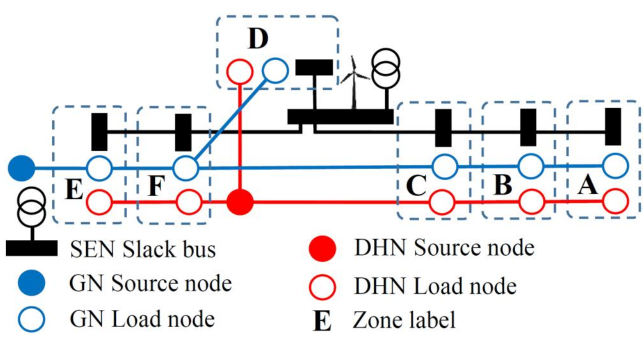

FIGURE 4 Schematic of the considered smart electricity network (SEN), gas network (GN) and district heating network (DHN)

3.3 | Scenarios description

Three scenarios were designed to address the research questions and to compare TEE performance of different IMVEN configurations.

3.3.1 | Scenario 1: Base case

In this scenario, the current and available heat and electricity loads and wind and PV generation profiles were considered.

3.3.2 | Scenario 2: High wind and PV

In this scenario, the load profiles are the same as scenario 1 (base case); however, it is assumed that the wind and PV generation levels have increased by 40% relative to scenario 1 to represent a region with high wind and PV generation levels.

3.3.3 | Scenario 3: Low wind and PV

In this scenario, it is assumed the load profiles are the same as scenario 1; however, the wind and PV generation levels are decreased by 40% relative to scenario 1 to represent a region with low wind and PV generation levels.

Scenarios 2 and 3 were considered to investigate the impact of wind and PV generation levels on the IMVEN design choices according to the specific wind and PV generation levels of a region. In all the designed scenarios, TEE performance of all the IMVEN configurations explained in Section 2.4 was evaluated. The values considered for all the parameters as well as the topology and input data of the case study are available in [31].

4 | RESULTS AND DISCUSSION

In this section, TEE performance of all the IMVEN configurations to meet the heat load of the case study in all the scenarios is presented. All the graphs and tables correspond to the operation of the IMVEN in the winter week (i.e. w/c 23 February 2015).

4.1 | TEE evaluation of scenario 1 (base case)

Figure 5[7] shows the values of TEE parameters of the scenario 1 (base case) for all the IMVEN configurations. There are negative values in configuration 5 (CHP) corresponding to electricity load since CHP was assumed to follow the heat load. Therefore, it generated surplus electricity that was exported to the upstream network (Figure 5(a)) and led to cost savings

[7]'Config.' in Figure 5 and Figure 6 denotes configuration.

(Figure 5(b)) and carbon emission savings (Figure 5(c)) for the operator of the SEN. Table 4[8] presents TEE comparison of the IMVEN configurations in the order of increase in TEE parameters (from top to bottom) based on the values shown in Figure 5. The increase in the values of TEE parameters means an increase in the dependency of the IMVENs on the upstream IMVENs, an increase in operational costs and an increase in carbon emissions.

4.1.1 | Technical evaluation

As can be seen in Table 4 in configuration 4a (HTGES with EH at DHN source), the lowest amount of energy is taken from upstream networks. This was expected since the renewable heat from HTGES ($\approx 650\, MWh$) was by far more than the heat load ($\approx 164\, MWh$) of the village and the small value of the heat load is actually the electricity load of the water pump of HTGES that was used to meet the heat load.

In the next step, configuration 3b (high penetration of HPs) imports less amount of energy from upstream networks compared to the configurations with LTGES (i.e. 4b, 6 and 7). This is due to the fact that HPs follow the heat load and thus produce the heat as much as required consuming much less amount of electricity compared to the required heat. However, LTGES produces a constant amount of heat at all times regardless of the heat load. Therefore, at times when the LTGES heat generation is less than the heat load, the rest of the heat load needs to be met using either EHs or GBs on top of the electric load of the HP and water pump associated with LTGES. Comparing LTGES configurations 4b (LTGES with EH at DHN source), 6 (LTGES with EH at final load) and 7 (LTGES with GB at final load) shows that the SEN has taken less energy from upstream to meet the heat load (configurations 4b and 6) relative to the GN (configuration 7), since the SEN benefits from renewable generation (i.e. wind and PV). Also, having the EH at DHN source (configuration 4b) leads to less energy imports from the upstream relative to having EH at the final load (configuration 6). This is because there is some electrical loss associated with EH at the final load, which is not the case when the EH is at the DHN source.

In the next step, in configuration 3a (low penetration of HPs) less energy is taken from upstream compared to configurations 1 (all electric) and 2 (all gas) since some part of the heat load is met by HPs with an electric consumption much less than the amount of heat load. In configuration 1 less energy is imported from upstream relative to configuration 2, which is due to SEN benefiting from wind and PV generation.

Finally, the highest amount of energy from upstream is in configuration 5 (CHP) since the thermal efficiency of CHP is much less than the efficiencies of EHs or GBs. Therefore, it is expected to import more energy from the upstream network to meet the heat load through CHP relative to only EHs or only GBs.

[8]'*EnP*' in Table 4 denotes environmental parameter.

4.1.2 | Economic evaluation

As expected, HTGES (configuration 4a) that meets all the heat load with renewable heat has the lowest cost of operation due to the small amount of electric load and hence cost of operation of its water pump.

In the next step, the configurations that meet the heat load through GN (3b, 7, 3a and 2) have lower operational costs compared to the configurations that meet the heat load through SEN (4b and 6) since the unit cost of operation of GN is around one-third of that of the SEN (Table 3). Among configurations 3b, 7, 3a and 2, the linear combination of energy taken from upstream and unit cost of energy in each configuration in this case study has led to the order presented in Table 4. On the other hand, configuration 4b has lower operational costs compared to configuration 6 due to the electrical losses of EH located at the final loads as explained in Section 4.1.1.

Finally, the cost of operation of configuration 1 (all electric) is more than that of configuration 5 (CHP) due to the higher operational costs associated with the electrical losses to meet the heat load.

4.1.3 | Environmental evaluation

The HTGES has the lowest carbon emissions due to the negligible amount of energy taken from upstream in this configuration due to the consumption of the water pump in this configuration.

In the next step, the configurations with greater shares of SEN (3b, 4b, 6 and 1) compared to configurations with greater shares of GN (3a, 2 and 5) for meeting the heat load produce less carbon emissions due to the renewable generation in SEN and lower unit carbon emissions factor of SEN compared to GN (Table 3). Again the linear combination of the energy taken from upstream networks and unit carbon emissions factor in this case study has led to the order of configurations presented in Table 4. Carbon emissions from CHP are greatest since the thermal efficiency of the CHP is generally less than 50%. Hence, more gas with a higher unit carbon emissions factor is consumed to meet the heat load.

4.2 | TEE evaluation of impact of wind and PV levels

Figure 6 shows the values of TEE parameters in scenarios 2 (high wind and PV) and 3 (low wind and PV) and compares them with TEE values of scenario 1 (base case) to evaluate the impact of wind and PV levels on TEE parameters. For this purpose, the scenarios are presented in the order of increase in wind and PV generation levels, i.e. scenario 3 (low wind and PV), then scenario 1 (base case) and finally scenario 2 (high wind and PV).

As can be seen in Figure 6 in the IMVEN configurations that meet the heat load only through GN, i.e. configurations 2

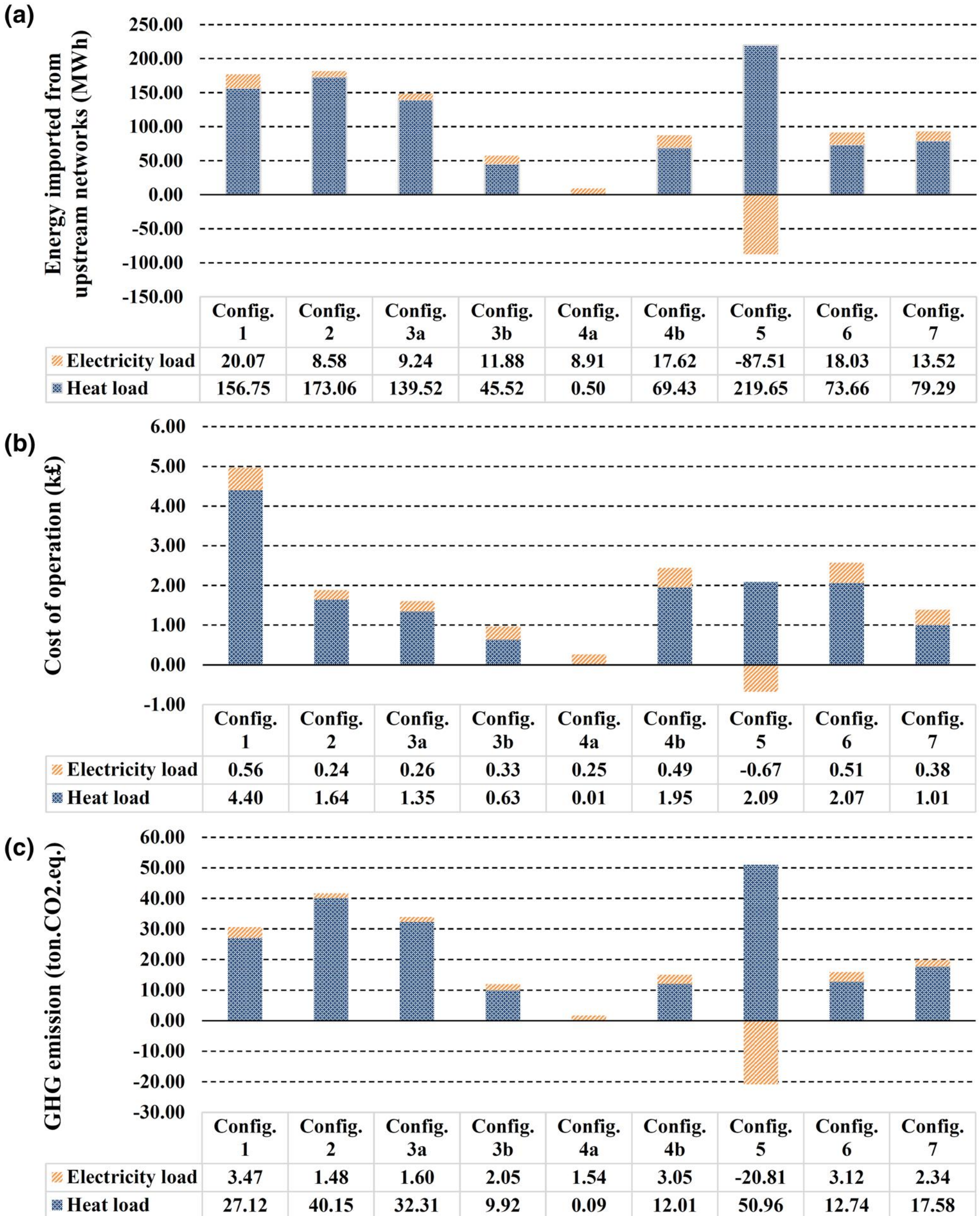

FIGURE 5 TEE parameters of the IMVEN configurations to meet the loads—scenario 1 (base case): (a) technical parameter, (b) economic parameter, and (c) environmental parameter

TABLE 4 Comparison of the IMVEN configurations in the order of ***increase from top to bottom*** in TEE parameters for scenario 1 (base case)

Energy imported from upstream (*TP*)	Cost of energy supply from upstream (*EcP*)	Carbon emission (*EnP*)
HTGES with EH at DHN source	HTGES with EH at DHN source	HTGES with EH at DHN source
Gas & electric (high HP_{pen})	Gas & electric (high HP_{pen})	Gas & electric (high HP_{pen})
LTGES with EH at DHN source	LTGES with GB at final load	LTGES with EH at DHN source
LTGES with EH at final load	Gas & electric (low HP_{pen})	LTGES with EH at final load
LTGES with GB at final load	All gas (GB)	LTGES with GB at final load
Gas & electric (low HP_{pen})	LTGES with EH at DHN source	All electric (EH)
All electric (EH)	LTGES with EH at final load	Gas & electric (low HP_{pen})
All gas (GB)	CHP	All gas (GB)
CHP	All electric (EH)	CHP

(all gas) and 5 (CHP), increasing wind and PV levels has no impact on the TEE parameters since there is no energy conversion from SEN to GN. However, in the rest of the configurations increasing wind and PV levels decreases the amount of energy imported from upstream (technical parameter), decreases operational costs (economic parameter) and decreases the amount of carbon emission (environmental parameter). In configuration 3a (low penetration of HPs), increasing renewable generation levels has slightly decreased TEE parameters since most of the heat load is met by the GN and only 20% of it is met by the SEN.

4.3 | TEE comparison of all the IMVEN configurations in all the scenarios

In this section, the impact of wind and PV generation levels on the design choice of the future energy system for the case study is investigated. This has been carried out to support the most efficient, cost effective and least carbon-intensive combination of networks to meet the heat load of the case study according to the ambient wind and PV levels of it. For this purpose, the TEE parameters of all the IMVEN configurations for all the scenarios have been ranked in Table 5 for technical parameter, in Table 6 for economic parameter and in Table 7 for environmental parameter in ascending order[9]. Similar to Figure 6, the columns of these tables are in the order of scenario 3 (low wind and PV), scenario 1 (base case) and scenario 2 (high wind and PV) to study the impact of increasing wind and PV levels on TEE ranking of the configurations.

4.3.1 | Technical comparison

As can be seen in Table 5, configurations 4a (HTGES), 3b (high HP penetration) and 4b (LTGES with EH at DHN source), respectively, are the configurations with the lowest technical parameter regardless of an increase in wind and PV levels. Then, in low wind and PV levels configuration 7 (LTGES with GB at final load) has lower technical parameter compared to configuration 6 (LTGES with EH at final load). However, in medium and high wind and PV levels, configuration 6 has lower technical parameter than configuration 7, which is due to importing less energy from upstream networks as a result of more available renewable generation. Afterwards, the configurations 3a (low HP penetration), 1 (all electric) and 2 (all gas) are in increasing order for the technical parameter regardless of an increase in the wind and PV levels. Finally, configuration 5 (CHP) has the highest technical parameter compared to all the configurations regardless of an increase in wind and PV levels.

[9]For the purpose of brevity, only the label of the configurations has been mentioned in Tables 5–7 and the description of the configurations can be found in Table 2.

4.3.2 | Economic comparison

Table 6 shows that configurations 4a (HTGES), 3b (high HP penetration), 7 (LTGES with GB at final load) and 3a (low HP penetration), respectively, are the configurations with the lowest economic parameters regardless of an increase in wind and PV levels. Following this, for low wind and PV levels, the configurations more reliant on GN, i.e. 2 (all gas) and 5 (CHP), have lower economic parameter relative to the ones more reliant on SEN, i.e. 4b (LTGES with EH at DHN source) and 6 (LTGES with EH at final load). However, at high wind and PV levels, the configurations more reliant on SEN, that is, 4b and 6, have lower economic parameters compared to the configurations more reliant on GN, that is, 2 and 5, due to the availability of renewable generation. Finally, configuration 1 (all electric) has the highest economic parameter regardless of an increase in wind and PV levels.

4.3.3 | Environmental comparison

As can be seen in Table 7, increasing the wind and PV levels has no impact on the order of the configurations from the environmental parameter point of view. The environmental parameter increases in the order of the configurations 4a (HTGES), 3b (high HP penetration), 4b (LTGES with EH at DHN source), 6 (LTGES with EH at final load), 7 (LTGES with GB at final load), 1 (all electric), 3a (low HP penetration), 2 (all gas) and 5 (CHP), respectively, regardless of an increase in wind and PV levels. This is due to the fact that the environmental parameter of each configuration decreases almost proportionally to the environmental parameter of the rest of the configurations by increasing the wind and PV levels (Figure 6(c)). Therefore, all the configurations are in the same order in the rank regardless of an increase in wind and PV levels. This proportional decrease in the environmental parameter is true for all the configurations except 3a, 2 and 5, which have the highest fixed value of environmental parameter and are, respectively, the last configurations in all the ranks.

4.3.4 | Summary

To summarise this subsection, configuration 4a (HTGES) has by far the lowest TEE parameters relative to all the other configurations regardless of an increase in wind and PV levels due to the renewable, cost- and carbon-free heat from HTGES. Then, configuration 3b (high HP penetration) has higher TEE parameters compared to HTGES. On the other hand, configurations 2 (all gas) and 5 (CHP), respectively, have the highest technical and environmental parameters and configuration 1 (all electric) has the highest economic parameter regardless of an increase in wind and PV levels. Finally, the rest of the configurations are somewhere within the TEE rank based on the linear combination of the technical parameter for this specific case study and unit cost and unit carbon emission factors.

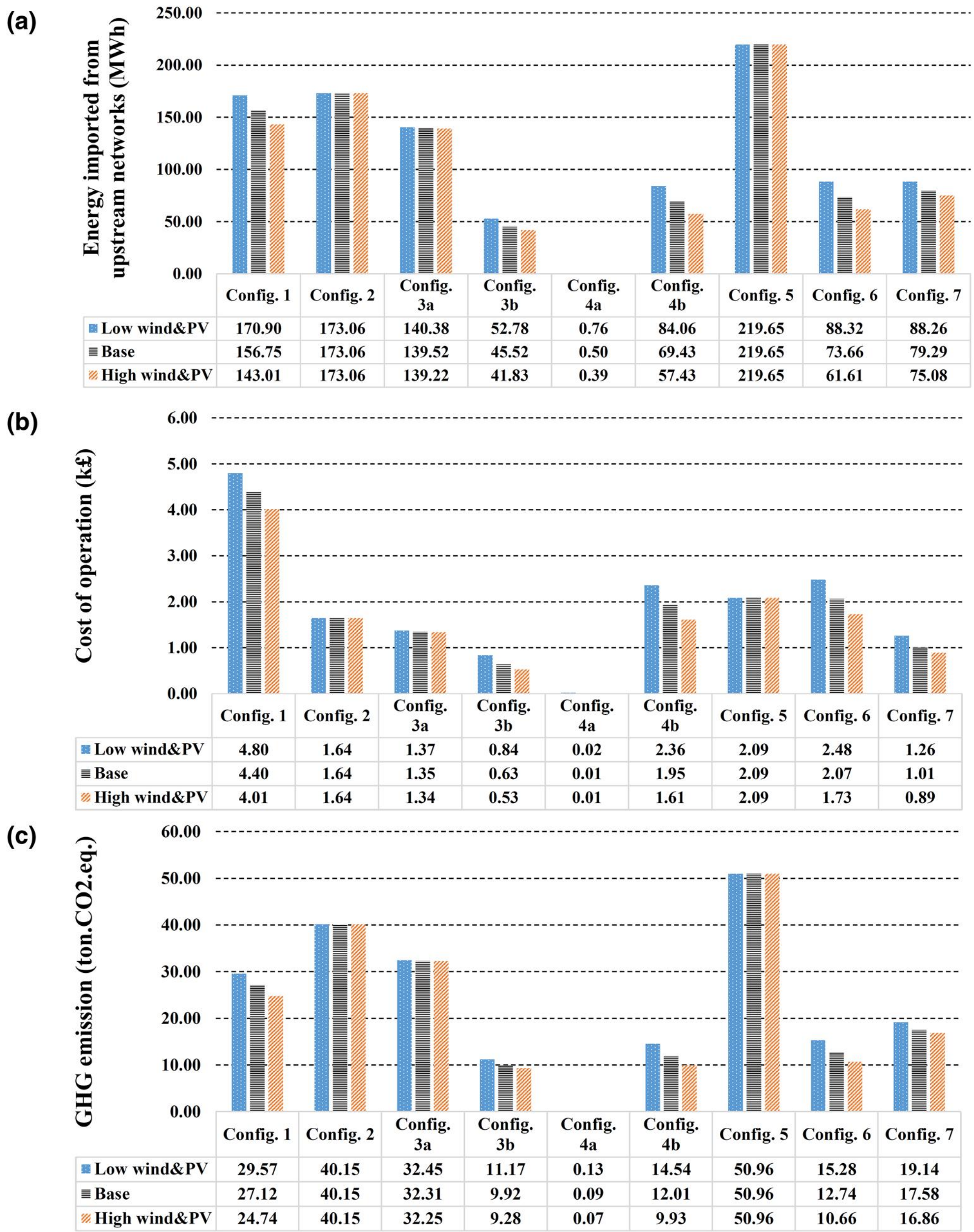

FIGURE 6 TEE evaluation of the impact of wind and PV generation levels from all the scenarios: (a) technical parameter, (b) economic parameter and (c) environmental parameter

TABLE 5 Order of IMVEN configurations based on ***increase from top to bottom*** in the technical parameter

Low wind and PV	Base case	High wind and PV
4a	4a	4a
3b	3b	3b
4b	4b	4b
7	6	6
6	7	7
3a	3a	3a
1	1	1
2	2	2
5	5	5

TABLE 6 Order of IMVEN configurations based on ***increase from top to bottom*** in the economic parameter

Low wind and PV	Base case	High wind and PV
4a	4a	4a
3b	3b	3b
7	7	7
3a	3a	3a
2	2	4b
5	4b	6
4b	6	2
6	5	5
1	1	1

TABLE 7 Order of IMVEN configurations based on ***increase from top to bottom*** in the environmental parameter

Low wind and PV	Base case	High wind and PV
4a	4a	4a
3b	3b	3b
4b	4b	4b
6	6	6
7	7	7
1	1	1
3a	3a	3a
2	2	2
5	5	5

4.4 | Computational effort

The TEE framework was developed and implemented in MATLAB [35]. The simulation results were obtained by running the framework on a PC with Intel Core i5-6600 3.30 GHz, CPU and 16 GB RAM and Windows 10 operating system. The average computation time was within the range from 3 to 7 minutes for the simulation of one week (with 5-minute time steps) of all the IMVEN configurations for every scenario, respectively.

5 | Discussion

According to the presented results, it was seen that the TEE evaluation framework developed in this study is:(i) a valid and useful tool to evaluate integration of GES in IMVENs; and (ii) able to quantify the performance of several IMVEN configurations to meet the heat load of a region in terms of TEE parameters. The framework helped to address the research questions for the study as follows:

- Two most common types of GES, i.e. LTGES and HTGES, were explained (Section 2.3.4) and their model was integrated within the TEE evaluation framework.
- Impact of LTGES and HTGES on operation of IMVENs to meet the heat load was investigated through several IMVEN configurations, in most of which LTGES and HTGES were the most important contributors (Table 2).
- The most efficient, cost effective and least carbon-intensive configuration is to use HTGES, where the renewable, cost- and carbon-free heat from GES can be used to meet the heat load. If this is not possible the next most efficient, cost effective and least carbon-intensive option is the high penetration of HPs.
- The impact of wind and PV generation levels on TEE performance of IMVENs to meet the heat load was studied. It was observed that increasing wind and PV levels decreases the TEE parameters in the configurations that include SEN as one of the networks to meet the heat load. Therefore, in case of meeting the heat load by only GB or CHP, the variation of wind and PV levels had no impact on TEE parameters. Also, in the case of low penetration of HPs it was observed that increasing the wind and PV levels slightly decreased TEE parameters (Figure 6).
- The impact of wind and PV levels on TEE comparison of design choices was investigated to find the most efficient, cost-effective and least carbon-intensive one (Tables 5–7). HTGES has by far the lowest TEE parameters relative to all the other configurations regardless of the increase in wind and PV levels due to the reason explained before. Then, high penetration of HPs has the lowest TEE parameters compared to the rest of the configurations. On the other hand, CHP configuration, respectively, has the highest technical and environmental parameters and all electric configuration has the highest economic parameter regardless of the increase in wind and PV levels.

It should be noted that the conclusions made based on the presented results are specific to this case study with the available load and LCESs' generation profiles. However, the TEE framework developed in this study can be applied to any other distribution or transmission case study to explore the TEE performance of different IMVEN configurations to meet the heat load to support the most efficient, cost-effective and least carbon-intensive design choice for any particular region according to the specific levels of energy generation from LCESs, including GES, wind and PV, of that region.

It is important to clarify the following two points:

- The future load scenarios can be considered by changing the input profiles of the electricity and heat loads; however, the change in the shape and amplitude of load profiles depend on the case study and the research questions that are investigated (future decarbonisation scenarios, for example). Hence, the input load profiles can be changed to represent any desirable future scenario.
- This framework is an off-line framework to be used to evaluate the TEE parameters of different IMVEN configurations to meet the heat load of a region based on any load and renewable generation profiles (whether historical or forecasted data). This means that the framework can use the forecasted profiles of loads and generations and consequently evaluate the TEE parameters of future operational scenarios; or use historical data to evaluate the TEE parameters corresponding to this operational scenario corresponding to these historical data.

6 | CONCLUSIONS AND FUTURE WORK

To enable deployment of SMEGs, a framework was developed to evaluate the operation of IMVENs from TEE point of view to meet the heat load of a region. The most common types of GES including HTGES and LTGES were simulated and integrated within the framework. TEE performance of several IMVEN configurations, in most of which HTGES and LTGES were contributors, was assessed. The TEE impact of wind and PV generation levels was evaluated by applying the framework on the available data from a real-world rural area in Scotland. The key findings of this research and the case study, are as follows:

- The most efficient, cost-effective and least carbon-intensive configurations to meet the heat load are HTGES, high HP penetration and LTGES, respectively (Table 4).
- Increasing wind and PV levels: (i) decreases the TEE parameters in configurations relying on SEN to meet heat load; and (ii) has no impact on the TEE parameters in configurations relying on GN to meet the heat load (Figure 6).
- Technical comparison of the impact of increase in wind and PV levels on the order of the configurations to meet the heat load shows that HTGES, high penetration of HPs and LTGES with EH at DHN source, respectively, are the configurations with the lowest technical parameter regardless of the increase in wind and PV levels (Table 5).
- Economic comparison of the impact of increase in wind and PV levels on the order of the configurations to meet the heat load shows that HTGES, high HP penetration, LTGES with GB at final load and low HP penetration, respectively, are the configurations with the lowest economic parameter regardless of the increase in wind and PV levels (Table 6).
- Environmental comparison of the impact of increase in wind and PV levels on the order of the configurations to meet the heat load shows that the order of the configurations is as follows regardless of the increase in wind and PV levels: HTGES, high HP penetration, LTGES with EH at DHN source, LTGES with EH at final load, LTGES with GB at final load, all electric, low HP penetration, all gas and CHP (Table 7).

Based on the simulation results, the framework is a valid and generic tool to quantify the amount of energy imported from upstream networks, operational costs (i.e. cost of supplying energy from upstream networks) and carbon emissions for any transmission or distribution case study with any IMVEN configurations. Moreover, it provides a basis to make well-informed decisions to support the most efficient, cost-effective and least carbon-intensive design choice according to the generation levels of LCESs, including GES, wind and PV, of a region to meet the heat load of it. Also, the possible benefits of implementation of the TEE evaluation framework include: (i) using the framework to design different components of the heat supply system including HPs and CHPs according to TEE objectives; (ii) comparing available and future scenarios for meeting the heat load in order to make informed decisions; (iii) smartening the overall energy system (IMVEN) by implementing a layer of control and management over the framework to perform control of IMVENs of the region; and (iv) developing business models to deploy the most suitable configuration for heat supply to a region.

Future work includes: (i) application of the TEE framework to a wider region and national level; (ii) inclusion of the storage devices in all the networks and investigating interactions between networks; and (iii) investment planning together with optimal scheduling of the coupling components and storage devices.

ACKNOWLEDGEMENTS

This work has been funded by EPSRC National Centre for Energy Systems Integration (CESI) (grant number: EP/P01173/1).

The authors would like to acknowledge the support from the Institute for Sustainable Building Design at Heriot Watt University, a partner of CESI, for providing the data of the case study.

CONFLICT OF INTEREST

None.

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How to cite this article: Hosseini SHR, Allahham A, Adams C. Techno-economic-environmental analysis of a smart multi-energy grid utilising geothermal energy storage for meeting heat demand. *IET Smart Grid*. 2021;4:224–240. https://doi.org/10.1049/stg2.12020