Graphical Abstract

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Highlights

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- A framework for evaluating the Technical, Economic, and Environmental (TEE) impacts of operation of Integrated Gas and Electricity Distribution Networks (IGEDN), was developed;
- Networks inter-dependencies and all the parameters affecting the TEE performance of IGEDN were considered in the framework;
- Both single-vector storage and vector-coupling storage devices have been considered in the TEE evaluation framework;
- Impact of storage configuration on the TEE performance of IGEDN was investigated.

Techno-Economic-Environmental Evaluation Framework for Integrated Gas and Electricity Distribution Networks Considering Impact of Different Storage Configurations

Seyed Hamid Reza Hosseini^a, Adib Allahham^a, Vahid Vahidinasab^a, Sara Louise Walker^a and Phil Taylor^{a,b}

^a*School of Engineering, Newcastle University, Newcastle upon Tyne NE1 7RU, UK*

^b*Pro Vice-Chancellor for Research and Enterprise, University of Bristol, Bristol BS8 1QU, UK*

ARTICLE INFO

Keywords:

Vector-Coupling Storage
Power-to-Gas
Single-Vector Storage
Integrated Gas and Electricity
Distribution Networks
Techno-Economic-Environmental
Renewable Energy Sources

Abstract

This paper presents an evaluation framework for Techno-Economic-Environmental (TEE) performance of the Integrated Gas and Electricity Distribution Networks (IGEDN). The proposed framework is based on a coupled gas and electric load flow model, facilitating the consideration of all the parameters affecting the operation of IGEDN, such as different gas mixtures, gas temperature, pipeline characteristics and the electricity network topology. This framework can assess the impact of different storage configurations, different levels of Renewable Energy Sources (RESs) and different levels of energy demand on the amount of imported energy from the upstream networks, operation costs and emissions of the IGEDN. The evaluation framework can perform the TEE operational analysis of future scenarios of IGEDN through various coupling components and storage devices including Single-Vector Storage (SVS) as well as Vector-Coupling Storage (VCS) devices to provide a basis for well-informed design choices for meeting the Greenhouse Gas (GHG) reduction targets. The TEE evaluation framework is tested on a real-world case study from a rural area in Scotland, and analysed from different aspects, to show the effectiveness of the model for analysis of the interactions of gas and electricity distribution networks. The results reveal that integrated operation of the gas and electricity networks improves all the considered technical, economic and environmental parameters.

1. Introduction

Governments around the world are working hard to reduce their Greenhouse Gas (GHG) emissions. In the UK, the government has set a target of “Net Zero” GHG emissions by 2050 in order to reduce contribution to global warming [1]. This necessitates the integration of more Renewable Energy Sources (RESs) into the energy networks and consequently reduction in the use of fossil fuels while meeting and reducing energy demand.

To achieve the aforementioned objective flexibly and reliably, it may be necessary to couple the energy networks using several network coupling components such as gas turbine (GT), power-to-gas (P2G) and Combined Heat and Power (CHP) [2]. Also, the energy networks may benefit from different types of Energy Storage Systems (ESSs) in order to be able to compensate for any energy carrier deficit or other constraints in energy supply in any of the networks [3].

1.1. Aims and Objectives

In order to comprehensively study multi-vector integrated energy systems and analyse ESS potentials, a Techno-Economic-Environmental (TEE) evaluation framework needs to be designed to investigate the mutual impacts of each of the networks on the operational, economic and environmental performance of others. This is the main aim of this study.

In this paper, ESSs are divided into two different categories of Single-Vector Storage (SVS) and Vector-Coupling Storage (VCS). The SVS refers to a storage device which is charged and discharged through one single vector (e.g. gas or electricity). Whereas, the VCS refers to a storage device which is charged by one of the vectors and discharges into the other vector. In other words, the VCS is at the interface of the two integrated networks and forms part of the coupling between the two networks.

A conceptual representation of these storage devices in an Integrated Gas and Electricity Distribution Networks (IGEDN) is demonstrated in Fig. 1.

Once the framework is developed then the performance of the future scenarios of the energy system can be assessed in terms of security, sustainability and affordability, namely the elements of the energy trilemma. In this way, the basis for well-informed design choices for meeting the GHG reduction targets is provided.

1.2. Literature Review

EnergyPLAN [4] and LUT-EST models [5–7] have been used to perform planning of the whole energy system of a few regions, namely Finland [4], India [5], Iran [6] and Europe [7] considering all the layers of the energy system from energy resources, energy transmission and distribution. Based on the documentation of EnergyPLAN [8] and LUT-EST model [9] these models do not perform a detailed operational analysis to ensure the integrated networks are operable and network constraints are not violated.

Different types of energy storage in multi-vector energy networks have been investigated at the hub level to perform techno-economic [10–15] or TEE [16–19] analyses. However, only a few of these references have studied the impact of the capacity of storage devices on technical [17], economic [10, 18] or techno-economic [16] parameters of the hub. Nevertheless, hub level analysis does not consider the detailed operation of the network to ensure the network is physically operable and will meet the load without violation of operational constraints.

On the other hand, references on operational analysis of integrated energy networks with storage at a detail network level have only carried out technical [20, 21] or techno-economic [22–27] analysis. None of these papers has performed an environmental analysis. Also, none of these research works has evaluated the impact of different storage configurations

*Corresponding author: Phil Taylor (E-mail: phil.taylor@newcastle.ac.uk)
ORCID(s):

Figure 1: A Conceptual Representation of the SVS and VCS devices in an Integrated Gas and Electricity Distribution Network.

Table 1
Positioning the contributions of this paper compared to the available literature.

Reference	Network Level Details	Single-Vector Storage	Vector-Coupling Storage	Environmental Analysis	TEE Impact of Storage
[4]	x	✓	x	✓	x
[5–7]	x	x	✓	x	x
[10, 13–15]	x	✓	x	x	x
[11, 12]	x	x	✓	x	x
[16–19]	x	✓	x	✓	x
[20–27]	✓	✓	x	x	x
This paper	✓	✓	✓	✓	✓

¹ on the TEE parameters of integrated gas and electricity networks. The other aspect that is not considered in the aforementioned references is the evaluation of the impact of different storage configurations on the TEE parameters. The framework presented in this paper can help in validating the solutions developed in these references in terms of the amount of imported energy from upstream networks, the operation costs and the emissions of IGEDN. In addition, since the framework is based on a more detailed model, it enables consideration of all the parameters affecting the operation of IGEDN, including various storage configurations as well as different percentages of gas mixtures, gas temperature, characteristics of the pipelines, and the electrical network topology and parameters.

Furthermore, there are several other references, such as [28–30], that have investigated either design or operational planning of different energy conversion/storage technologies in a single energy vector (usually electricity). Although, these references have considered the point(s) of connection to the other energy vector(s), i.e. gas or heat networks, they have not considered the operation of those other coupled energy network(s). It is to be noted that considering the main research direction of this paper, only the references on more than one energy vector have been reported and summarised here and the papers on a single energy vector have not been considered.

In brief, a taxonomy of previously published works in the area is presented in Table 1 which highlights the main

contributions of the current work.

1.3. Research Gap

The aforementioned literature review on the integrated energy networks including storage demonstrates that the following gaps need to be further investigated:

- Previous works on detailed network level operational analysis has only performed a techno-economic analysis and the environmental analysis is not yet considered.
- Previous work has not investigated the impact of different storage configuration, including types and capacities, on the TEE parameters of the networks.
- Previous work has not studied the impact of single-vector storage and vector-coupling storage, simultaneously.

1.4. Contributions

According to the identified gaps, the main contributions of this paper can be summarized as follows:

- * Development of an evaluation framework to investigate the performance of IGEDN in terms of the energy trilemma, to assess the environmental-techno-economic performance of IGEDN, through network level detailed operational analysis model.
- * A precise model is developed of IGEDN to consider the inter-dependency of the networks and at the same time all the parameters affecting the TEE performance of the integrated networks.

¹The term "storage configurations" refers to the type and capacity of them.

Figure 2: Algorithm of the proposed TEE evaluation framework.

- * Application of the framework allows to evaluate the impact of different storage configurations on the TEE performance of IGEDN.
- * Evaluation of the impact of including both of SVS and VCS devices for better integration of the networks.

The proposed framework will enable researchers and decision-makers to assess future energy scenarios in terms of TEE parameters and hence make well-informed design choices for the energy system to meet specific GHG reduction targets. The framework will also help in addressing the following questions:

- i) What are the TEE benefits of the integrated operation of gas and electricity distribution networks with storage in both networks?
- ii) How does the variation of storage configurations impact the TEE parameters of IGEDN?
- iii) How do load profiles and renewable generation profiles impact the TEE performance of IGEDN?

1.5. Organisation of the Paper

The rest of the paper is structured as follows. Section 2 describes the proposed TEE evaluation framework. The case study and description of the developed scenarios are reported in Section 3. Results and discussions on the case studies are explained in Section 4. Finally, the conclusion and future works are presented in Section 5.

2. The Proposed TEE Evaluation Framework

In this section, the proposed TEE evaluation framework for investigating the performance of an IGEDN in terms of the energy trilemma is presented.

2.1. Definition of the TEE Parameters

A) Technical parameter: The technical parameter is represented by the amount of energy imported from the upstream network (here, transmission level) into the distribution networks. Integration of operation of the gas and electricity networks (with considering the storage devices) help the

networks to be more self-sufficient and as a result import less energy from upstream, which therefore imposes less losses on the transmission level. Consequently, the level of security of supply and the independence of the local distribution network from the upstream network can be evaluated, as can the impact of ESS and RESs. This technical parameter can be an index for the network operators for more integration of the distribution networks, more incorporation of storage and more local use of RESs at distribution level.

B) Economic parameter: The economic parameter is represented by operation cost of the energy system, which is determined based on the amount of money paid to purchase the energy carriers from the transmission networks. In this paper, the economic evaluation quantifies the cost-saving resulting from more integration of the distribution networks and more utilisation of storage and local RESs in the distribution level.

C) Environmental parameter: The environmental parameter is represented by the amount of CO₂ equivalent emitted as a result of the final use of energy that has been transported in the distribution network, which is directly related to the amount of energy imported from the upstream network. The environmental evaluation quantifies the amount of reduction in GHG emission as a result of more integration of the distribution networks, storage and local RESs in distribution level.

Once the TEE parameters are calculated, a multi-dimensional performance evaluation of the IGEDN is therefore done based on the amount of energy imported from the upstream (technical evaluation), the cost of operation of the network (economic evaluation) and the amount of GHG emission from the distribution network (environmental evaluation).

2.2. Algorithm of the TEE Evaluation framework

The infographic of the proposed TEE evaluation framework is shown in Fig. 2 and described as follows. As it can be seen, the inputs to the framework include the topology, load, generation and storage specifications of the gas and electricity distribution networks, thermal properties of the components of the natural

gas mixture, the efficiency of the coupling component (here, P2G) and the unit parameters for economic and environmental evaluation.

The TEE analysis is then performed based on a gas and electric load flow engine which: (i) performs the power flow analysis of the electricity network using the MATPOWER toolbox [31] in MATLAB [32]; (ii) implements a storage management system in order to determine the action needed to be taken to store any possible surplus of RESs, such as the use of the electricity storage, or the use of P2G and VCS; and (iii) performs the gas flow analysis. Once the operation of the IGEDN is determined the TEE parameters are calculated.

The outputs of the algorithm are the technical, economic and environmental parameters of the gas and electricity networks operation.

2.3. Mathematical Representation of the Gas and Electric Load Flow Engine

A gas and electric load flow engine was developed for operational analysis of gas and electricity networks with gas and electricity storage in both networks. The steady-state representation of AC power flow in the electricity network and gas flow in the gas network were formed and solved using the Newton method. The two networks were soft-linked in order to obtain a coupled gas and electricity network model. The details of the equations are presented in the following subsections.

2.3.1. Model of the Electricity Network

The equations for balance of active and reactive power flow at each bus of the electricity network (except the point of common coupling (PCC), i.e. the slack bus²) in electric power flow problem, are shown in equations (1) and (2), respectively [33]:

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

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

where P_{G_i} is the net active power generation and P_{L_i} 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 Y_{BUS} corresponding to the i th row and j th column. Also, Q_{G_i} is the net reactive power generation and Q_{L_i} is the net reactive load at bus i , $|V_i|$ and $|V_j|$ are voltage magnitude of the two ends of the branch ij (i.e. from bus i to bus j) and δ_i and δ_j are Voltage angle of the two ends of the branch ij , respectively.

There is PV generation at some buses of the network, but as the values of these PV generations are known, therefore, in this study, all the buses of the network are considered as PQ type buses. Also, a balanced load on the three phases of the electricity distribution network has been considered, which is reasonable for the purpose of scope of this paper. Once the aforementioned set of nonlinear power flow equations is solved, the values of the voltage magnitudes and angles of all the buses, as well as the active and reactive power flow of all the lines of the network, are determined.

²In this paper, the PCC is selected to be the connection point of the electricity network of the IGEDN to the electricity transmission network.

2.3.2. Model of the Gas Network

The gas flow balance equation at each node of the gas network is as follows:

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

where $\sum_j q_{j,in}$ is the sum of all gas flows entering node j from its connected branches, $\sum_j q_{j,out}$ is the sum of all the gas flows leaving node j from its connected branches, and $q_{L,j}$ (m^3/h) is the gas load at node j .

The gas load at node j , is calculated based on the heat load of the node as follows:

$$q_{L,j} = \frac{P_{h,j}}{GCV_{mix} \eta_b} \quad (4)$$

where $P_{h,j}$ is the heat load (kW) at node j , GCV_{mix} is the gross calorific value of gas mixture (kJ/m^3) and η_b is the efficiency of gas boiler.

GCV_{mix} is calculated using the Gross Calorific Values (GCV_i) and molar fractions (X_i) of the components of natural gas mixture as follows [34]:

$$GCV_{mix} = \frac{\sum_{i=1}^{N_c} (X_i GCV_i)}{Z_{mix}} \quad (5)$$

where N_c is the total number of components of the gas mixture and Z_{mix} is the compressibility factor of the gas mixture which will be calculated using the Equation (11).

The general flow equation was used for calculating the gas flow in the branches of the gas network as follows (assumptions and simplifications are summarised in [35]):

$$q_k = \pi \sqrt{\frac{R_{air}}{8} \frac{T_n}{p_n}} \sqrt{\frac{(p_i^2 - p_j^2) D^5}{f S_{mix} L T Z_{mix}}} \quad (6)$$

where q_k is the gas flow in branch k , R_{air} is air constant, T_n is the standard temperature ($T_n = 288.15K$ [35]), p_n is the standard pressure ($p_n \approx 0.1 MPa$ [35]), p_i is pressure at node i , D is pipe diameter, f is friction factor, S_{mix} is specific gravity of the gas mixture, L is length of the pipe and T is temperature of the gas.

Friction factor f is calculated based on the value of the Reynolds number (Re) of the gas flow:

$$Re = \frac{D v \rho_{mix}}{\mu_{mix}} \quad (7)$$

where the value of the velocity of the gas flow (v) is calculated using the pipe cross sectional area (A) as follows:

$$v = \frac{q}{A} = \frac{q}{(\pi/4) D^2} \quad (8)$$

and the value of density of the gas mixture (ρ_{mix}) is calculated using:

$$\rho_{mix} = S_{mix} \rho_{air} \quad (9)$$

where the specific gravity of the gas mixture (S_{mix}) is as follows [34]:

$$S_{mix} = \frac{Z_{air} \sum_{i=1}^{N_c} (X_i M_i)}{M_{air} Z_{mix}} \quad (10)$$

and the value of compressibility factor of the gas mixture (Z_{mix}) is obtained by [34]:

$$Z_{mix} = 1 - \left(\sum_{i=1}^{N_c} (X_i c_i) \right)^2 \quad (11)$$

Also, the value of dynamic viscosity of the gas mixture (μ_{mix}) is computed as follows [36]:

$$\mu_{mix} = \frac{\sum_{i=1}^{N_c} (X_i \mu_i M_i^{0.5})}{\sum_{i=1}^{N_c} (X_i \cdot M_i^{0.5})} \quad (12)$$

where ρ_{air} is the density of air at standard temperature and pressure condition (STP), Z_{air} is compressibility factor of air at STP, M_i is molar mass of the component i in the gas mixture, M_{air} is molar mass of air, c_i is the summation factor (based on the standard ISO 6976:1995 [34]) and μ_i is the dynamic viscosity of the component i in the gas mixture.

By substituting the equation (11) in (10), then (10) in (9) and replacing the equations (8), (9) and (12) in (7), the equation for calculation of Reynolds number, after some simplifications, will be as follows:

$$Re = \left(\frac{\rho_{air}}{(\pi/4)} \right) \left(\frac{S_{mix}}{D} \right) \left(\frac{\sum_{i=1}^{N_c} (X_i M_i^{0.5})}{\sum_{i=1}^{N_c} (X_i \mu_i M_i^{0.5})} q \right) \quad (13)$$

Once the value of the Reynolds number is calculated, the value of the friction factor (f) can be calculated based on the regime of the flow as follows:

1) Laminar Flow ($Re < 2300$):

$$f = \left(\frac{64}{Re} \right) \quad (14)$$

2) Turbulent Flow ($Re > 4000$): In this case, which frequently happens in gas networks, the friction factor is calculated using Colebrook's equation:

$$\frac{1}{\sqrt{f}} = -2 \log_{10} \left(\frac{\epsilon/D}{3.7} + \frac{2.51}{Re \sqrt{f}} \right) \quad (15)$$

where ϵ is the roughness of the internal surface of the pipe.

Solution of the model of the gas network: Table 2 shows the summary of all the parameters and variables of the model of the gas network. Also, the flowchart of the algorithm developed for solution of the model of the gas network is presented in Fig. 3. As can be seen in Fig. 3, once the known parameters are input to the algorithm, the procedure starts by guessing values for the nodal pressures. Then, for every branch, these steps are carried out in order:

- A guess value for q , the flow of the branch, is considered.
- The value of Re , Reynolds number of the flow, is calculated using equation (13).
- The value of f , friction factor, is calculated using either equations (14) or (15) depending on the regime of the flow.
- The value of q is updated using equation (6).
- This process is iterated until convergence of the value of q .

Once the values of gas flow of all the branches are calculated as aforementioned, these values are substituted in the set of equations (3). If the set of equations (3) have not converged, then the Newton method is used to update the values of nodal pressures. Afterwards, the aforementioned steps for calculation of the values of gas flow of the branches is repeated. The process of update of the nodal pressures and consequently update of the gas flows of the branches is iterated until the set of equations (3) converges. At this point, the final values of nodal pressures and gas flow of the branches are considered as the solution of the problem.

2.3.3. Model of Vector-Coupling Components

Vector-coupling components, including P2G and VCS, are able to couple the gas and electricity networks in such a manner that the device can be charged by the surplus generation (especially from RESs) in electricity vector and discharged into the gas vector.

A) Model of P2G: The equation used for correlating the power consumption of the P2G unit and the gas flow production is [37]:

$$q_{P2G} = \frac{\eta_{P2G} * P_{P2G}}{GCV_{mix}} \quad (16)$$

in which: q_{P2G} is the gas flow production, P_{P2G} is active power consumption in the P2G and η_{P2G} is the efficiency of P2G, respectively.

B) Model of VCS: The state of stored energy in VCS is defined by the level-of-gas (LoG_{VCS}) and defined as:

$$LoG_{VCS} = \frac{V_{VCS}^{Available}}{C_{VCS}} * 100 (\%) \quad (17)$$

where $V_{VCS}^{Available} (m^3)$ is the amount of gas available in the VCS and $C_{VCS} (m^3)$ is the capacity of the VCS. The change in the level-of-gas of the VCS (ΔLoG_{VCS}) during time step t with the length $\Delta t(h)$ is as follows:

$$\Delta LoG_{VCS} = \frac{q_{i/o} \Delta t}{C_{VCS}} \quad (18)$$

where $q_{i/o} (m^3/h)$ is the input/output gas flow into/out of VCS during the time period Δt .

2.3.4. Model of the SVS Devices

The SVS, in this research, refers to a storage device which is charged and discharged through one single vector, i.e. electricity (SVS_E) or gas (SVS_G). Here, the state-of-charge of the electricity storage (SoC_{SVS_E}) as a SVS is defined as:

$$SoC_{SVS_E} = \frac{E_{SVS_E}^{Available}}{C_{SVS_E}} * 100 (\%) \quad (19)$$

in which $E_{SVS_E}^{Available}$ (MWh) is the amount of available energy and C_{SVS_E} (MWh) is the capacity of the electricity SVS storage, respectively. The change in the state-of-charge of the electricity storage (ΔSoC_{SVS_E}) during the time step t with the length $\Delta t(h)$ was calculated using:

$$\Delta SoC_{SVS_E} = \frac{E_{SVS_E}^{Charge/Discharge}}{C_{SVS_E}} \quad (20)$$

in which $E_{SVS_E}^{Charge/Discharge}$ (MWh) is the amount of charged or discharged energy from the SVS_E during the time step t with the length $\Delta t(h)$.

Figure 3: Algorithm developed for solution of the model of the gas network.

Table 2

A summary of all the parameters and variables of the model of the gas network.

The known input parameters	The calculated variables
η_b : efficiency of gas boiler	$\sum_j q_{j,in}$: sum of all gas flows entering node j
GCV_i : gross calorific value of the components of natural gas mixture	$\sum_j q_{j,out}$: sum of all the gas flows leaving node j
X_i : molar fractions of the components of natural gas mixture	$q_{L,j}$: gas load at node j
N_c : total number of components of the gas mixture	$P_{h,j}$: heat load at node j
R_{air} : air constant	GCV_{mix} : gross calorific value of gas mixture
T_n : standard temperature	Z_{mix} : compressibility factor of the gas mixture
p_n : standard pressure	q_k : gas flow in branch k
D : pipe diameter	p_i : pressure at node i
L : length of the pipe	f : friction factor
T : temperature of the gas	S_{mix} : specific gravity of the gas mixture
A : pipe cross sectional area	Re : the Reynolds number
ρ_{air} : density of air at STP	v : velocity of the gas flow
Z_{air} : compressibility factor of air at STP	ρ_{mix} : density of the gas mixture
M_i : molar mass of the component i in the gas mixture	μ_{mix} : dynamic viscosity of the gas mixture
M_{air} : molar mass of air	
c_i : summation factor	
μ_i : dynamic viscosity of the component i in the gas mixture	
ϵ : roughness of the internal surface of the pipe	

2.3.5. Storage Management

The pseudo-code of the algorithm of the developed framework for the management of both SVS and VCS devices is presented in Algorithm 1. As can be seen, at first, power flow is performed in the electricity network and accordingly, the required energy (E_{RQD}) from the PCC is calculated. Now, the E_{RQD} is compared with the available generation from RESs. If generation from RESs is smaller than the E_{RQD} , then the RESs and the available storage in the electricity side meet all or part of the E_{RQD} . Otherwise, all the generation of RESs is supplied to the network and the surplus ($E_{SUR} = E_{RES-E} - E_{RQD}$) will be stored in the electricity storage, provided that it is not full. If the electricity storage becomes full, or if it was already full,

then the rest or all of the surplus generation of RESs is directed to the P2G unit to be converted into natural gas and stored in the VCS. If VCS is full, then the output of the P2G is directly injected into the gas network.

Algorithm 1 Pseudo-code of the Storage Management Plan**Result:** Updated SoC of $SVSE$ and LoG of VCS devices;**Data:** System inputs were listed in Figure 1;**Initialization:****Perform:** Power Flow and Gas Flow analysis;**Calculate:** The required energy (E_{RQD}) from the PCC (slack bus);**Calculate:** The difference between E_{RQD} and the available generation from RESs (E_{RES});**if** $E_{RES} \leq E_{RQD}$ **then**Discharge the $SVSE$ such that: $E_{SVS}^{Discharge} = E_{RQD} - E_{RES}$;**else if** $E_{RES} > E_{RQD}$ **then**Calculate surplus energy (E_{SUR}) as the difference between E_{RQD} and the available generation from RESs (E_{RES});**if** $SoC_{SVSE} < 100\%$ **then****if** $E_{SUR} \leq ((100 - SoC_{SVSE}) * C_{SVSE})$ **then**Charge the SVS such that: $E_{SVSE}^{Charge} = E_{SUR}$;**else if** $E_{SUR} > ((100 - SoC_{SVSE}) * C_{SVSE})$ **then**

Charge the SVS until it becomes full;

if $LoG_{VCS} < 100\%$ **then****if** *Remained energy is lower/equal than/to the remained capacity of VCS;* **then**Charge the VCS such that: $E_{VCS}^{Charge} = E_{SUR} - ((100 - SoC_{SVSE}) * C_{SVSE})$ **else**

Charge the VCS until it becomes full and convert the remained energy via P2G and inject it into the gas network;

end**else if** $LoG_{VCS} = 100\%$ **then**

Convert the remaining energy into gas using P2G and inject it into the gas network;

end**end****else if** $SoC_{SVSE} = 100\%$ **then****if** $LoG_{VCS} < 100\%$ **then****if** E_{SUR} is lower/equal than/to the remained capacity of VCS **then**Charge the VCS such that: $E_{VCS}^{Charge} = E_{SUR}$;**else**

Charge the VCS until it become full and convert the remained energy into gas via P2G and inject it into the gas network;

end**else if** $LoG_{VCS} = 100\%$ **then**Convert all the E_{SUR} to gas using P2G and inject it into the gas network;**end****end****end**

It should be noted that $SVSE$ is usually used to cover the short-term energy shortage, while VCS can be considered as long-term storage. Hence, the charging priority is given to $SVSE$. Additionally, in every conversion unit, some part of the energy is lost due to conversion inefficiencies.

Furthermore, the emission of the electricity network is higher than the emission of the gas network. Therefore, the surplus of RESs is first directed to the electricity storage and

Table 3

Assumed values for cost of operation and GHG emission

Parameter	Gas Network	Electricity Network
Cost of Operation ^a (£/MWh)	9.73	33.69
GHG Emission ^b (kgCO ₂ e/MWh)	360.00	419.40

^a Estimated network costs per domestic customer (GB average), ofgem, 2019.

^b Houses of Parliament: Parliamentary office of science technology, 2017. 'Decarbonising the Gas Network'.

then to the gas storage after conversion. Finally, it is noted that for obtaining an accurate TEE evaluation, the initial and final value of SoC and LoG of all storage devices are considered to be equal to zero.

2.4. Assumptions of TEE Analysis

Table 3 shows the unit parameters considered for calculation of the cost of operation of gas [38] and electricity [39] distribution networks, and the GHG emission of these networks [40] based on the UK generation mixture. In each case, the total cost of operation or emission of the network is calculated by multiplying the energy supplied to the network from the upstream, which is obtained based on the technical calculations presented in Subsection 2.3, by the corresponding value in Table 3.

3. Case study

The case study considered in this paper is a real-world case study from a rural area in Scotland, which comprises of 120 dwellings and circa 300 residents. The village is connected to the electricity distribution network and also benefits from a small wind farm and roof-top PVs. However, it is not connected to a gas distribution network. Hence, the heat load is met by a mixture of energy technologies including electric boiler, air source heat pump and oil/gas boiler. Data for this village, including electricity and heat loads and wind and PV generation, with a fine time granularity (5-minute time steps), was available and used in this paper.

3.1. Load and Generation Profiles

Raw historical data for electricity and heat loads of several domestic and non-domestic buildings and for wind and PV generation of this village was available. However, the electricity and heat loads were processed/synthesised (in [41]) for all the buildings for a sample winter week (w/c 23 February 2015) for energy simulation and analysis purposes. The total electricity and heat load, as well as the total wind and PV generation for the entire village for this week, are available in [42].

3.2. Studied Gas and Electricity networks

A) Separate Gas and Electricity Networks Without Storage: Fig. 4 shows the schematic of the gas and electricity distribution networks considered for this village. As can be seen, the village was divided into 6 zones spatially in a way that both domestic and non-domestic consumers appear in all the zones. For power flow studies, a PQ bus was considered for each zone and the total electricity load of the zone was placed on the bus. The location of the main substation of the village is known. Therefore, all the buses were connected to this substation using a radial network. The values assumed for the impedance of the

Figure 4: The schematic of the the studied rural area in Scotland including the separate gas and electricity networks (without considering P2G and VCS) and IGEDN (with considering P2G and VCS) [41].

electricity network were taken based on the available data-sheets for similar electricity distribution networks in the UK.

Also, the wind generation was connected to the substation bus. The wind generation is known (as depicted in [42]) and input to the model. PV generation is considered locally at the zones to meet part of the electricity load of the zone. As mentioned previously this village is not connected to a gas distribution network. However, a “hypothetical gas distribution network” was designed for it. A gas node was considered for each zone and the gas load, which was calculated based on the heat load, was placed on the node. It was assumed that a source node operating at 2 bar (absolute) is supplying the gas network of the village. The values for diameter and roughness of the pipes were taken from similar real gas distribution networks in the UK, operating at the same pressure level. Based on the gas flow analysis the nodal pressures were all more than 1 bar absolute, meaning the network is operable and a pressure regulator needs to be placed locally at the zones to reduce the pressure further down to 50 mbar for the end-user consumption.

B) IGEDN with P2G and Storage Devices: To make the IGEDN, a SVS_E and a P2G unit along with a VCS is considered in the village, as demonstrated in Fig. 4. The SVS_E and P2G unit are connected to the main bus of the electricity network and otherwise, the network is the same as before. The nominal capacities of the VCS and SVS_E devices are 500 m³ (~ 5 MWh) and 2 MWh, respectively. The values assumed for the rest of the parameters used in the model are presented in [42].

3.3. Gas and Electricity Loads and PV Generation of the Zones

The total electricity and heat load of each zone were obtained by aggregating all the individual loads of domestic and non-domestic loads in each zone. Then, the gas load of the zones was obtained by converting the heat load into gas load using equation 4. In this way, the profiles for gas and electricity loads of all the zones were calculated.

Only zones C and D benefit from roof-top PV generation, which are monitored. By aggregating all these generation profiles, the total PV generation profile for these two zones are also obtained.

3.4. Scenarios Description

Three scenarios were designed to demonstrate the ability of the framework to answer the research questions and to compare TEE benefits of IGEDN through SVS_E as well as P2G and VCS devices. These scenarios are as follows:

3.4.1. Scenario 1: Base case

In this scenario, the base operation of the networks using the current load and generation profiles was considered. The total gas and electricity loads of the zones were calculated according to the explanation presented in Subsection 3.3. The total wind and PV generation profiles of the zones are known and input to the framework.

3.4.2. Scenario 2: High RESs

In this scenario, it was assumed that both of the gas and electricity loads are increased by 40% relative to scenario 1, to represent a peak-load profile. This represents a possible extension of the village and/or concurrent severe weather conditions. Also, the RES profiles were assumed to increase by 40% relative to scenario 1 as a result of possible increased wind and solar irradiation and/or possible improvements in related technology in the future.

3.4.3. Scenario 3: Low RESs

The load profiles for scenario 3 were the same as scenario 2. However, it was assumed the generation from RESs has decreased by 40% relative to scenario 1, representing, for example, the maintenance of some part of the wind farm at the same time as the peak-load condition.

Scenarios 2 and 3 were designed in order to compare the TEE analysis of high renewable generation with low renewable generation conditions. The percentages assumed for the increase of load or variation of the renewable generation (wind and PV) are realistic, relatively extreme and stretching in order to test the extent of the model developed. In all the considered scenarios, the simulation and analysis were performed on the two network configurations presented in Subsection 3.2 (Fig. 4).

Table 4

TEE analysis of the three considered scenarios.

Scenario Number		Scenario 1		Scenario 2		Scenario 3	
Networks Configuration		Separated	Integrated	Separated	Integrated	Separated	Integrated
Total Energy from Upstream (MWh)	Gas	172.96	156.06	242.18	219.83	242.18	240.35
	Electricity	12.05	2.98	17.76	5.63	26.23	20.95
	Total	185.01	159.04	259.94	225.46	268.41	261.30
Total Operation Cost (k£)	Gas	1.68	1.52	2.36	2.14	2.36	2.34
	Electricity	0.41	0.1	0.6	0.19	0.88	0.71
	Total	2.09	1.62	2.96	2.33	3.24	3.05
Total GHG Emissions (tCO_2e)	Gas	62.27	56.18	87.19	79.14	87.19	86.53
	Electricity	5.05	1.25	7.45	2.36	11.00	8.79
	Total	67.32	57.43	94.64	81.50	98.19	95.32

Figure 5: Analysis of the behaviour of storage devices (SVS_E and VCS) in different scenarios.

4. Results and Discussion

In this section, the performance of the integrated networks in terms of TEE parameters and SoC_{SVS_E} and LoG_{VCS} parameters of storage devices in the designed scenarios are presented. All the graphs correspond to the operation of the networks in one winter week (i.e. w/c 23 February 2015).

4.1. TEE Analysis of Scenarios 1 to 3

Fig. 5a shows the SoC of the SVS_E and LoG of the VCS device for the IGEDN with P2G and storage. As it can be seen once the SVS_E becomes full the surplus of the generation of the RESs is transferred to the VCS through P2G. Also, once the VCS becomes full, it remains full and does not interact with the main gas supply until a final discharge of both storage devices in the last 12 hours of the simulation. The SVS_E, however, fulfils some part of the load as required and hence discharges at different times of the studied week.

Table 4 presents the TEE parameters consisting of the total energy supplied, the total cost of operation, and total GHG emission from the upstream networks for both gas and electricity networks. As it can be seen, the share of the gas network in the TEE parameters is much more than the share of the electricity network, which is due to the fact that the gas load of the zones is much higher than the electricity load.

Also, it can be observed that integration of the operation of the gas and electricity distribution networks through P2G and VCS has reduced the total energy supplied from upstream gas and electricity networks, reduced total cost of operation of the networks and reduced total GHG emission from the networks. Moreover, it can be seen that both gas and electricity networks have benefited from integration of operation in terms of TEE parameters for all scenarios, meaning TEE parameters of both have decreased as a result of integration (75% decrease for the TEE parameters of the electricity and 10% decrease for the TEE parameters of the gas network). However, the decrease in TEE parameters as a result of integration in the low RESs scenario

Figure 6: TEE comparison of scenario 2 with scenario 3

(scenario 3) is less than the high RESs scenario (scenario 2).

Fig. 5b and Fig. 5c compare the SoC of SVS_E and LoG of VCS devices in scenarios 2 and 3 during the studied week, respectively. As it can be seen more storage was utilised in the high RESs scenario 2 than the low RESs scenario 3 as it can be expected due to more surplus of RESs in scenario 2. On the other hand, these figures show that SVS_E has become full sooner in scenario 2 than in scenario 3 as a result of more surplus RESs. Therefore, VCS has become full in scenario 2 and never becomes full in scenario 3.

Fig. 6 compares the percentage reduction in TEE parameters due to integration of the networks for scenarios 2 and 3. Each element in this figure has been calculated as the difference between the value of the parameter (total of the gas and electricity networks) in the separated and integrated networks divided by the value of the parameter (total of the gas and electricity networks) in the separate networks for each scenario. This is performed in order to compare the impact of RESs levels on the benefits of the integration of the networks in terms of the TEE parameters.

The percentage decrease in each TEE parameter is greater

Figure 7: Variation of TEE parameters with variation in the capacity of electricity storage (SVS_E)

Table 5

Base values used to normalise the TEE parameters

Network	Technical (MWh)	Economic (k£)	Environmental (tCO_2e)
Gas	219.83	2.14	79.14
Electricity	5.63	0.19	2.36
IGEDN	225.46	2.33	81.50

for scenario 2 than scenario 3. This was already expected as a result of more RESs generation and hence more utilisation of SVS_E and VCS devices in scenario 2 than in scenario 3. Also, the increase in RESs level had the greatest impact on the technical performance parameter which was 5 times greater for the high RESs (scenario 2) compared to low RESs (scenario 3). Additionally, all the TEE parameters improved as a result of the integration of the networks, with the greatest improvement in the economic parameter.

4.2. Impact of Variation in Storage Capacity on TEE Parameters of the IGEDN

4.2.1. Impact of SVS_E Capacity Variation

The impact of variation of capacity of SVS_E on the TEE parameters of the IGEDN was investigated by slightly increasing the electricity storage capacity from the original value of 2 MWh to 3 MWh and then 4 MWh while keeping the value of the capacity of the VCS at the original value of 500 m^3 at the conditions of high RESs of scenario 2. The TEE values were normalised according to the base values from scenario 2 shown in Table 5.

Fig. 7 shows the variation in TEE parameters of the electricity, gas and the whole IGEDN with the variation of the electricity storage capacity (SVS_E). Also, Fig. 8 presents the electricity storage utilisation (Fig. 8a) and SoC of VCS (Fig. 8b).

As it can be seen in Fig. 7a, increasing the capacity of electricity storage SVS_E decreases TEE parameters of the electricity network. A more electricity is stored by increasing the capacity of the electricity storage, and therefore there is less need to import from the upstream electricity network. However, increasing the capacity of electricity storage slightly increases TEE parameters of the gas network Fig. 7b. This is due to the fact that more surplus of renewable generation is still stored in the electricity storage and less is transferred, converted and stored in the VCS and eventually injected in the gas network. Therefore, the gas network has to import more from the upstream network. Hence, the TEE parameters of the gas network increase by increasing the capacity of the electricity

Figure 8: Storage utilisation with variation of SVS_E capacity.

storage. According to Fig. 7c, the TEE parameters of the whole IGEDN decrease with the increasing capacity of the electricity storage. For example, increasing the electricity storage capacity from 2 MWh to 3 MWh (50% increase) decreases the TEE parameters of the whole IGEDN by 0.23%, 1.41% and 0.31%, respectively. Increasing the capacity of the electricity storage has more impact on the TEE parameters of the electricity network than on the TEE parameters of the gas network. The decrease in the TEE parameters of the whole IGEDN is because of the decrease of the TEE parameters of the electricity network is greater than the increase of the TEE parameters of the gas network.

4.2.2. Impact of VCS Capacity Variation

The impact of variation of VCS capacity on the TEE parameters of the IGEDN was investigated by increasing the capacity of VCS from the original value of 500 m^3 to 600 m^3 and finally 700 m^3 while keeping the value of the capacity of the SVS_E at the original value of 2 MWh at the conditions of high RESs of scenario 2. These values were normalised according to the same base values in Table 5.

Figs. 9a and 9b show the variation in TEE parameters of gas (Fig. 9a) and the whole IGEDN Fig. 9b with variation of

(a) Gas network

(b) Whole IGEDN

Figure 9: Variation of TEE parameters with variation in the capacity of VCS.

the VCS capacity. Also, Fig. 10a presents the SoC of the SVS_E and Fig. 10b shows utilisation of the VCS (LoG) over the studied week.

Increasing the capacity of VCS has no impact on the TEE parameters of the electricity network since the flow of the surplus of energy is from the electricity network to the gas network. Hence, any changes in the VCS capacity does not impact TEE performance of the electricity network. The same profile of SoC of the SVS_E with increasing the capacity of the VCS (Fig. 10a) also confirms this.

Fig. 9b shows that increasing the capacity of the VCS decreases the TEE parameters of the gas network. This was also expected since more gas is stored in the VCS by increasing the capacity of it. In other words, in the long-term, the gas network will import less from the transmission level, which leads to a reduction in TEE parameters of the gas network. This is more significant when there is a great amount of generation from RESs. As it can be seen in Fig. 9b, increasing the capacity of the VCS decreases the TEE parameters of the whole IGEDN. This was expected as the TEE parameters of the electricity network remained unchanged and the TEE parameters of the gas network decreased with an increase in the capacity of the VCS. As an example increasing the VCS capacity from 500 m³ to 600 m³ (20% increase) decreases TEE parameters of the whole IGEDN by 0.31%, 0.29% and 0.31%, respectively.

To conclude, increasing the storage capacity within a network, e.g. electricity network, decreases the amount of imported energy from upstream, the cost of operation and the emissions of that network as well as the whole IGEDN since more capacity of the storage is utilised within that network. Furthermore, all TEE parameters are improved by integration of the two networks. It should be noted that the above results are valid for this configuration of the IGEDN. However, the TEE framework is capable of evaluating TEE parameters of any

(a) Electricity SVS SoC

(b) Utilisation of the VCS

Figure 10: Storage utilisation with variation of gas storage capacity.

IGEDN with arbitrary configuration with different load profiles, different generation profiles and different storage configurations.

4.3. Computation Effort

The TEE framework was developed and implemented in MATLAB [32]. The simulation results were obtained by running the framework on a PC with Intel Core i5-6600 3.30GHz, CPU and 16 GB RAM and Windows 7 operating system. The average computation time was within the range from 19 to 22 minutes for the simulation of one week (with 5-minute time steps) for the separate and integrated networks, respectively.

4.4. Discussion

According to the results of the three scenarios, the TEE framework provided a suitable quantitative evaluation of the benefits of the integration of the operation of gas and electricity distribution networks through P2G and storage in both networks. The TEE benefits, which were observed even in a small rural area during a single week, were most pronounced during the periods of high generation from RESs. Integration of operation of the networks helped this rural area to be more self-sufficient and import less energy from upstream, (which imposed less losses on the transmission level) and reduced both the operation costs and the GHG emissions. Also, both gas and electricity networks, as well as the whole IGEDN of the studied area, benefited from the integration of the operation of the networks. Additionally, the TEE framework was used to calculate the impact of the integration of the networks and the storage configurations on the TEE parameters, for each individual network as well as the whole IGEDN.

It can be concluded that there are significant TEE benefits if medium pressure gas distribution networks are integrated with medium voltage electricity distribution networks through

several coupling components with storage devices in both networks. These TEE benefits are reduction of use or import of limited natural resources, reduction in the cost of operation of the networks and hence energy costs savings for both network operator and the final energy consumer, and reduction in GHG emissions of the use of the energy distributed through the networks. These benefits can be quantified and different future energy scenarios can be evaluated in terms of TEE parameters using the evaluation framework presented in this work in order to make well-informed design choices for meeting the GHG reduction targets.

The framework was used for different load and generation profiles as well as different storage configurations. It can be concluded that the framework developed for TEE analysis of IGEDN with P2G and storage is valid, meaning that it can be applied to any IGEDN with any topology, load and generation profile to evaluate the TEE performance. This is concluded because it was observed that any variation in loads or generation presents rational impact on the TEE performance of the IGEDN. Therefore, it is possible to study the extent of impact of any change in loads, generation or storage configurations on TEE parameters of the integrated networks using the developed framework.

5. Conclusions and Future Work

A framework was developed to quantify and evaluate the technical, economical and environmental benefits of the integrated operation of gas and electricity distribution networks with storage devices in both networks and tested on a real-world rural area in Scotland. This framework can assess the impact of different storage configurations, different level of RESs and different levels of gas and electricity load on the amount of imported energy from the upstream networks, operation costs and GHG emissions of IGEDN. The evaluation framework provides the ability to perform TEE operational analysis of future scenarios of IGEDN through the coupling components and storage devices to provide the basis for well-informed design choices for meeting the GHG reduction targets. In brief, the main specifications and achievements of this work are as follows:

1. The developed TEE framework for IGEDN including storage is generic and can be applied to any IGEDN with any topology, load and generation profile and storage configurations.
2. The single-vector storage and vector-coupling storage devices were modelled and comprehensively analysed in the case study.
3. Integration of operation of the gas and electricity distribution networks including single-vector storage and vector-coupling storage devices has several technical, economical and environmental (i.e. TEE) benefits.
4. Due to the inter-dependencies of the networks, increasing the size of storage in a network decreases the TEE parameters of that network as well as the TEE parameters of the whole IGEDN.

The future work includes investigating: (i) TEE benefits of integrated gas, electricity and district heating networks with coupling components and storage devices in all the networks, (ii) using the developed TEE framework for optimal storage sizing in integrated gas, electricity and district heating networks, (iii) TEE benefits of integrated gas and electricity

distribution and transmission networks with storage in all forms, and (iv) developing TEE indices as indicators for TEE performance evaluation and comparison of different integrated energy networks.

6. 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.

The energy-related icons in Figure 1 and Figure 3 are designed by Freepik.com.

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