CESI

National Centre for
Energy Systems
Integration

Techno-Economic-Environmental Evaluation Framework

for the

Operation of Integrated Energy Systems

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Techno-Economic-Environmental Evaluation Framework for the Operation of Integrated Energy Systems

Abstract

The international aspiration to reach net zero carbon in energy systems by 2050 is growing. In the UK, the government has set a target of 'Net Zero' Greenhouse Gas (GHG) emissions by 2050 in order to reduce contribution to global warming. Energy networks (including gas, electricity, and district heating/ cooling networks) are still predominantly operated separately.

However, there are several drivers for the integrated operation of these networks including reduction of the use of primary energy, increasing integration of renewable energy sources (RESs), and facilitating a low carbon economy. In order to understand the intrinsic properties of each vector of the Integrated Energy Systems (IESs), this integrated operation of energy networks necessitates performing energy evaluation through a system-of-systems approach, from natural resources and distribution to the final energy user as well as the interactions and interdependencies between the different energy vectors.

This evaluation of the operation of IESs is crucial for informing the energy stakeholders about the potential benefits of the integrated operation of the energy networks.

Researchers from the UK National Centre for Energy Systems Integration (CESI) have been working intensively to model IESs and evaluate their operation from the lens of energy trilemma: security of supply, flexibility, and affordability. CESI is an EPSRC-funded centre that aims to reduce risks associated with securing an integrated energy system for the UK by adopting a multi-vector approach.

In this white paper, we present the evaluation framework developed by CESI researchers to quantify the impact of integration of the energy networks.

This framework is able to consider the impact of uncertainty associated with forecasted loads, RES generation, energy prices and other operational cost parameters, as well as emissions associated with the future networks and energy conversion technologies.

CESI's framework provides a basis for making well-informed and risk-based design choices towards the GHG emission targets. The framework presented in this white paper ensures that:

- Inter-dependency of the networks and at the same time all the parameters affecting the operational performance of the integrated networks are considered
- Impact of different storage configurations, including the geothermal storage on the operational performance of integrated networks are evaluated
- Impact of different sources of uncertainty on the operational performance of integrated energy networks (IENs) is quantified

We discuss key findings of the work undertaken in CESI and identify future directions.

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Problem statement

The UK Government has committed to a 'Net Zero' carbon economy by 2050. To decarbonise the energy sector, it is essential to increase the penetration of low-carbon energy sources in integrated energy systems. This, consequently, has an impact on the operation of IESs from the techno-economic-environmental (TEE) point of view.

In this context, how energy networks are integrated, what the role of storage assets energy systems is, and how can different sources of uncertainty affect the operation of IESs, are open research questions that require novel modelling paradigms that consider the Inter-dependency of the networks and at the same time all the parameters affecting the operational performance. This paper addressed the challenges that integrated energy system models are facing as follows.

- What are the TEE benefits of the integrated operation of gas and electricity distribution networks with storage in both networks? What is the TEE impact of different levels of network integration on the operation of integrated energy networks (IENs)?
- How does the variation of storage configurations affect the TEE parameters of IENs?
- How do load profiles and renewable generation profiles affect the TEE performance of IENs?

Background

Studying and evaluating comprehensively the operation of multi-vector integrated energy systems requires a Techno-Economic-Environmental (TEE) evaluation framework, which can investigate the mutual impacts of each of the integrated networks on the operational, economic and environmental performance of others [1], [2]. In addition, the required TEE framework must be able to evaluate the performance of integrated energy networks with simultaneous presence of uncertainty of loads, generations from renewable energy sources (RESs), and the economic and environmental evaluation parameters. The framework has also to facilitate the consideration of all the key parameters affecting the operation of integrated networks, the different storage configurations including types and capacities, and the different levels of networks integration.

Once the framework is developed, 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 greenhouse gas (GHG) reduction targets can be provided.

CESI researchers have developed a TEE evaluation framework for IESs. The evaluation in this framework is through the lens of energy trilemma. The first criteria is the flexibility of operation, which means how much integrated networks can respond to any change, including the increase in demand without violating the operational conditions or technical limits.

The second criterion is the security of supply, which means the extent that one network vector can support (in terms of meeting the demand) the operation of other networks in the case of a fault occurrence in part of those coupled networks, or a shortage of supply in those coupled networks. The third criterion is the affordability, which means the amount of costs associated with the operation and dispatch of the IENs. These costs could include operational and maintenance costs. The fourth criterion is the environmental one, which estimates the amount of CO2 emissions intensity for the evaluated operation, the percentage of renewable energy integration, and the overall efficiency.

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Techno-Economic-Environmental Evaluation Framework

TEE framework

The block diagram of the TEE evaluation framework is shown in Figure 1 and described as follows [3], [4]. As it can be seen, the TEE framework is composed of three parts. The inputs to the framework include:

I. the topology, loads, generations, and level of uncertainty of loads and generations of the electricity network;

II. the topology, loads and level of uncertainty of loads of the gas network;

III. the capacity and the initial state of charge of the electricity storage (ES) and gas storage (GS) devices;

IV. the connections and efficiency of the coupling components; and

V. the unit factors and the associated level of uncertainty for economic and environmental evaluation.

Afterwards, evaluation is performed through a Monte-Carlo Simulation (MCS) in two steps: firstly, the technical simulation engine (TSE) calculates the amount of the energy imported from the upstream of integrated gas electricity heating networks (IGEHN) through performing a gas and power flow operational analysis for all the configurations.

Then, economic and environmental evaluation is performed based on the amount of energy imported. Hence, TEE parameters of IGEHN operation are determined. In this stage, the probabilistic approach has been implemented by considering a Gaussian distribution for the sources of uncertainty, which is sampled through MCS.

The outputs of the TEE evaluation framework are the technical, economic, and environmental performance parameters of the operation of integrated networks, which can be described as follows.

The technical parameter is represented by the amount of energy imported from the upstream networks into the distribution networks. Integration of operation of the energy 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. This technical parameter can be an index of the network operators for more integration of the distribution networks, more incorporation of storage and more local use of RESs at the distribution level.

The economic parameter is represented by the operational 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 at the distribution level.

The environmental parameter is represented by the amount of CO_2 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 at the distribution level.

Once the TEE parameters are calculated, a multi-dimensional performance evaluation of the integrated networks 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).

Another capability of this framework is to perform an optimal gas and power flow with an objective to minimise the operational cost of the integrated networks. The framework outputs are the operation set points of the different assets including the coupling components, the operational cost, and the CO_2 emissions. Other parameters can be calculated such as the percentage of RES integration, CO_2 emissions intensity, overall efficiency, abatement cost of CO_2, and total cost [5].

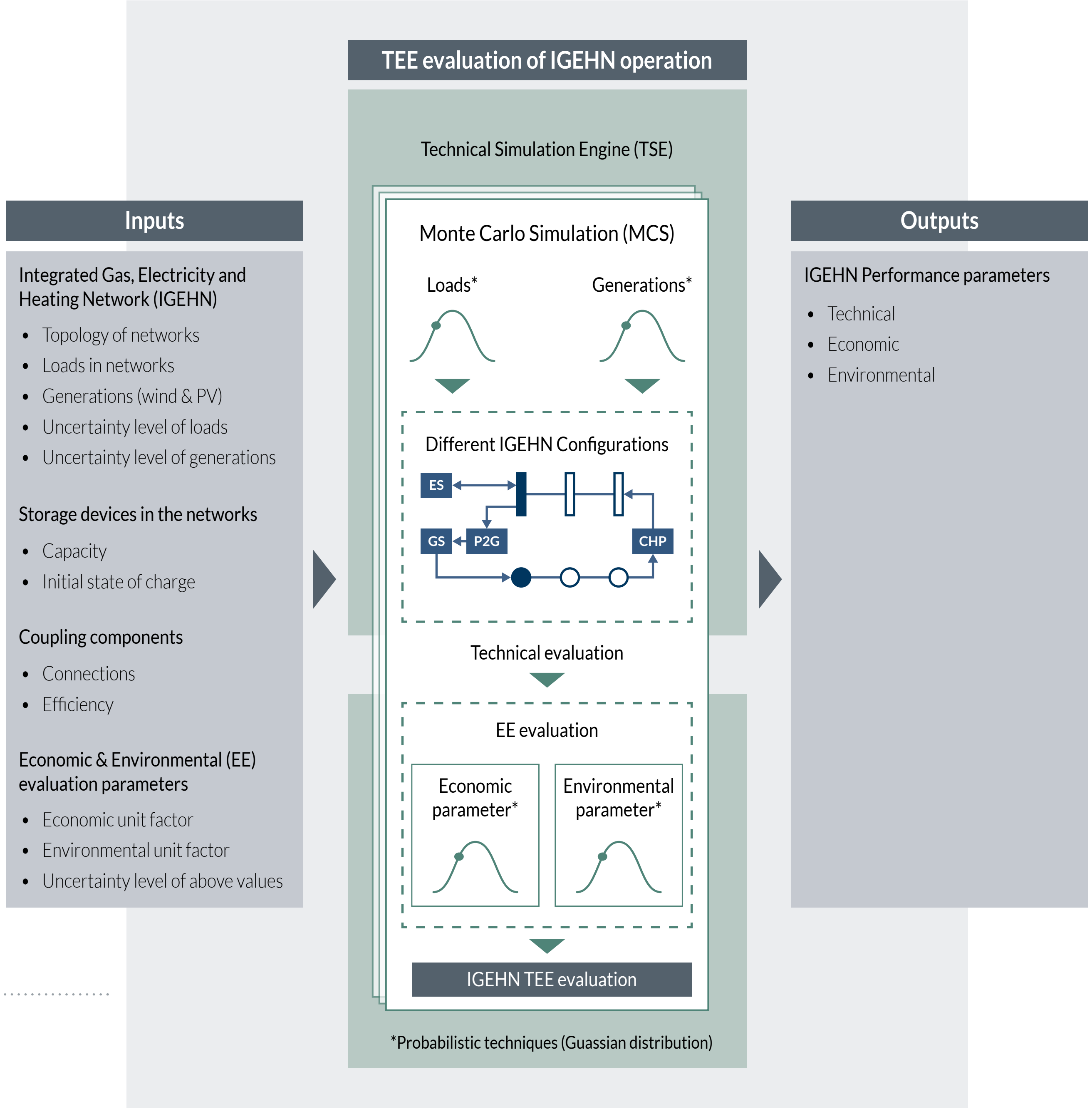

Figure 1: Block diagram of the TEE evaluation framework

Instances of application of TEE evaluation framework

I) TEE analysis of storage configuration in gas and electricity distribution networks

The framework has been used for TEE analysis of storage configuration in gas and electricity distribution networks. This analysis is performed on a real-world case study, which is a small rural village in Scotland. This village comprises around 300 residents in approximately 100 dwellings, with a small wind farm and rooftop PVs. The data of wind and PV generation, and heat and electricity load (with a 5-minute time step) for a representative winter day was used. Single vector storage is considered by including storage in the electrical and gas networks. Furthermore, vector coupling storage (VCS), shown in Figure 2, has been also included where the energy is generated in one vector and stored in another vector. In this case study, the electrical energy is converted through the Power-to-Gas (P2G) to gas stored in the gas storage. The evaluation results show that:

- 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 change in the VCS capacity does not impact the TEE performance of the electricity network.
- 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 this storage. In other words, the gas network will import less from the transmission level, which leads to a reduction in the TEE parameters of the gas network. This is more significant when there is a great amount of generation from RESs.
- Consequently, increasing the capacity of the VCS decreases the TEE parameters of the whole integrated networks.

More results about the role of single vector storage and vector coupling storage can be found in [3].

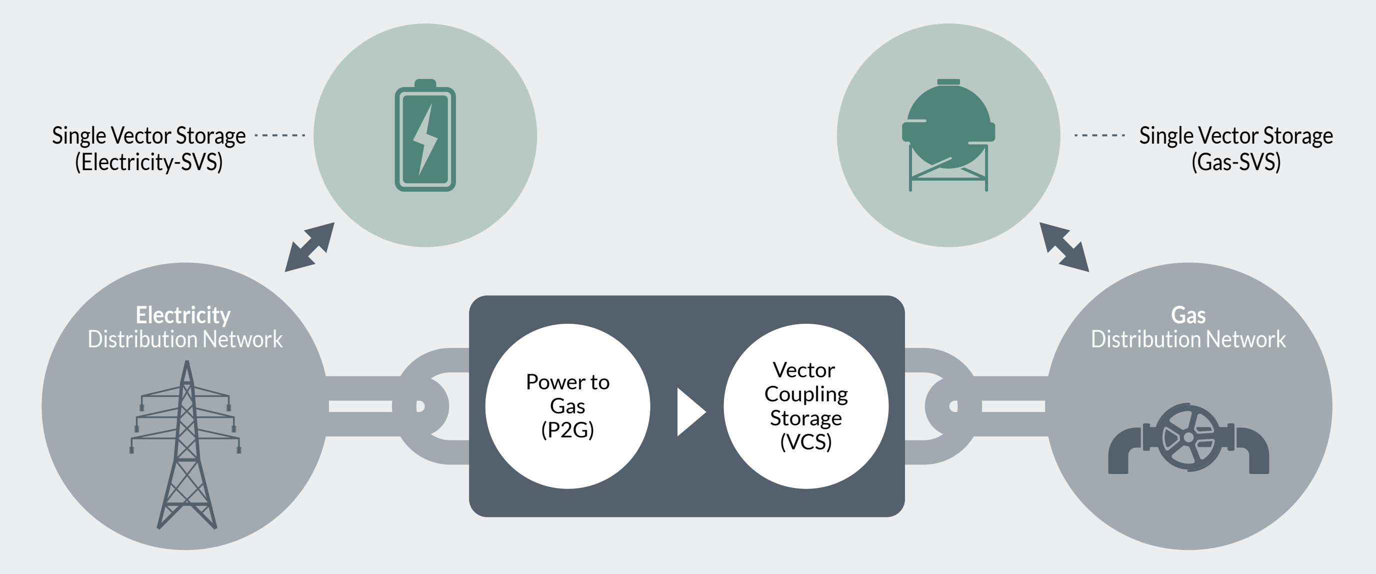

Figure 2: Vector coupling storage

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II) TEE performance of the integrated multi-vector energy networks including geothermal energy storage for meeting the heat demand

There are two most common types of geothermal energy storage (GES) which are the high-temperature GES and low-temperature GES. These two types were modelled and integrated within the framework.

In the high-temperature geothermal storage (HTGES) shown in Figure 3.a, water with a temperature around 80°C is extracted from the underground and transferred back to the underground reservoir once the heat is extracted from it.

The high temperature of this water makes it suitable for direct use by the district heating network (DHN) source. In the low-temperature geothermal energy storage (LTGES), shown in Figure 3.b, water is taken from a flooded mine with temperature of around 15°C. The low temperature of this water is not sufficient to directly supply the DHN source. Therefore, a heat pump (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.

Different configurations are developed for meeting the heat load in Findhorn where the data of heat and electricity load for a representative winter day was used. In the first configuration, the head demand will be supplied from the electric network. In the second configuration, the demand was met from the gas network through the gas boilers.

In the third configuration, the load was met through the gas boilers (GB) and the heat pumps.

In the fourth configuration, the load was supplied through the HTGES or LTGES with electric heater (EH). In the fifth configuration, the combined heat and power (CHP) was used to supply the load. In the last two configurations, the LTGES was used in addition to either EH or GB.

The results of the TEE evaluation of the different configurations show that the most efficient, cost-effective, and least carbon-intensive configurations to meet the heat load are HTGES and high HP penetration with LTGES, respectively.

More results about the performance evaluation of the aforementioned configurations can be found in [6].

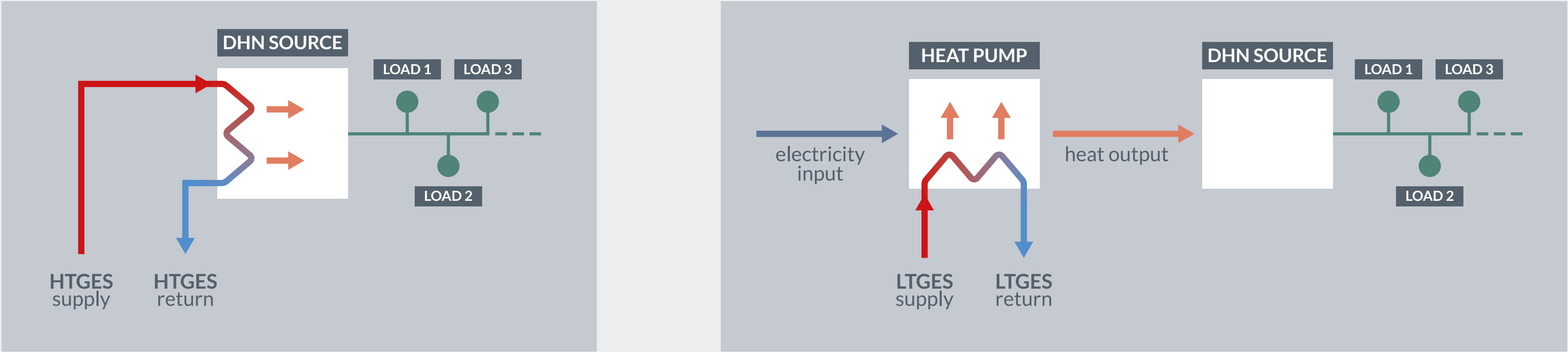


Figure 3: Geothermal Energy Storage

a- HTGES

b- LTGES

Instances of application of TEE evaluation framework

III) Uncertainty analysis of the impact of networks integration level and storage on TEE performance

The operation of integrated gas and electricity networks (IGENs) in Findhorn has been analysed using the developed framework. Figure 4 shows the considered IGEN configurations to investigate the impact of the types of energy storage system (ESS) and integration level of gas and electricity networks in the presence of uncertainty of several sources.

The considered sources of uncertainty were the uncertainty of the electricity and heat loads; the uncertainty of wind and PV generation; and the uncertainty of economic and environmental unit factors.

As can be seen in Figure 4, configurations 1, 2 and 3 correspond to networks without any integration, networks with one direction of energy conversion between vectors, and networks with bidirectional energy conversion between vectors, respectively.

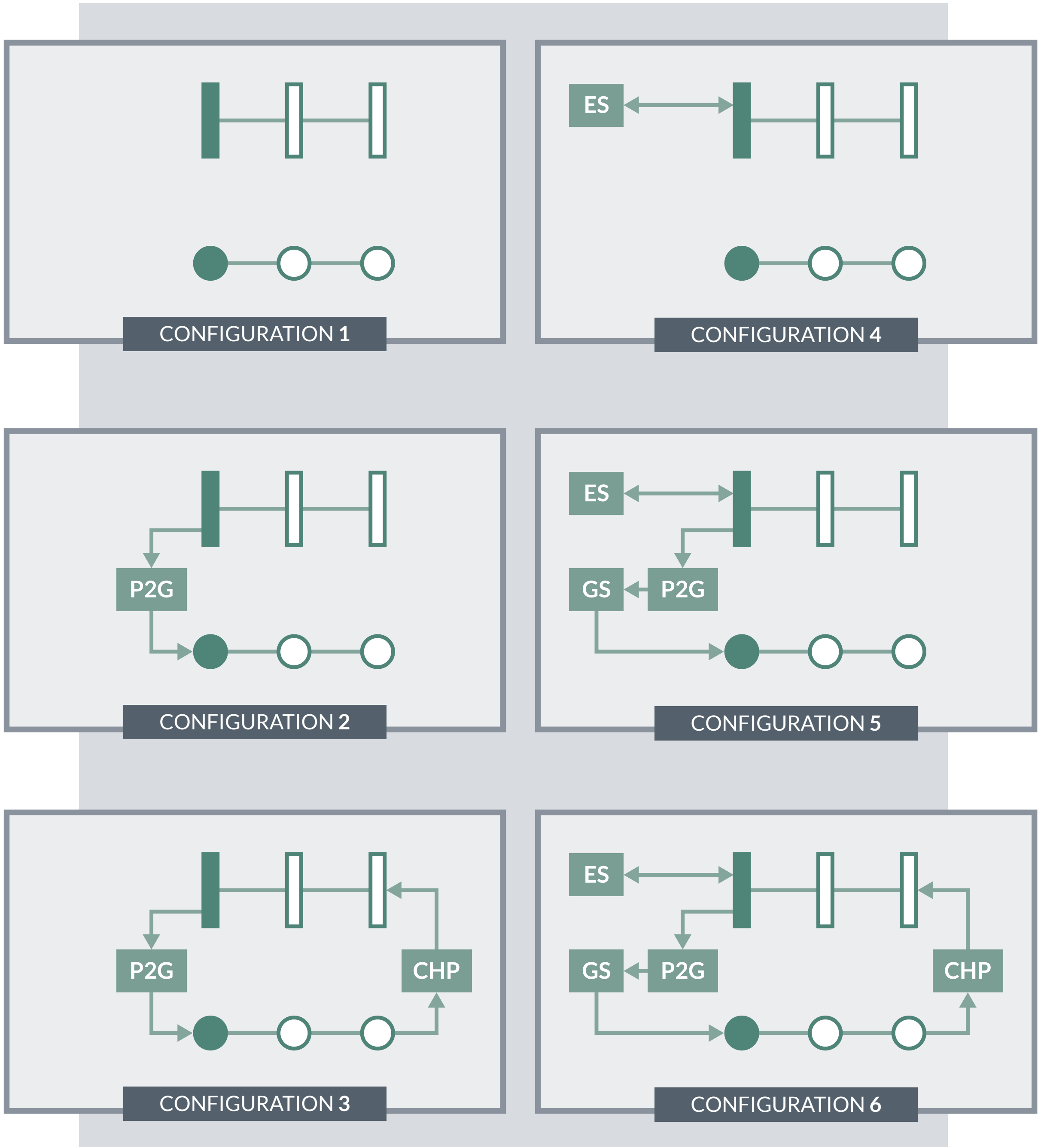
These configurations investigate the impact of increasing the integration level of the networks on the TEE performance of IGENs. On the other hand, configurations 4, 5 and 6 benefit from possible energy system (ES) types for the corresponding configurations 1, 2 and 3, respectively. These configurations study the impact of ESSs and the different levels of networks' integration on the TEE performance of IGENs.

Four scenarios were designed to evaluate and compare the TEE performance of all the IGEN configurations at every scenario. Scenario 1 represents the base case where the available values of loads and RES generation profiles, collected from the data acquisition system in Findhorn, were considered. Scenarios 2, 3, and 4 represent future possible conditions for energy systems including improvement in the efficiency of energy technologies (Scenario 2) and different levels of change of the load and RES generation (Scenarios 3 and 4). Evaluation results reveal that:

- Configuration 5, which benefits from electricity storage (ES), P2G, and gas storage GS, has the lowest TEE parameters compared to the rest of the configurations (most reduction of 11.5% in the technical parameter, 18.53% in the economic parameter and 10.34% in the environmental parameter compared to configuration 1).
- In comparison to no integration in configuration 1, all the rest of the configurations with/without storage and/or some level of integration lead to improvement (reduction) in the TEE performance parameters for the whole IGEN.
- The improvements in the efficiencies of the coupling components reduce the TEE parameters, and these reductions are highest in the bidirectional energy conversion configurations compared to the configurations with single direction energy conversion.

  This finding holds true for all the values considered in the uncertainty analysis. It is clear that efforts to improve the efficiency of coupling components by equipment manufacturers are very important goals in pursuit of lower TEE parameters in future integrated networks.
- When the electrical renewable generation grows with respect to the total demand, the value of integrated operation of the networks also grows by the reduction in the TEE parameters.
- Demand reduction and decarbonisation of electricity and gas networks is a priority, the coupled configurations are likely to become more attractive between now and 2050. This finding also holds true for all the values considered in the uncertainty analysis.

More results about the uncertainty analysis of the impact of networks integration level and storage on TEE performance can be found in [4]. The analysis of uncertainty propagation from one network to the other within the IGENs are also presented in [7].



▮ EN slack bus

▯ EN load bus

● GN source node

○ GN load node

Figure 4: Configuration of IENs in Findhorn

Conclusion

A framework was developed to evaluate the impact of different integration levels and storage devices on the Techno-Economic-Environmental (TEE) performance of Integrated Gas and Electricity Networks (IGENs). In addition, several sources of uncertainty consisting of electricity and heat loads, generation from renewable energy sources, and unit factors for Economic and Environmental (EE) evaluation were considered in the framework.

Additionally, several IGEN configurations, including different integration levels and different storage devices, were considered in the framework. Based on the results obtained by application of the TEE evaluation framework to a real-world case study in Scotland, it can be concluded that the framework is a valid tool in quantifying the amount of energy supplied from upstream networks, operational costs (i.e. cost of supplying energy from upstream) and carbon emission of IGENs.

In this way, the framework provides a basis to make well-informed and risk-based decisions on IGEN design choices to support the most suitable future configuration of IGENs towards 2050 GHG emission targets in the presence of the aforementioned sources of uncertainty, from the TEE viewpoint.

There is significant interest in the potential role of hydrogen in energy futures, particularly in hard-to-decarbonise sectors such as industry, heavy transport, and heating for difficult-to-insulate buildings. Hence, the framework will be extended to consider the role of hydrogen in the future energy system and the potential for hydrogen in resilient energy systems.

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