An Optimisation Study on Integrating and Incentivising Thermal Energy Storage (TES) in a Dwelling Energy System

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Abstract: In spite of the benefits from thermal energy storage (TES) integration in dwellings, the penetration rate in Europe is 5%. Effective fiscal policies are necessary to accelerate deployment. However, there is currently no direct support for TES in buildings compared to support for electricity storage. This could be due to lack of evidence to support incentivisation. In this study, a novel systematic framework is developed to provide a case in support of TES incentivisation. The model determines the costs, CO_2 emissions, dispatch strategy and sizes of technologies, and TES for a domestic user under policy neutral and policy intensive scenarios. The model is applied to different building types in the UK. The model is applied to a case study for a detached dwelling in the UK (floor area of 122 m^2), where heat demand is satisfied by a boiler and electricity imported from the grid. Results show that under a policy neutral scenario, integrating a micro-Combined Heat and Power (CHP) reduces the primary energy demand by 11%, CO2 emissions by 21%, but with a 16 year payback. Additional benefits from TES integration can pay for the investment within the first 9 years, reducing to 3.5–6 years when the CO2 levy is accounted for. Under a policy intensive scenario (for example considering the Feed in Tariff (FIT)), primary energy demand and CO2 emissions reduce by 17 and 33% respectively with a 5 year payback. In this case, the additional benefits for TES integration can pay for the investment in TES within the first 2 years. The framework developed is a useful tool is determining the role TES in decarbonising domestic energy systems.

Keywords: TES; multi-period mixed integer linear program; incentives; techno-economic analysis

1. Introduction

1.1. Background

Integration of Low-to-Zero Carbon (LZC) technologies in domestic buildings might go a long way in achieving the UK target for 80% reduction in greenhouse emissions by 2050 (from 1990 levels). Major barriers to implementation are: (1) large seasonal variations in space heating and electricity requirements; (2) sporadic nature of renewable energy; and (3) high capital costs. Thermal Energy Storage (TES) allows better integration of heat and electricity systems, and storage of energy for use during peak times, thereby addressing the first two barriers. However, despite these benefits, the penetration rate of TES in buildings in Europe is low [1].

Micro-generation can protect against future end-use energy cost and encourage household self-sufficiency [2]. Due to low penetration rates, a number of fiscal instruments have been introduced for micro-generation in the UK. There is a strong argument that fiscal incentives designed to increase

uptake of technologies can in the long run decrease the cost of technologies [3]. An example is the Feed in Tariff (FIT). FITs are fixed electricity prices paid to micro-generation producers per unit of energy produced and injected into the electricity grid. The ability of FIT to stimulate development of less mature LZC technologies in many countries has been established [3,4]. However, the potential of the FIT to increase uptake of TES has not been analysed. In the UK, there is no incentive for homeowners to accommodate TES in their dwellings and communities. Policy makers in the UK have yet to consider storage a critical component of the UK energy future [5]. This could be due to uncertainty about the benefits of TES integration and lack of a reliable cost recovery mechanism for TES. This work seeks to address these challenges through the development of a systematic framework to evaluate the benefits of TES integration in a dwelling energy system, and determine if the additional investment in TES is economically viable. The framework is first mentioned in Oluleye et al. [6], and is extended in this paper.

Modelling and optimisation studies exist to determine the design and dispatch of LZC technologies and TES. However, there are still challenges in: (1) balancing complexity and robustness through the selection of appropriate temporal precision and time bands to represent energy demand and technology characteristics; and (2) representing storage and allowing the TES size to be determined optimally. These challenges are addressed in this work, through the development of a more accurate integrated framework for optimal design and operation of a low carbon dwelling energy system. The framework forms the basis of a case to support incentivising TES in dwellings.

1.2. Literature Review

A high share of micro-generation technology for satisfying the energy demand of the building sector could result in reduction in CO_2 emissions, if an optimal operation strategy is pursued [7]. Reduction in primary energy consumption is also possible with a Micro-Combined Heat and Power (CHP) [8], and further reductions when TES is integrated [9]. Fubara et al. [10] records a 6–10% reduction in primary energy from integrating a micro-CHP. Murugan and Horak [11] identify primary energy savings and emissions reduction from micro-CHP, and their large market potential. Further reductions are possible from integrating heat storage with micro-CHP [8]. Improved capacity factor, and reducing low utilisation plant are benefits of generating and storing heat during periods of low demand and regenerating at periods of high demand [12]. Diaz and Moreno [9] records cost improvements when a micro-CHP is supplemented by TES. Storing heat improves the synchronisation of the demand for heat and electricity in buildings [13]. In spite of these benefits, LZC technologies and TES still have a small percentage of the market [14], implying low adoption by homeowners.

Furthermore, it is unclear if the benefits from TES integration make the additional investment worthwhile. The economic viability could be determined by estimating how long it takes to payback the additional investment in TES and if the investment has a positive return. Such analysis has not been done before.

Economic benefits in terms of operational savings are made possible by charging an accumulator when electricity is high, and releasing heat during cheap night hours [15,16]. However, analysis was done on a district scale. An advantage of district heating is that bigger size technologies are required thereby benefitting from economies of scale. This implies, the additional cost of the TES may be less than in an individual home. Even though district heating has been identified as a way of decarbonising domestic heating in the UK, the estimated deployment of district heating in 2030 is 6% of the total heat demand according to the 4th carbon budget [17]. Furthermore, district heating is not economically viable for lower population density areas. There is a need to evaluate the benefits of TES integration in an individual home (considering different dwelling types), as such an analysis has not been done before.

The development of a framework for system design is required before a techno-assessment of the design, and impacts of TES can be determined. These models account for technical and economic parameters, and boundary conditions like heat and electricity demands. Frameworks for system

design are based on detailed buildings and technology physics, heuristics and optimisation. A detailed building simulation model is applied by Kelly et al. [18] to determine the amount of thermal storage needed to shift heat pump operation to off-peak periods. Salata et al. [19] also applies a detailed simulation model to evaluate the impact of micro-CHP. Detailed building models determine the potential effect on the end user in terms of comfort; however, technology selection and dispatch determination is not addressed. Furthermore, capturing design trade-off is not done systematically. Therefore, designs obtained are suboptimal in relation to delivery of energy and costs, making them insufficient as a framework to quantify the benefits of TES integration, and determine if the additional investment in TES is worthwhile.

Heuristics based on operational logic have been applied to size thermal stores [20]. A heuristic approach for economic optimisation for a single CHP plant and TES capacity is also applied in Vogelin et al. [21]. Heuristics are often iterative in nature, therefore, solving larger models becomes challenging; making them insufficient to form the basis to provide a case to support incentivizing TES.

Optimisation frameworks are able to capture capital-energy trade-offs systematically, and produce optimal designs. LZC technologies have been modelled to determine capacity and dispatch based on linear models [22,23], non-linear models [24] and mixed integer linear models [25,26]. Linear models underestimate the optimal unit capacity by 15% [27], whilst non-linear models suffer from long solution times and local optima [25]. Furthermore, selection of technologies and their capacities is not addressed in linear and non-linear models. Mixed integer linear models are suitable for solving scheduling problems with binary variables and obtaining a global optimal solution rapidly. Thus providing a useful tool to provide evidence to support TES incentivisation.

Such models are often complex due to the varying nature of energy demand and technology characteristics. To reduce model size and complexity, the size of the thermal store is sometimes predetermined [8,13], resulting in non-optimal designs. However, within the Mixed Integer Linear Program (MILP) modelling framework appropriate use of integer variables can obtain good compromise with model complexity whilst ensuring the designs are optimal. Furthermore, integers have been used in a crude way, that is, only associated with selection of technologies. A compromise with model complexity is possible using integers for operation of technologies, charging/discharging TES, import/export of electricity per temporal precision. The later use of integers ensures the operations do not occur simultaneously. In previous research, charging/discharging the store was only based on excess heat available, neglecting price signals. In this present work, in addition to the heat balance, TES is actively regulated to account for gas and electricity price signals.

A model's environmental and economic outcome is influenced by the temporal precision [28] and the banding structure used to represent energy demand [16]. Different temporal precisions have been applied by various authors: 1 h [9,13,21,29–32] and 15 min [25]. Too large temporal precisions could introduce errors in technology sizing and ignore peak demands. Fine temporal precision (5–10 min) is required to adequately capture the characteristics of demand from an economic and environmental viewpoint [28]. Banding structures are used to simplify demand representation; 39 time bands (7 for weekdays, 6 for weekends and 3 seasons in a year) [16], bands of 3 weeks taken from 3 seasons with a time zoom factor for result scale up [25], 3 representative days [9], monthly time bands [33], 3 non-consecutive weeks for 3 seasons and multiplied by a weighing factor [26] and transition and winter days [8]. Choice of technology capacity becomes challenging with large time bands, and they may be errors in the techno-economic assessment [16]. A reduced time slice and band can guarantee a more reliable analysis of the system, as real peaks will be accounted for. The challenge in time slice and band selection is the trade-off between model complexity and accuracy. In the novel framework developed, a temporal precision of 5 min for all the days in the year is used to accurately determine the economic and environmental outcomes. The multi-period MILP model is selected to guarantee a global optimum and prevent the need to iterate when non-linear models are used. In addition to the heat balance, TES is actively regulated to account for gas and electricity price signals.

1.3. Contributions of This Work

A novel systematic framework based on a multi-period MILP model is proposed for the integration and assessment of TES in an existing dwelling. To improve the model accuracy finer temporal precisions are used considering 365 days in the year. The novel model is also able to determine the optimal LZC technology size. The assessment of the benefits of TES considers how long it will take to payback the additional investment compared to the system payback, and if the additional investment in TES has a positive return. Such an analysis of the benefits of TES integration has not been done before. This could provide evidence to support TES incentivisation. The analysis also considers different house types representative of the UK building sector, that is, detached, semi-detached, terrace and flat.

2. Methodology

A techno-economic assessment of the system is required to provide a case to support TES incentivisation. First, the energy system is designed systematically and the results forms the basis for the techno-economic study. A multi-period mixed integer linear program is proposed to design the energy system. Additional binary variables are included to address electricity import/export and TES charging/discharging. The model summary is provided in Figure 1. The scope considers integrating a micro-CHP, an auxiliary boiler and TES into an existing building.
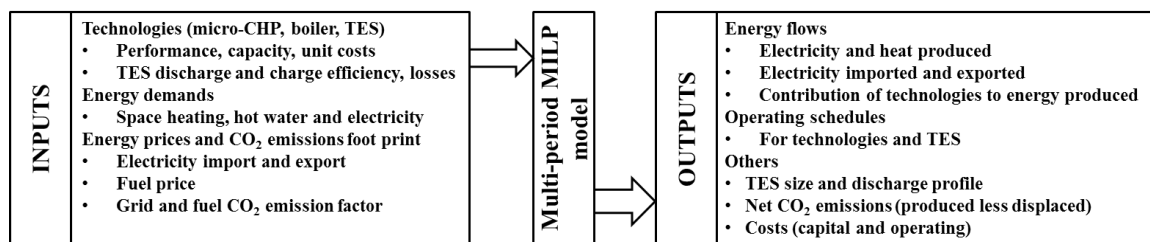

INPUTS	OUTPUTS
Technologies (micro-CHP, boiler, TES) • Performance, capacity, unit costs • TES discharge and charge efficiency, losses **Energy demands** • Space heating, hot water and electricity **Energy prices and CO$_2$ emissions foot print** • Electricity import and export • Fuel price • Grid and fuel CO$_2$ emission factor	**Energy flows** • Electricity and heat produced • Electricity imported and exported • Contribution of technologies to energy produced **Operating schedules** • For technologies and TES **Others** • TES size and discharge profile • Net CO$_2$ emissions (produced less displaced) • Costs (capital and operating)

Figure 1. Model summary. CHP: Combined Heat and Power; TES: Thermal Energy Storage.

2.1. Design Statement

A more specific definition of the design problem is:

- Given:

  ○ Set of LZC technologies (different sizes of micro-CHP).
  ○ The energy demands of a dwelling: space heating, hot water and electricity provided in 5 min temporal precision for all the days in a year. The electricity demand is for combined appliances, electronics and lighting.
  ○ Energy prices (electricity and fuel), electricity tariff structure, technology costs.

- Determine:

  ○ Optimal energy system design

    ✧ Technologies selected, capacities and dispatch strategy

    ✧ Contribution of technologies to heat and power provision

  ○ Energy flows, economics and CO2 emissions

- Subject to:

  ○ Energy (both heat and electricity) balances

○   Technology capacity constraints

• In order to:

○   Minimise the EAC of meeting dwelling energy demand to a residential user

A detailed building model was developed in Environmental Systems Performance - Research (ESP-r) to determine the space heating and hot water demands [34]. The demands are evaluated based on building geometry, thermal characteristics and weather forecasts. The European Electrical Standard profiles, by Annex 42 of the IEA's ECBCS [35], were used for the electricity load. The micro-CHP applied is the gas engine due to maturity, fuel adaptability, fast responses to load changes and presence in the market [9]. The alternative to these is a gas boiler for meeting the heating demand, and electricity imported from the grid.

2.2. Mathematical Formulation

The optimal design is obtained by minimising the systems Equivalent Annual Cost (EAC), defined as the sum of the annualised capital, fuel and maintenance cost less the net electricity cost (Equation (1)). Breakdown of each component of the objective is provided in Equations (2)–(5), and the annualisation factor in Equation (6).

The annualized capital cost in Equation (2) takes into account the installed capital (IC) of the micro-CHP and TES. The TES size ($Size^{TES}$) is a degree of freedom in the model. Several sizes of the micro-CHP are included in the analysis, that is, 1, 2 and 4 kWe, and the binary variable Z^{CHP} selects from the available sizes. The fuel costs (Equation (3)) is a sum of the fuel consumed in the micro-CHP and the boiler. Assumptions of the CHP performance ($Perf^{CHP}$) and boiler performance ($Perf^{BOI}$) are in Table A1. t is the time resolution used (5 min) and r is the number of time periods used to represent the annual energy demand and technology characteristics. The net electricity cost (Equation (5)) is the cost of electricity import less the revenue from electricity exported from the micro-CHP. Assumptions of electricity prices are in the Appendix A.

Equality and inequality constraints to describe the feasible region are also defined. Energy balances for heat and electricity is provided in Equations (7) and (8). In Equation (7), the heat produced from the micro-CHP, the boiler, and heat diverted out of storage must satisfy the thermal energy demand. No dumping of heat is allowed. Also in Equation (8), electricity produced from the micro-CHP and any electricity imported less electricity exported must satisfy the electricity demand. The technology operation is constrained in Equations (9) and (10). When Y^{CHP} is 1, the unit operates between the minimum and maximum allowed. In Equation (11) if a unit is not selected (determined by the binary variable Z^{CHP}), it does not operate.

$$\text{Min}: ACC + FC + MC + W_{\text{GRID,NET}} \tag{1}$$

$$ACC = AF \times \left(\left(Size^{CHP} \times Z^{CHP} \times IC^{CHP} \right) + \left(Size^{TES} \times IC^{TES} \right) \right) \tag{2}$$

$$FC = \left[\sum_r \left(\frac{\left(\left(Q^{CHP}_r + W^{CHP}_r \right) \times ts_r \right)}{Perf^{CHP}} \right) + \sum_r \left(\frac{\left(\left(Q^{BOI}_r \right) \times ts_r \right)}{Perf^{BOI}} \right) \right] \times NGP \tag{3}$$

$$MC = \left(\sum_r \left(W^{CHP}_r \times ts_r \right) \times MC^{CHP} \right) + \left(\sum_r \left(Q^{TES,OUT} \times ts_r \right) \times MC^{TES} \right) \tag{4}$$

$$W_{\text{GRID,NET}} = \sum_r \left(\left(W^{IMP}_r \times ts_r \times GIMP_r \right) - \left(W^{EXP}_r \times ts_r \times GEXP_r \right) \right) \tag{5}$$

$$AF = \frac{IR \times (1 + IR)^n}{(1 + IR)^{n-1}} \tag{6}$$

$$Q^{CHP}_r + Q^{BOI}_r - Qdemand_r + Q^{TES,OUT}_r - Q^{TES,IN}_r = 0, \ \forall \, r \, \in \, R \tag{7}$$

$$W^{CHP}_r + W^{IMP}_r - Wdemand_r - W^{EXP}_r = 0, \ \forall \, r \, \in \, R \tag{8}$$

$$W^{CHP}_r - Lo \times Y^{CHP}_r \geq 0; \ \forall \, r \, \in \, R \tag{9}$$

$$W^{CHP}_r - Uo \times Y^{CHP}_r \leq 0; \ \forall \, r \, \in \, R \tag{10}$$

$$Y^{CHP}_r - Z^{CHP} \leq 0; \ \forall \, r \, \in \, R \tag{11}$$

In order to define whether electricity is imported or exported, a binary variable, Y^{EI}, and a series of constraints are formulated in Equations (12) and (13). Electricity export and import cannot occur together in any time slice. U_{EI} is a number some orders of magnitude larger than electricity import/export. The same formulation is done for charging/ discharging the store in Equations (14) and (15). The heat diverted out of the store, $Q^{TES,OUT}$ and heat diverted into the store $Q^{TES,IN}$ are degrees of freedom in the model. Y^{TES} represents the binary variable for operating the store. Equation (14) and (15) are formulated to ensure charging and discharging the store does not occur simultaneously in any time period r.

$$W^{IMP}_r - U_{EI} \times Y^{EI}_r \leq 0, \ \forall \, r \, \in \, R \tag{12}$$

$$W^{EXP}_r - U_{EI} \times \left(1 - Y^{EI}_r\right) \leq 0, \ \forall \, r \, \in \, R \tag{13}$$

$$Q^{TES,OUT}_r - U_{TES} \times Y^{TES}_r \leq 0, \ \forall \, r \, \in \, R \tag{14}$$

$$Q^{TES,IN}_r - U_{TES} \times \left(1 - Y^{TES}_r\right) \leq 0, \ \forall \, r \, \in \, R \tag{15}$$

In each time slice, the energy content of the store is subject to the below constraint in Equation (16). Where θ is the daily storage loss, ISH is the Initial Store Heat.

$$0 \leq \sum_{r=r}^{r=1} \left(\left(\left(Q^{TES,IN}_r \times \eta_{charge}\right) - \left(\frac{Q^{TES,OUT}_r}{\eta_{discharge}}\right) - \left(Size^{TES} \times \theta\right)\right) \times ts_r\right) + \left(Size^{TES} \times ISH\right) \leq Size^{TES} \tag{16}$$

Equation (17) states that the heat transferred into the store is equal to the heat recovered from it during 24 h. Therefore, at the end of each day:

$$\left(Size^{TES} \times ISH\right) - 0.1 \leq \left[\sum_{r=r}^{r=1}\left(\left(\begin{array}{c}\left(Q^{TES,IN}_r \times \eta_{charge}\right) \\ -\left(\frac{Q^{TES,OUT}_r}{>\eta_{discharge}}\right) \\ -\left(Size^{TES} \times >\theta\right)\end{array}\right) \times ts_r\right) + \left(Size^{TES} \times ISH\right)\right] \leq \left(Size^{TES} \times ISH\right) + 0.1 \tag{17}$$

After obtaining the optimal design based on Equations (1)–(17), a techno-economic analysis of the design follows. The criteria for assessment are the Equivalent Annual Income (EAI), the designed system payback and Net Present Value (NPV), payback and NPV associated with the additional investment in TES, the total delivered energy (TDE) and the net CO_2 emissions ($NTCO_2$).

The EAI is the difference between the cost of energy for a Business as Usual (BAU) system and the EAC in Equation (1). Traditionally, a dwelling space heating and hot water demand is satisfied by a boiler and electricity imported from the grid. The energy cost of a BAU system is calculated using Equation (18). The difference in the energy cost for a BAU system and the EAC for the optimized design with TES, gives the EAI associated with integrating TES. A positive EAI implies the homeowner has some savings from integrating the new system. The payback and the NPV for the additional investment in the TES is calculated using the difference in investment, and savings for design without TES and design with TES. The TDE is the fuel value of energy flows calculated in Equation (19), and the net CO_2 emissions is estimated using Equation (20) taking into account CO_2 from fuel, electricity import and CO_2 displaced when electricity is exported. The model was implemented using the GAMS 24.7.3 software (24.7.3, GAMS Development Corporation, Fairfax, VA, USA) and solved with the CPLEX solver on a 64 bit 3.40 GHz Intel® Core™ i7-6700 CPU with 32 GB RAM machine.

$$C^{BAU} = \left(\sum_r \left(\frac{Qdemand_r \times ts_r}{Perf^{BOI}} \right) \times NGP \right) + \sum_r (Wdemand_r \times ts_r \times GIMP_r) \tag{18}$$

$$TDE = \left(\begin{array}{c} \sum_r \left(\frac{((Q^{CHP}_r + W^{CHP}_r) \times ts_r)}{Perf^{CHP}} \right) \\ + \left(\sum_r \left(\frac{((Q^{BOI}_r) \times ts_r)}{Perf^{BOI}} \right) \right) \end{array} \right) + \frac{\left(\sum_r \left(W^{IMP}_r \times ts_r \right) \right) - \left(\sum_r \left(W^{EXP}_r \times ts_r \right) \right)}{GEE} \tag{19}$$

$$NTCO_2 = \left(\begin{array}{c} \sum_r \left(\frac{((Q^{CHP}_r + W^{CHP}_r) \times ts_r)}{Perf^{CHP}} \right) \\ + \left(\sum_r \left(\frac{((Q^{BOI}_r) \times ts_r)}{Perf^{BOI}} \right) \right) \end{array} \right) \times FEF + \left(\begin{array}{c} \left(\sum_r \left(W^{IMP}_r \times ts_r \right) \right) \\ - \left(\sum_r \left(W^{EXP}_r \times ts_r \right) \right) \end{array} \right) \times GEE \tag{20}$$

3. Case Study

The case study is on integrating micro-CHP and TES into an existing dwelling with an objective to analyse the benefits from its integration, and determine if the additional investment is economically viable, and how it can be incentivised. Four building types representative of UK housing stock are investigated.

3.1. Design Problem

Given the energy demands for different dwelling types, the space heating demand for a detached house, semi-detached house, terrace and flat are presented in Figure 2, associated hot water demand in Figure 3, summary provided in Table 1. Simulation models of four key UK house types is presented in Allison et al. [34]. The simulation models enable the dynamic thermal demand (heating and hot water) of each house to be quantified over a range of different operating conditions. Occupancy, insulation levels, and construction thermal characteristics are defined in the earlier work done in Allison et al. [34]. A micro-CHP, boiler and TES are available to satisfy the energy demand. Different design scenarios were developed and analysed to assess TES integration. They are, design with and without TES, and design with/without incentives. Since TES is not a stand-alone technology, fiscal incentives such as the FIT to support the deployment of micro-CHP is adapted; where the value for production and export are 13.45 and 4.91 p/kWh respectively [36]. Another instrument explored is the exemption from the CO_2 levy (current central value is 0.063 £/kg) [37], especially when the CO_2 of the system designed is less than the BAU.

Table 1. Energy demand and house characteristics.

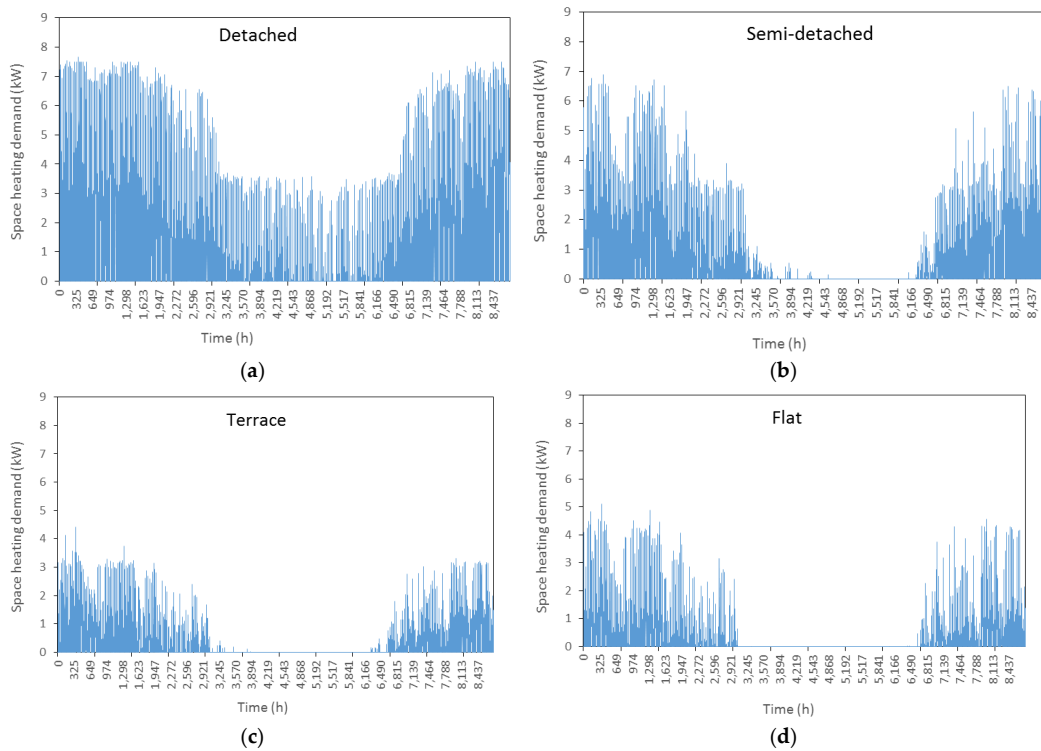|		Detached	Semi-Detached	Terrace	Flat
Peak demand (kW)	Space heating	7.65	6.89	4.42	5.11
	Hot water	27.2	34.9	34.6	34.7
Total demand (kWh/year)	Space heating	9904	5400	2480	1940
	Hot water	1712	1590	1351	1304
Floor area (m^2)	-	121–152	74–93	66–83	45–57

Figure 2. Space heating demand for all house types: (**a**) Detached; (**b**) Semi-detached; (**c**) Terrace; (**d**) Flat.
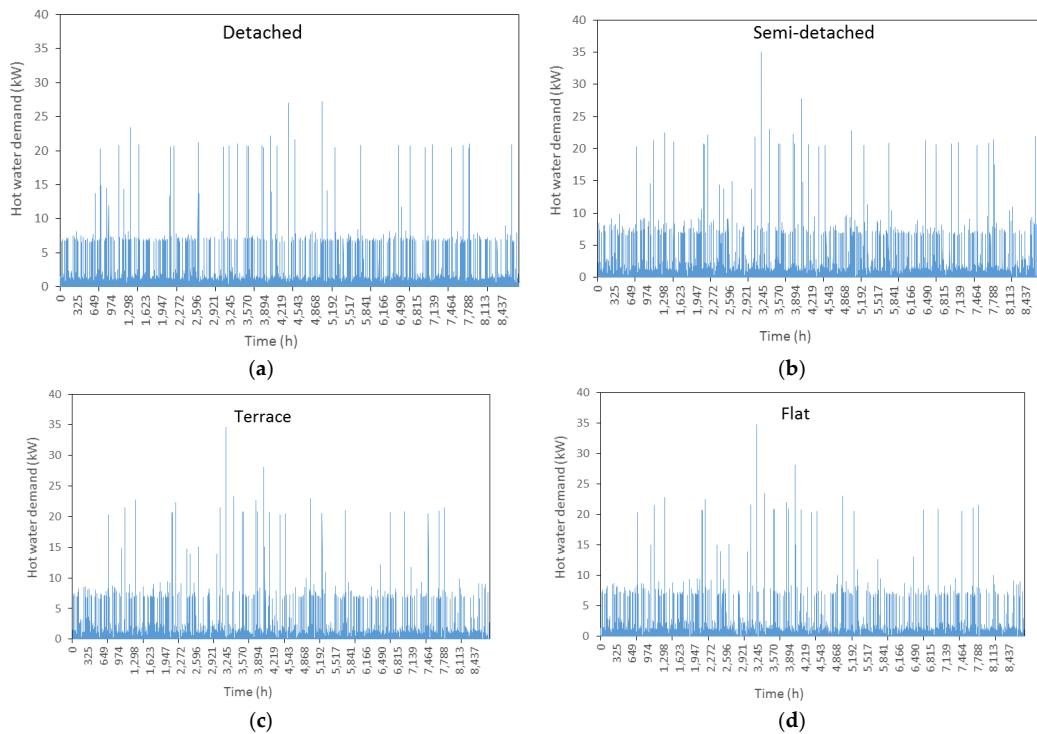

Figure 3. Hot water demand for all house types: (**a**) Detached; (**b**) Semi-detached; (**c**) Terrace; (**d**) Flat.

3.2. Results and Discussion

The contribution of each technology to heat produced under different scenarios are presented in Figures 4–7. In the absence of incentives, and for design without TES, the micro-CHP contributes more to the heat supply compared to the auxiliary boiler. The contribution depends on the house type, increasing from detached to flats. A micro-CHP is better suited to a house with high demands, hence the EAI is highest for a detached house as shown in Table 2. The optimiser maximises the use of the micro-CHP for the semi-detached, terrace and flat, in order to improve their economics. For design with TES, the boiler contribution reduces to 0% for a flat. The majority of the heat in the store is supplied from the micro-CHP. The TES size for a semi-detached, terrace and flat is higher than for a detached house, because since the design for the other houses are uneconomic, the optimiser will maximise the use of storage to improve the economic viability. This will ensure the micro-CHP does not operate all the time resulting in a decrease in operational costs. Hence the heat diverted to storage increases from detached to flat (Figure 6). The heat diverted to storage is more for a non-incentivised design compared to the design with incentives.

Other benefits of TES integration are reduction in net CO_2 emissions, TDE, and in this case more income for the home owner (Tables 2 and 3). The benefits are dependent on house type, increasing based on the total space heating and hot water demand.
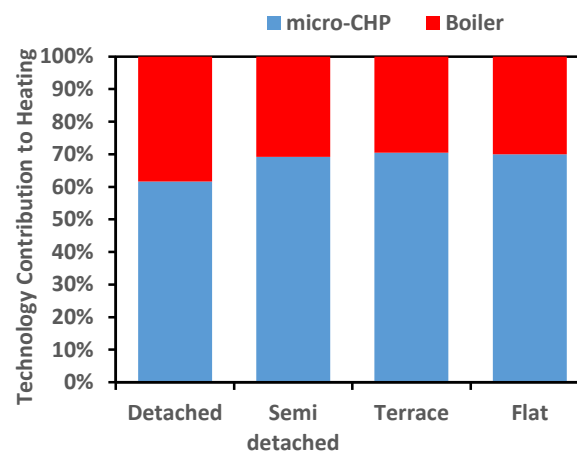

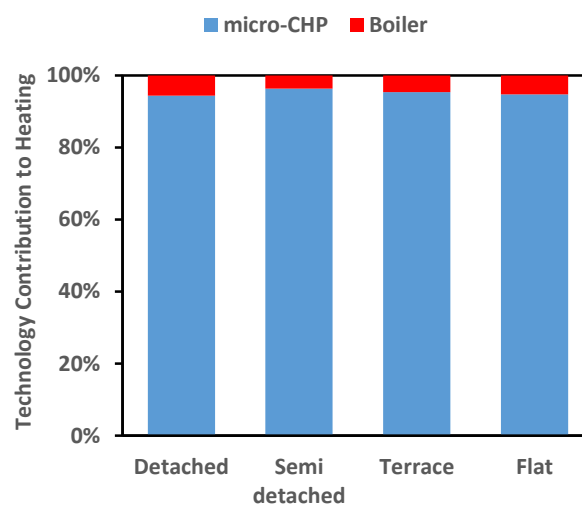**Figure 4.** Non-incentivised design without thermal energy storage (TES).

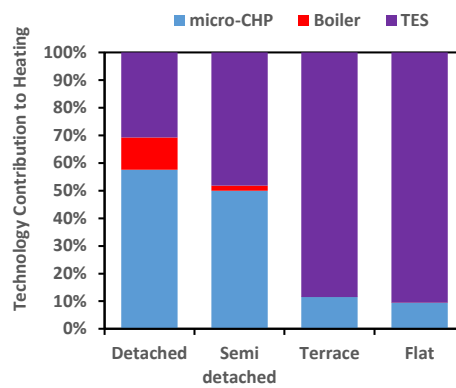**Figure 5.** Incentivised design (Feed in Tariff (FIT)) without TES.

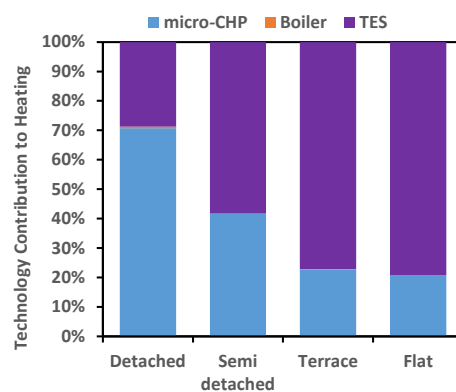**Figure 6.** Non-incentivised design with TES.

Figure 7. Incentivised design (FIT) with TES.

A major barrier to implementing micro generation is cost, when the FIT is introduced in the optimisation, the income for the home owner increases (Table 3). A further increase is possible when TES is integrated. However, for this design the net CO_2 emissions and TDE is slightly higher (Table 3) due to an increase in the micro-CHP fuel consumption. For the design without TES, over 90% of the heat is supplied from the micro-CHP. With TES, the boiler's contribution is negligible for a detached house, and nil for the remaining house types (Figure 7). Grid electricity import increases from detached to flat for the cases, that is, without and with incentives. The contribution from the grid is more when thermal storage is not integrated. Contribution from the grid is less with TES and incentives, however, there is no change for terraces and flats.

Table 2. Non-incentivised design results.

		Detached	**Semi-Detached**	**Terrace**	**Flat**
EAI (£/year)	Design with TES	100.9	−19.2	−133.84	−132.48
	Design without TES	41.22	−52.5	−138.5	−156
System payback (year)	Design with TES	14	20	36	36
	Design without TES	16	24	43	51
System NPV (£)	Design with TES	−1348	−2680	−3860	−3830
	Design without TES	−1716	−2690	−3580	−3760
NTCO$_2$ (kg/year)	Design with TES	6233	5416	4967	4876
	Design without TES	6379	5514	4984	4889
TDE (kWh/year)	Design with TES	29,286	25,609	23,640	23,242
	Design without TES	30,078	26,161	23,788	23,367
TES size	-		26	34	34	32

Table 3. Incentivised (FIT) design results.

		Detached	Semi-Detached	Terrace	Flat
EAI (£/year)	Design with TES	751	414	125	91
	Design without TES	610	296	51	4
System Payback (year)	Design with TES	4.9	7.4	12.8	14.0
	Design without TES	5.5	8.7	15.8	18.7
System NPV (£)	Design with TES	5525	2019	−928	−1266
	Design without TES	4186	933	−1616	−2103
NTCO$_2$ (kg/year)	Design with TES	6009	5407	4954	4864
	Design without TES	5966	5308	4881	4802
TDE (kWh/year)	Design with TES	28,169	25,551	23,579	23,191
	Design without TES	28,025	25,138	23,275	22,933
TES size	-	13	13	9	7

Without incentives, the payback of the accompanying system is greater than 10 and has a negative return on investment. A higher payback and lower NPV is observed for design without TES. Additionally, the TES size is greater compared to the incentivised design in Table 3. The TES is also discharged more efficiently (Figures 8 and 9). A higher TES size is selected in order to maximise the use of the micro-CHP for off-setting the increased costs when electricity import tariff is high. Therefore, more heat is diverted to storage (Figure 8) compared to Figure 9. For the incentivised design, it is economic to integrate the micro-CHP, hence the need to reduce the cost becomes less and the TES size reduces (Table 3 and Figure 9). The x-axis in Figures 8 and 9 are the temporal precision of the first 10 days in the year.

(a)

(b)
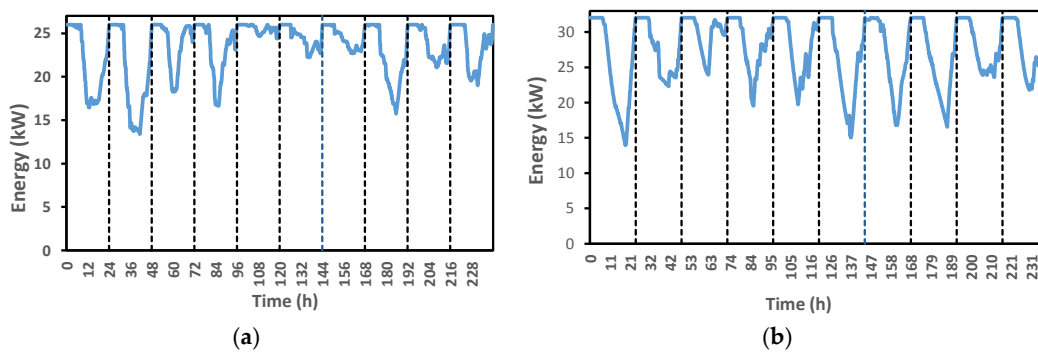
Figure 8. TES discharge profile for non-incentivised design: (**a**) detached house; (**b**) flat.

(a)

(b)
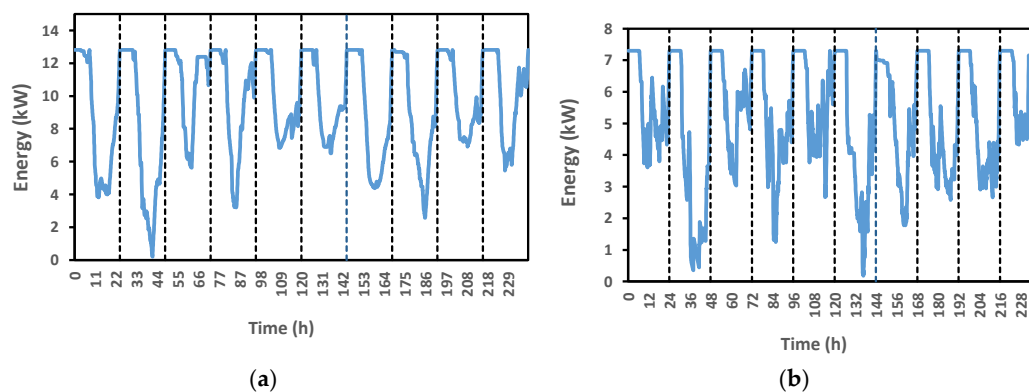
Figure 9. TES discharge profile for incentivised design: (**a**) detached house; (**b**) flat.

In the non-incentivised scenario with TES, the system payback is 14 years for a detached house; additional benefits from TES integration (i.e., increase in the EAI), can pay for the additional investment in TES within the first 6.24 years, with a positive NPV of £368 (Figure 10a). The TES payback and NPV is different for each house type. Whilst in the incentivised scenario (based on the FIT) TES investment can be paid for during the first 1.78 years for a system payback of 4.9 years. The NPV is £1339 (Figure 10b). Another way to incentivise is savings based on reduced CO_2 emissions when TES is integrated (Table 2). In 2016, the CO_2 central non-traded levy is 0.063 £/kg [36]. Using the CO_2 reduced, the savings for a detached, semi-detached, terrace and flat are £70, £57, £37 and £32. This has potential to reduce the additional investment in TES. When incentivised using the CO_2 levy, the TES investment is paid back in the first 5.65 years, with NPV of £463.60 (Figure 10c). There is a clear relationship with the type of house; the payback increases and NPV reduces (negative in some houses). Hence, even when the system is not economically viable, TES integration is economically viable.

The benefit of micro-CHP and TES in a single dwelling has been established. Even though the NPV in system investment is negative (Table 2), the NPV for TES investment is positive even in the absence of incentives (Figure 10a).
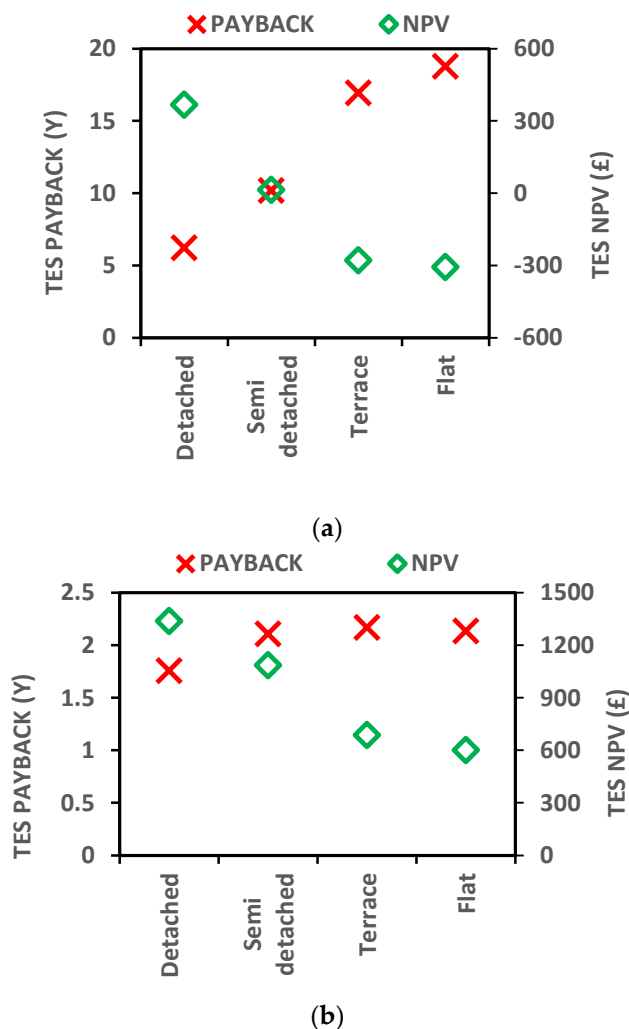

(a)

(b)

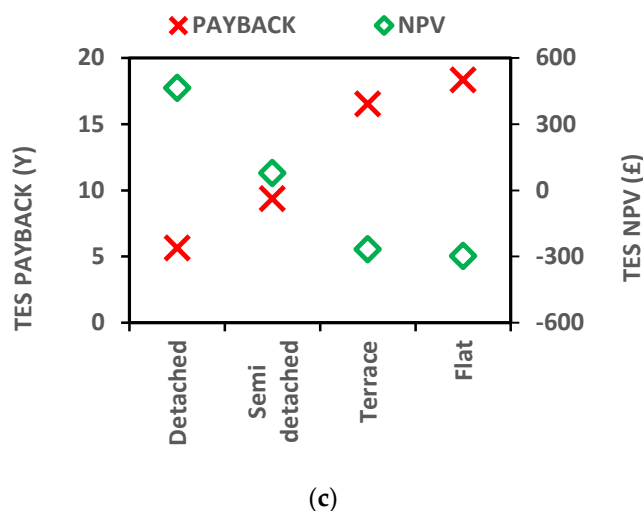**Figure 10.** *Cont.*

(**c**)

Figure 10. Payback and Net Present Value (NPV) associated with TES investment for (**a**) non-incentivised design; (**b**) incentivised design (FIT); and (**c**) incentivised design (CO_2 levy exemption).

3.3. Limitations of This Work

The findings of this work need to be viewed alongside the assumptions on demand, energy prices, and CO_2 emission factors. Whilst the assumptions have been taken from reputable sources, they are subject to variations. Furthermore, the support mechanisms mentioned in the report are currently in operation and are also dynamic.

4. Conclusions

A multi-period MILP model is presented and used to provide a case to support incentivising TES. The accuracy of the model is improved through the use of less temporal precision to represent demand and technology characteristics. The introduction of additional binary variables for charging/discharging the store, and import/export of electricity also reduces the model complexity.

The case to support incentivising TES was established based on a techno-economic assessment of the design obtained with and without TES, and with and without incentives. Assessment metrics used were the EAI for a homeowner, net CO_2 emissions, the TDE, and the system payback and NPV. A new assessment based on the payback and NPV associated with additional investment in TES was also introduced. Results show the benefit from micro generation and TES integration depend on the house type; in this case highest for a detached house. For a detached house, TES integration reduces the TDE by 792 kWh/r, CO_2 by 146 kg/year and the homeowner makes 60 £/year. These additional incomes means TES investment can be paid for in the first 6.24 years during the 14 years of system payback. This provides evidence to support incentivisation. When value is added to CO_2 reduction based on CO_2 levy, the payback for TES reduces to 5.65 years and NPV also increases. With the FIT scheme, for a system payback of 4.9 years, TES investment can be paid back during the first 1.759 years. In the non-incentivised case, even though investment in micro-CHP is not economically viable, the additional investment in TES is economically viable. Therefore, TES incentivisation needs to receive more attention. The future uptake of LZC technologies will be influenced by financial incentives to encourage end-user investments.

There is need to establish which of the accompanying technologies is more beneficial. This forms the basis of future work. Another area worth investigating is establishing the flexibility potential of thermal storage in domestic houses.

Author Contributions: Gbemi Oluleye and Adam Hawkes defined the research questions, and contextualized the problem statement; Gbemi Oluleye wrote the GAMS code and ran the optimization model; John Allison and

Nomenclature

Sets

$r \in R$	Set of all time periods

Independent variables

Q^{CHP}	Heat produced from micro-CHP (kW)
Q^{BOI}	Heat produced from boiler (kW)
$Q^{TES,IN}$	Heat diverted into storage, (kW)
$Q^{TES,OUT}$	Heat delivered from storage (kW)
$Size^{TES}$	Total storage capacity (kWh)
W^{IMP}	Electricity imported to satisfy demand (kW)
W^{EXP}	Electricity exported (kW)

Dependent variables

ACC	Annualised capital cost (£/year)
EAC	Equivalent Annual Cost (£/year)
FC	Fuel cost (£/year)
MC	Maintenance cost (£/year)
$W_{GRID,NET}$	Net electricity cost (£/year)

Binary variables

Y^{CHP}	Binary variable for technology operation
Y^{EI}	Binary variable for export/import of electricity
Y^{TES}	Binary variable for charging/discharging the store
Z^{CHP}	Binary variable for technology existence

Parameters

FEF	Fuel emission factor (kg/kWh)
GIMP	Grid electricity import price (£/kWh)
GEXP	Grid electricity export price (£/kWh)
GEE	Grid energy efficiency (%)
GEF	Grid emission factor (kg/kWh)
IC^{CHP}	Micro-CHP installed capital (£/kW)
IC^{TES}	TES installed capital (£/kW)
ISH	Initial store heat (%)
IR	Interest rate
θ	Storage losses (%)
Lo	Lower limit
MC^{CHP}	Micro-CHP maintenance cost (£/kWh)
MC^{TES}	TES maintenance cost (£/kWh)
n	Technology lifetime (years)
$Perf^{BOI}$	Boiler performance
$Perf^{CHP}$	Micro-CHP performance
Qdemand	Heat demand (both hot water and space heating) (kW)
$Size^{CHP}$	Micro-CHP capacity (kW)
ts	Time precision
U_{EI}	Upper limit for electricity export and import
Uo	Upper limit for micro-CHP power
Wdemand	Electricity demand (kW)
η_{charge}	TES charge efficiency (%)
$\eta_{discharge}$	TES discharge efficiency (%)

Appendix A

Table A1. Technical attributes of technologies in superset [7,29].

Technical Attributes	Natural Gas Boiler	Micro-CHP (1 kW)	Micro-CHP (2 kW)	Micro-CHP (4 kW)	Hot Water Tank
Turnkey cost (£/kW)	163	3110	2400	1900	20
Maintenance cost (£/kWh)	0.001	0.01	0.01	0.01	0.001
Performance	0.895	0.9	0.9	0.9	2.75
Charge efficiency (%)	-	-	-	-	90
Discharge efficiency (%)	-	-	-	-	90
Initial store heat (%)	-	-	-	-	100

The micro-CHP heat to power ratio is 0.385. The design year is 2016. Off-peak and peak electricity import tariffs are 5.5 and 15.29 p/kWh, and fuel price is 3.48 p/kWh [36]. The average CO_2 factor associated with natural gas and electricity was assumed to be 0.185 and 0.519 kg/kWh [36]. Technology lifetime is 15 years and discount rate 5%. CEPCI cost factors were applied to adjust the costs from the year provided to 2016.

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