# 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 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 to support 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. Results show reduction in $CO_2$ emissions and costs when TES is integrated. The benefits from integration can pay for the additional investment in TES. The framework developed is a useful tool for determining the role of TES in decarbonising domestic energy systems.

**KEYWORDS**

Thermal energy storage, Multi-period Mixed Integer Linear Program, incentives, techno-economic analysis.

## INTRODUCTION

### 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 in the benefits from 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.

**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 [6]. Reduction in primary energy consumption is also possible with a Micro-CHP [7], and further reductions when TES is integrated [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 [9]. However, 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 possible from charging an accumulator when electricity is high, and releasing heat during cheap night hours [10, 11]. 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 [12]. Furthermore, district heating is not economically viable for lower population density areas. There is need to evaluate the benefits of TES integration in an individual home (considering different dwelling types).

The development of a systematic framework for optimal system design is required before a techno-assessment of the design, and impacts of TES can be determined. Such models are most times 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 [7, 13], resulting in non-optimal designs. However, within the MILP modelling framework appropriate use of integer variables can obtain good compromise with model complexity whilst ensuring the designs are optimal. The use of integers can ensure charging/discharging operations do not occur simultaneously. The representation of energy demand and technology characteristics has also been simplified to reduce the model complexity. For example, the use of hourly time slices and characteristic days is used in [10], and hourly time slices for all the days in the year [6, 14]. However, fine temporal precision (5 – 10 min) is required to adequately capture the characteristics of demand from an economic and environmental perspective [15]. Fine temporal precision of 5 min for 365 days in the year is adopted in the multi-period MILP model proposed. 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.

## Contributions of this work

A 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 times slices are used considering 365 days in the year. 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. This could provide evidence to support TES incentivisation. The analysis also considers different house types representative of the UK building sector i.e. detached, semi-detached, terrace and flat.

## 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 Fig. 1. The scope considers integrating a micro-CHP, an auxiliary boiler and TES into an existing building.

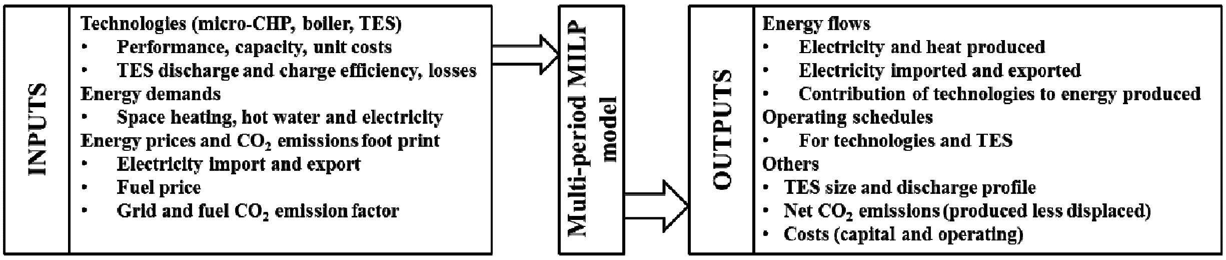


Figure 1. Model summary

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 (Eq. 1). Breakdown of each component of the objective is provided in Eq. 2 – Eq. 5, and the annualisation factor in Eq. 6. Equality and inequality constraints to describe the feasible region is also defined. Energy balances for heat and electricity is provided in Eq. 7 and 8. The technology operation is constrained in Eq. 9 and 10. When $Y^{CHP}$ is 1, the unit operates between the minimum and maximum allowed. In Eq. 11 if a unit is not selected (determined by the binary variable $Z^{CHP}$), it does not operate.

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

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

$$FC = \left[\sum_{r}\left(\frac{\left(\left(Q^{CHP}{}_{r} + W^{CHP}{}_{r}\right) \times ts_{r}\right)}{Perf^{CHP}}\right) + \sum_{r}\left(\frac{\left(\left(Q^{BOI}{}_{r}\right) \times ts_{r}\right)}{Perf^{BOI}}\right)\right] \times NGP \quad (3)$$

$$MC = \left(\sum_{r}\left(W^{CHP}{}_{r} \times ts_{r}\right) \times MC^{CHP}\right) + \left(\sum_{r}\left(Q^{TES,OUT} \times ts_{r}\right) \times MC^{TES}\right) \quad (4)$$

$$W_{GRID,NET} = \sum_{r}\left(\left(W^{IMP}{}_{r} \times ts_{r} \times GIMP_{r}\right) - \left(W^{EXP}{}_{r} \times ts_{r} \times GEXP_{r}\right)\right) \quad (5)$$

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

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

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

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

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

$$Y^{CHP}{}_r - Z^{CHP} \leq 0; \qquad \forall\, r \in R \quad (11)$$

In order to define whether electricity is imported or exported; a binary variable, $Y^{EI}$, and a series of constraints are formulated in Eq. 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 Eq. 14 and 15.

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

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

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

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

In each time slice, the energy content of the store is subject to the below constraint in Eq. 16.

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

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

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

After obtaining the optimal design based on Eq. 1 – 17, a techno-economic analysis of the design follows. The criteria for assessment are the Equivalent Annual Income (EAI), system payback and Net Present Value (NPV), TES payback and NPV, 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 Equivalent Annual Cost in Eq. 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 Eq. 18. 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 total delivered energy is the fuel value of energy flows calculated in Eq. 19, and the net $CO_2$ emissions is estimated using Eq. 20 taking into account $CO_2$ from fuel, electricity import and $CO_2$ displaced when electricity is exported.

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

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

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

## 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.

### Design Problem

Given the energy demands for different dwelling types, summary provided in Table 1. A micro-CHP, boiler and TES are available to satisfy the energy demand. The micro-CHP is a 2 $kW_e$ natural gas engine with an overall efficiency of 90%, and a heat to power ratio of 0.385. The turnkey cost for the engine and the hot water tank are 2400 £/kW and 20 £/kW, maintenance cost 0.01 £/kWh and 0.001 £/kWh respectively [6, 16]. Off-peak and peak electricity import tariffs are 5.5 and 15.29 p/kWh, and fuel price is 3.48 p/kWh. 90% is assumed as the TES charge and discharge efficiency. The average $CO_2$ factor associated with natural gas and electricity was assumed to be 0.185 and 0.519 kg/kWh. Technology lifetime is 15years and discount rate 5%. CEPCI cost factors were applied to adjust the costs from the year provided to 2016. 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. Another instrument explored is the exemption from the $CO_2$ levy (current central value is 0.063 £/kg), 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 (kW) | Space heating | 9,904 | 5,400 | 2,480 | 1,940 |
| | Hot water | 1,712 | 1,590 | 1,351 | 1,304 |
| Floor area ($m^2$) | | 121 – 152 | 74 – 93 | 66 – 83 | 45 – 57 |

**Results and discussion**

The contribution of each technology to heat produced under different scenarios are presented in Figs. 2 – 5. 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. 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 (Fig. 4). 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, total delivered energy, and in this case more income for the home owner (Table 2 and 3). The benefits are dependent on house type, increasing based on the total space heating and hot water demand.

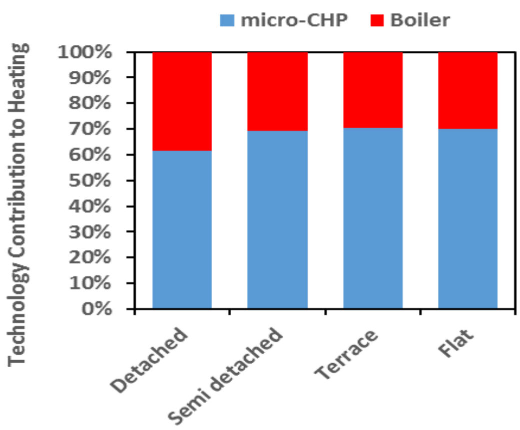



Figure 2. Non-incentivised design without TES

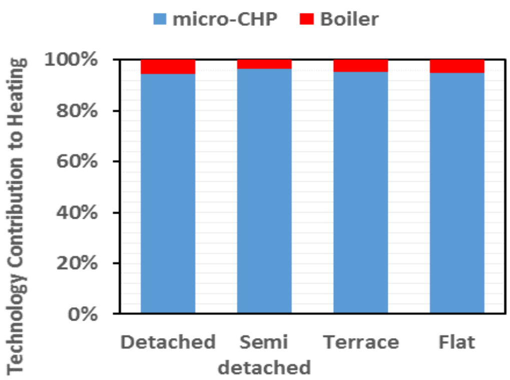
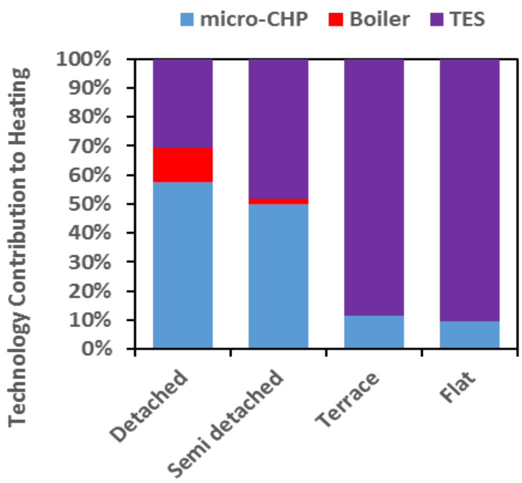



Figure 3. Incentivised design (FIT) without TES



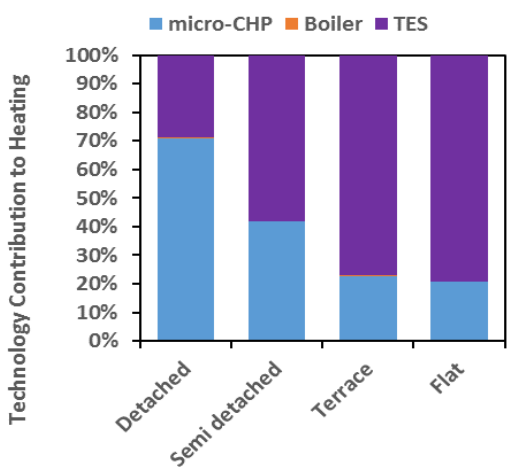




Figure 4. Non-incentivised design with TES Figure 5. Incentivised design (FIT) with TES

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 total delivered energy 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 (Fig. 5). Grid electricity import increases from detached to flat for the cases i.e. 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

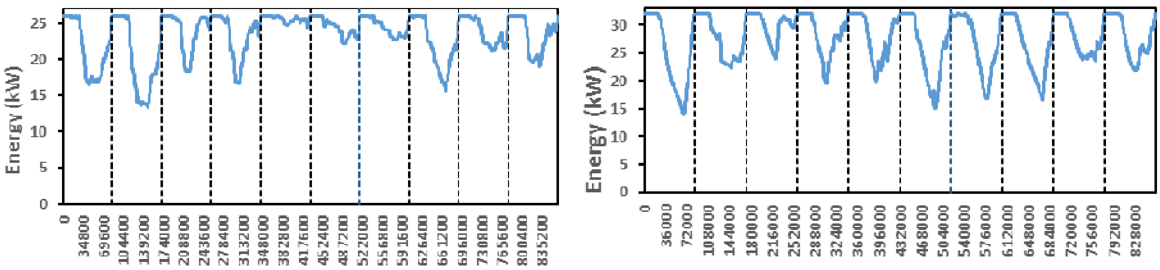
| | | Detached | Semi-detached | Terrace | Flat |
|---|---|---|---|---|---|
| EAI (£/yr) | Design with TES | 100.9 | -19.2 | -133.84 | -132.48 |
| | Design without TES | 41.22 | -52.5 | -138.5 | -156 |
| System payback (yr) | Design with TES | 14 | 20 | 36 | 36 |
| | Design without TES | 16 | 24 | 43 | 51 |
| System NPV (£) | Design with TES | -1,348 | -2,680 | -3,860 | -3,830 |
| | Design without TES | -1,716 | -2,690 | -3,580 | -3,760 |
| $NTCO_2$ (kg/yr) | Design with TES | 6,233 | 5,416 | 4,967 | 4,876 |
| | Design without TES | 6,379 | 5,514 | 4,984 | 4,889 |
| TDE (kWh/yr) | 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 (£/yr) | Design with TES | 751 | 414 | 125 | 91 |
| | Design without TES | 610 | 296 | 51 | 4 |

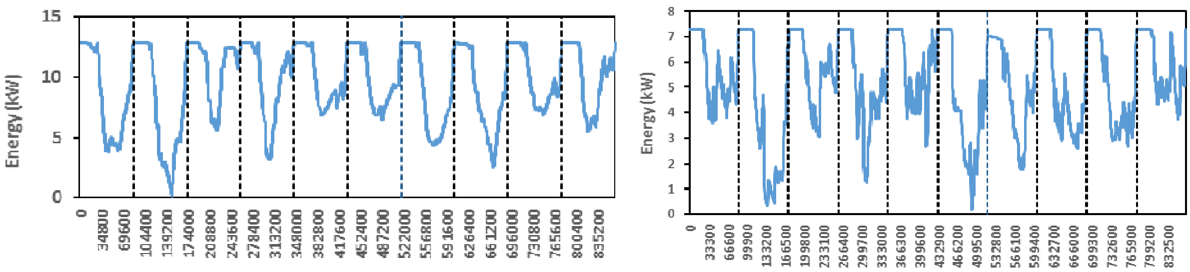
| | | | | | |
|---|---|---|---|---|---|
| System Payback (yr) | Design with TES | 4.9 | 7.4 | 12.8 | 14.0 |
| | Design without TES | 5.5 | 8.7 | 15.8 | 18.7 |
| System NPV (£) | Design with TES | 5,525 | 2,019 | -928 | -1,266 |
| | Design without TES | 4,186 | 933 | -1,616 | -2,103 |
| $NTCO_2$ (kg/yr) | Design with TES | 6,009 | 5,407 | 4,954 | 4,864 |
| | Design without TES | 5,966 | 5,308 | 4,881 | 4,802 |
| TDE (kWh/yr) | 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 (Figs. 6 and 7). 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 (Fig. 6) compared to Fig. 7. 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 Fig. 7). The x-axis in Figs. 6 and 7 are the time slices of the first 10 days in the year.




(a) (b)

Figure 6. TES discharge profile for non-incentivised design (a) detached house, (b) flat

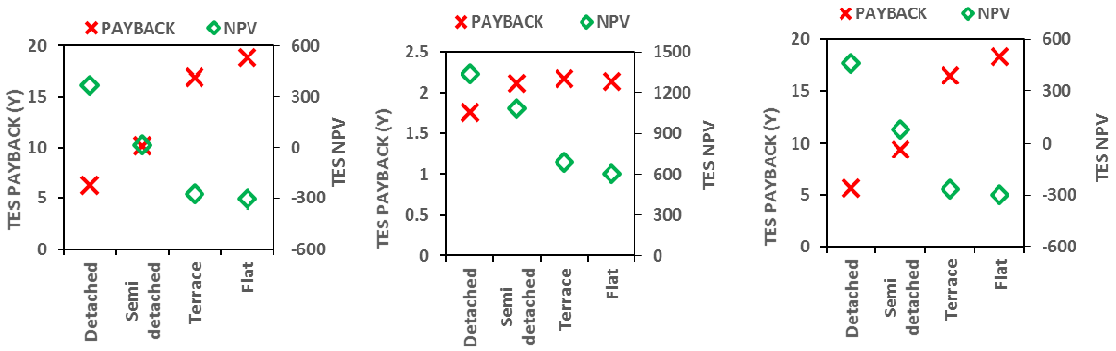



(a) (b)

Figure 7. 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 (Fig. 8a). 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. 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. 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. 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 (Fig. 8a).




(a) (b) (c)

Figure 8. Payback and NPV associated with TES investment for (a) non-incentivised design, (b) incentivised design (FIT), and (c) incentivised design ($CO_2$ levy exemption)

**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.

## CONCLUSION

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 fewer time slices to represent demand and technology characteristics. The introduction of additional binary variable 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 equivalent annual income for a homeowner, net $CO_2$ emissions, the total delivered energy, and the system payback and net present value. 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/yr, $CO_2$ by 146 kg/yr and the homeowner makes £60/yr. These additional incomes means TES investment can be paid for in the first 6.24 year 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.

## NOMENCLATURE

Symbols in the list should be included in a nomenclature list, which should be placed before the references.

| Symbol | Description | Unit |
|---|---|---|
| ACC | Annualised Capital Cost | £/yr |
| AF | Annualisation factor | - |
| BOI | Boiler | - |
| CHP | Combined heat and power | |
| FC | Fuel cost | £/yr |
| GIMP | Grid import tariff | £/kWh |
| GEXP | Grid export tariff | £/kWh |
| GEE | Grid energy efficiency | % |
| IC | Installed capital | £/kW |
| IMP | Import | |
| ISH | Initial store heat | % |
| Lo | Lower limit | |
| MC | Maintenance cost | £/yr |
| NGP | Natural gas price | £/kWh |
| Perf | Performance | |
| Q | Quantity of heat flow | kW |
| r | Number of Time slice | |
| ts | Hours in a time slice | hr |
| Uo | Upper limit | |
| W | Quantity of electricity flow | kW |
| Y | Binary variable for technology operation | |
| Z | Binary variable for technology existence | |
| $\Theta$ | Thermal storage daily losses | % |

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