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A general framework for customized transition to smart homes

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Abstract: Smart homes have the potential to achieve efficient energy consumption: households can profit from appropriately scheduled consumption. By 2020, 35% of all households in North America and 20% in Europe are expected to become smart homes Johan Fagerberg (2015). Developing a smart home requires considerable investment, and the householders expect a positive return. In this context, we address the following question: what and/or when equipment should be bought for a specific site to gain a positive return on the investment? We propose a framework to guide the smart-home transition considering customized electricity usage. The framework is based on linear models and gives a payback analysis of each combination of equipment acquisition for a specific user. The results quantify the dependence of the payback on the site and the application.

Keywords: Smart Home, energy management system, payback, return on investment.

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1 Introduction

With the growth of smart grids worldwide El-hawary (2014); Fadaeenejad et al. (2014) and the increased use of demand-response pricing mechanisms in the residential sector, the number of smart homes is expected to increase significantly. Governments support this trend for two reasons. First, distributed generation by smart homes allows investment in the grid infrastructure to be postponed. Second, the environmental impact is reduced if local renewable generation is used. Smart home owners may be interested in making a profit (or at least reducing their electricity bill) or maintaining a certain level of comfort via the scheduling of appliances De Souza Dutra et al. (2019).

Householders need to know the payback of the investment in smart-home transition, and the analysis should take into account the future value of money. We define smart-home components (SHCs) to be the appliances, machines, and technologies available for smart homes, such as photovoltaic panels (PVs), wind turbines (WTs), combined heating and power (CHP), energy storage systems (ESSs), water heaters (WHs), electric vehicles (EVs), heating, ventilation, and air-conditioning (HVAC), and solar collectors (SCs).

Our main contributions are that we create a general framework that gives a payback analysis of each SHC combination for a specific user, and we investigate whether there is a synergistic effect in the payback and the return on investment.

The remainder of this paper is organized as follows. Section 2 presents related work, and Section 3 presents our framework. Section 4 discusses the mathematical model, which is based on De Souza Dutra et al. (2019), and gives computational results. Section 5 provides concluding remarks.

2 Related work

To the best of our knowledge, a general framework that provides a payback analysis of each possible SHC acquisition combination for a specific user is not yet available.

Xu et al. (2012) propose a scheduling model that finds the best combination and the optimal capacities of batteries, water tanks, and ice/heat storage units under time-of-use electricity prices. They consider PV, SC, WH, CHP, and HVAC as well as these storage devices. Their mixed-integer linear program (MILP) minimizes the total cost of electricity, natural gas, and the investment cost of the storage devices. For each of the three cities considered, the authors compare a solution from a deterministic scenario with solutions that consider the solar radiation and demand profiles to be uncertain. Their tree method considers the expected cost in all scenarios jointly. The costs are minimized and projected over a one-year horizon. The results show that thermal storage units and water tanks are profitable, but batteries have short lifetimes and high investment costs.

van der Stelt et al. (2018) present a techno-economic analysis of household batteries and community energy storage, i.e., an ESS shared by several houses, for residential prosumers with smart appliances. Using real demand and PV generation data from 39 households in the Netherlands, the authors calculate the levelized costs of energy and the payback period for the ESS systems. Shiftable appliances are also considered. They formulate an MILP that minimizes the cost of energy acquisition from the grid. They assume that the user can inject electricity into the grid but without remuneration. The horizon is one year. They find that the savings are too small to recover the investment costs within the lifetime of the systems: the payback ranges from 26 to 43 years.

Akinyele and Rayudu (2014) present a comprehensive review of energy storage technologies with their technological development status and capital costs. They show a high cost (500–2500 $/kWh) for lithium-ion batteries.

Monyei et al. (2018) propose a biased load manager home energy management system for low-cost residential buildings using the Matlab simulation environment. A case study in Naira (Nigeria) shows that the payback is between 8.4 and 25 years.

Barbieri et al. (2012a) study the profitability of μ-CHP systems for residential buildings. They show that the Stirling engine has the best performance, with payback of 7 and 14 years if prices are respectively 3000 and 6000 kW. They build a simulation model in Excel in which there is a scheduling optimization problem for a μ-CHP component that is solved by a genetic algorithm.

Asaee et al. (2015) investigate, in a Canadian context, the energy system, greenhouse gas (GHG) emissions, and economic performance of a co-generation system based on an internal combustion engine (ICE). The analysis is based on the whole building through simulation with the ESP-r software. As the capital cost estimation was not available, the measure used was the tolerable capital cost. The results showed that the ICE is cost-effective.

Barbieri et al. (2012b) conclude, in 2012 for the UK, that the absence of subsidies and, in particular, a reduction in taxes on natural gas did not make certain μ-CHP technologies attractive. Later, Conroy et al. (2014) studied a Stirling engine in the UK, comparing the economic performance and the GHG of the μ-CHP against a condensing gas boiler. They found that the payback is 13.8 years higher than that for the boiler. Their study was based on field trial data for June 2004 to July 2005.

In the UK context, Merkel et al. (2015) propose a scheduling MILP to minimize the total annual cost. While the μ-CHP is more detailed, the thermal storage is represented by a temporal balancing equation and the boiler has power-limit constraints. They use three weeks per season with a scaling factor to represent a year. They find that the payback for a system with boilers and μ-CHP is not economical in three of the five buildings. For the other two buildings, the paybacks are 18.6 and 19.2 years. With thermal storage and μ-CHP, the system is profitable for all five buildings, with a payback between 13.1 and 17.3 years.

Six et al. (2009) study market opportunities for μ-CHP in Flanders using simulation with TRNSYS. The results show that the payback is greater than the life-span of the project.

Dufo-López et al. (2009) present an hourly management method for energy generated in grid-connected wind farms using battery storage (wind–battery systems) and hydrogen (wind–hydrogen system); these are analyzed technically and economically. They calculate the investment cost and discounted present values for large systems (2.5 MW for WT and 2 MWh for batteries). They perform a simulation over one year with the GRHYSO software to represent the system life-span of 20 years. They find that when the electricity selling price is higher than the market average, a system composed of batteries and WTs is more cost-effective than wind-only systems.

Akter et al. (2017) present an Australian case: they propose a framework that assesses a battery system with PVs. The results show that the payback and net present value (NPV) of this system are worse than those for systems with PVs only. PVs are found to be profitable in on-grid systems but unprofitable in off-grid systems because of the waste of energy, after a threshold of installed capacity. The authors consider different tariffs and reductions in CO_2 emissions, using simulation to explore the scenarios for a project with a life-span of 25 years.

Cherrington et al. (2013) perform a financial analysis of two installations in Cornwall (UK) to determine the impact of different feed-in tariffs (FITs) in a PV system with a capacity around 2 kW. The capital cost is £11000. Given annual inflation of 8%, a grid injection limit from PV generation of 50%, an annual efficiency loss, and an annual reduction in the total installation cost, the authors find paybacks in the range of 9–12 years and net profit in the range of £14400–32543. However, a similar study Pillai et al. (2014) that considers a PV of 3 kW with the same capital cost and annual inflation of 6% shows that PV without FIT is not profitable in 17 of 20 British cities. With FIT and a grid injection limit from PV generation of 50%, in all 20 cities the PV capital cost is decreased by £1000–7000. The authors perform a simulation using the PVSyst software in which the PV generation profiles are estimated by the average of twelve PV hourly outputs.

Aagreh and Al-Ghzawi (2013) present a feasibility analysis for a small hotel of combinations of PV, WT, an off-grid system with a battery, and an on-grid system. They perform a simulation with the HOMER software for a 25-year horizon. In the on-grid case, when the price for selling electricity back to the grid is null, the payback for the PV system exceeds the life-span. When the selling price is half of the market price, PVs become profitable for small capacities. WT systems without batteries and PVs are profitable (see Tables 2 and 3 of Aagreh and Al-Ghzawi (2013)) for the cases considered. The paybacks for system with batteries are not given.

Mamouri and Bénard (2018) present an evaluation of solar water heaters in 26 dispersed locations in Michigan for an average life-span of 20 years. They use the System Advisor Model simulation software and find a payback between 8.1 and 9.3 years.

Xie et al. (2017) study a detailed house design using the SketchUp modeling software. They analyze the payback for PVs, SC, a hybrid of PV and thermal panels (PVT), heat pumps, phase-changing materials, and μ-CHP systems. The results show paybacks of at least 6.5, 13, and 11 years for WH, μ-CHP, and PVs/PVT, respectively.

To the best of our knowledge, there are no studies of EV payback in the context of smart homes. However, a comprehensive ownership cost model to calculate the costs of purchase and use has been developed Al-Alawi and Bradley (2013).

The literature has focused on payback for isolated or specific sets of SHC. The results suggest that each system will have its own payback. However, current research does not explore SHC acquisition for a specific user. As mentioned in Akinyele and Rayudu (2014), the benchmarking costs of ESS depend on the application and the site. We assume that every system depends on the application, in our case, a specific consumption pattern. The goal is a tool to assist householders in their decisions about the transition to a smart home. Our work is related to Xu et al. (2012) and van der Stelt et al. (2018) since we too use optimization methods.

3 Framework

Our framework is illustrated in Figure 1: the ellipses represent optimization problems and the rectangles represent results.

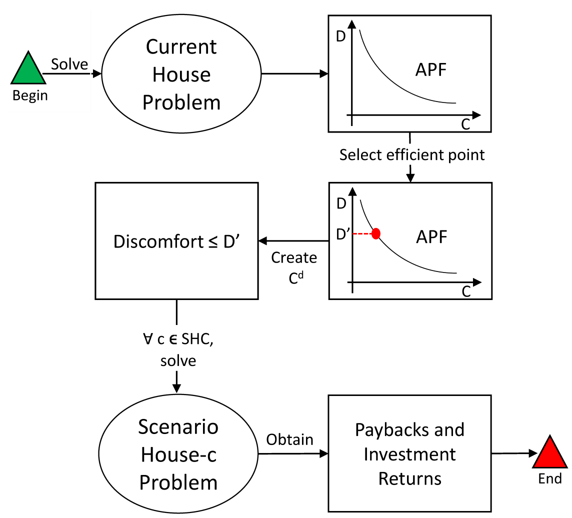

Figure 1: Proposed framework.

Let SHC^- be the set of SHC that are not already available at the house. Our goal is to calculate the payback and the return on investment of every combination in SHC^-. The first step is to determine the compromise between cost and comfort level. These are conflicting objectives, and there are multiple Pareto-optimal solutions. Hence, multi-objective optimization (MOO) Deb et al. (2002) can be applied to obtain an approximate Pareto front (APF) of this trade-off.

A detailed model has been presented De Souza Dutra et al. (2019) to find an optimal trade-off between cost and comfort by minimizing a weighted sum of the two objectives. We can adapt it to the APF approach. The model schedules the energy consumption for one day in T time intervals with a fixed length of Δ_t. The appliances are grouped as follows:

- A: set of electrical appliances.
- $A_{IEUI} \subseteq A$: set of appliances with uninterruptible operation.
- A^t_{IEUI}: set of tasks for appliances $a \in A_{IEUI}$.
- $A_{Phases} \subseteq A$: set of appliances with interruptible phases.
- A^t_{Phases}: set of tasks for appliances $a \in A_{Phases}$.
- $A^t = \{A^t_{Phases} \cup A^t_{IEUI}\}$: set of tasks for appliances $a \in A$.

The objective function is a weighted sum of three functions:
$\min_{\Xi} w_c f_c(\Xi) + w_t f_t(\Xi) + w_u f_u(\Xi)$, where:

- $f_c(\Xi) = \sum_{t \in T} \left(C^t + C^t_{CHP} \right) + C_{ev}$,
- $f_t(\Xi) = \sum_{t \in T} \sum_{a \in A} V^t_a$,
- $f_u(\Xi) = k_1 \sum_{a \in A^t_{phases}} \sum_{p=1}^{|PH_a|} \Psi_{a,p} + k_2 \sum_{a \in A^t_{IEUI}} \zeta_a + \sum_{t \in T} \sum_{a \in A^t} U^t_a$.

C^t is the cost at $t \in T$ [\$] of buying from and selling to the grid, C^t_{CHP} is the CHP operational cost at $t \in T$ [\$], C_{ev} is the fuel cost for a hybrid vehicle [\$], V^t_a is the discomfort related to the deviation from the target temperature of appliance a at $t \in T$ [^{o}C], U^t_a is the discomfort related to the usage-time deviation from the target time for appliance a at $t \in T$ [h], ζ_a is the discomfort related to the omission of task $a \in A^t_{IEUI}$[h], and $\Psi_{a,p}$ is the discomfort associated with the omission of phase p of task $a \in A^t_{Phases}$[h].

We define the "Current House Problem" to be

$$\min_{\Xi} \; [f_c(\Xi), f_d(\Xi) = \alpha_t f_t(\Xi) + \alpha_u f_u(\Xi)] \tag{1}$$

$$\Xi \in \text{Constraints} \tag{2}$$

where α_t [discomfort/^{o}C] and α_u [discomfort/h] are discomfort factors. The first step uses the above model to compute an APF, which is shown in the first rectangle in Figure 1. The next step is to select an efficient point on the APF. Suppose the decision-maker has selected a point with discomfort level D': see the red point in the second rectangle in Figure 1. Then, D' is used in the constraint $C^d : f_d(\Xi) \leq D'$. This is represented by the third rectangle.

For each subset $c \subseteq SHC^-$, the framework solves the optimization problem SHP^c with the constraint C^d and the constraint(s) for the components in c. The flow conservation constraint is modified to consider the components from the current house in addition to the components of c. Suppose $SHC^- = \{\text{PV,WH,EV}\}$ and $c^k = \{\text{EV,WH}\}$. Then SHP$^{c^k}$ is

$$\min_{\Xi} \quad f_c(\Xi) \tag{3}$$

$$f_d(\Xi) \leq D' \tag{4}$$

$$EV \quad \text{Constraints} \tag{5}$$

$$WH \quad \text{Constraints} \tag{6}$$

$$\Xi \in \text{Constraints} \tag{7}$$

Objective function (3) is the same as (1). Constraint (4) ensures a maximum discomfort level D'. Constraints (5) and (6) control the operation of the EV and WH, respectively. Finally, (7) are the constraints from (2) with the flow conservation constraint adjusted to consider the EV and WH.

Let D^p be the project duration, Pay^B the payback period, s^{slp} the savings over the life-span, T^I the total investment, and I^R the return on investment. The payback is calculated Akter et al. (2017) as $Pay^B = D^p T^I / s^{slp}$ and $I^R = s^{slp} - T^I$. If Pay^B is greater than the life-span then the project is not cost-effective.

4 Results and discussion

We now apply our framework to three case studies. We consider an horizon of 25 years, and the exchange rates used are 1 USD = 0.71 GBP, 1 USD = 1.27 CAD, and 1 USD = 3.3 BRL. The houses have appliances with distinct daily tasks A^t, a fridge, a shower, and an HVAC system. We consider houses in Belo Horizonte (BH), Brazil; London, U.K.; and Montreal, Canada.

For BH and London, we do not consider inflation; we assume that the customer wishes to acquire a system now. We evaluate 1024 systems based on an annual savings approach: 365 days are optimized and the sum of the daily savings gives the annual savings. The total saving for a specific project is the product of the annual saving and the duration.

For Montreal, we consider inflation: the cost of the SHCs changes over time. We evaluate 64 systems. The optimization is applied daily from 2019 to 2080, covering projects starting between 2019 and 2055, since each has a duration of 25 years. If a project starts in January 2020, we sum the savings of the next 365×25 days to obtain the total savings. At the end, we want to discover what and when the SHCs for a specific user in Montreal should be acquired such that it will be profitable.

For the appliances $a \in A_{IEUI} \cup A_{Phases}$, a dataset with real daily load profiles is available Kelly and Knottenbelt (2015). We create a set of load profiles for each day of the week. In our optimization, for each day of the week, we randomly select a load profile from the corresponding set.

4.1 BH case

The BH house does not have PV, Battery, WT, SC, WH, EV, or μ-CHP. We considered the $SHC^- = \{$PV 3.5 kW, PV 6.5 kW, Battery 26 kWh, Battery 13 kWh, WT 3 kW, WT 7 kW, SC, WH, EV, μ-CHP$\}$. When similar components are in the same subset $c \subseteq SHC^-$, we replace them by a new component with a capacity equal to the sum of the capacities of these components. The house does not have the infrastructurefor natural gas, so the ICE is set to μ-CHP. Table 1 summarizes the set SHC^-. The first column lists the element and the second column gives its brand and model. The third column gives the warranty, which is considered to be the life-span, and the fourth and fifth columns give the prices, in USD and BRL respectively. The sixth column gives the total price including installation cost. Unless otherwise stated, we did not consider maintenance costs: when the warranty ends, the SHC is replaced. The total daily distance (in km) for EVs is drawn from the uniform distribution U[0,70]. For the solar radiation, we used the percentage of clouds for each month from Weatherspark.com, which is shown in Figure 2. This avoids underestimating the solar radiation by assuming clear skies. The other parameters are set as in De Souza Dutra et al. (2019).

4.1.1 APF results

We used the ϵ-constraint (Laumanns et al., 2006, Algorithm 1) to obtain an APF, which is shown in Figure 3. The efficient solutions found in Figure 3 could be presented to the DM, but to aid the selection process we used MDIPNW Clemente-Císcar et al. (2014) to select an efficient point with coordinate (C',D'). With this coordinate, we can create a constraint C^d to control the maximum level of discomfort.

Table 1: SHC summary for BH case.

SHC	Brand and Model	Life-span (years)	Price (USD)	Price (R$)	Total Cost (R$)
PV 3.5 kW	14 × CS CS5P-250M	25^a	14 × 225 GoGreenSolar	11781^b	17671.50
Battery 26 kWh	2 × Tesla Powerwall	10 Tesla	12500 Tesla	41250^b	61875
WT 3 kW	3 × Bergey Excel 1 kW	5^a	3 × 4995^c	49450.5^b	74175.75
SC	Coupled Tempersol TemperSol	5^a		1400 TemperSol	2100
WH	Rheem 80G	10 Rheem	1899 Rheem	6266.7^b	9400.05
EV	2018 Nissan Leaf	5^a	30000 Nissan (a)	120000 UOL	43500
μ-CHP	Yanmar CP5WN-SNB	2^a		3950 Hikari	5925
PV 6.5 kW	26 × CS CS5P-250M	$25^{\ a}$	26 × 225 GoGreenSolar	21879^b	32818.5
Battery 13 kWh	1 Tesla Powerwall	10 Tesla	6600 Tesla	21780^b	32670
WT 7 kW	Bergey Excel 1 kW + Bergey Excel 6 kW	5^a	10000^c	330000^b	49500
WT 10 kW	Bergey Excel 10 kW	10 Bergey	31770^c	104841^b	104841

a: According to the manufacturers's datasheet
b: Value converted from USD to BRL
c: Given by the manufacturer
CS: Canadian Solar

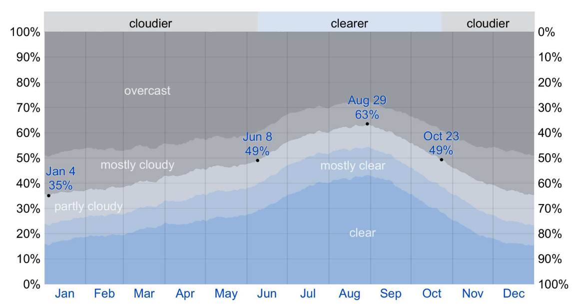

Figure 2: Percentage of time spent in each cloud cover band at BH, categorized by the percentage of the sky covered by clouds: clear < 20%; mostly clear < 40%; partly cloudy < 60%; mostly cloudy < 80%; overcast > 80%. Source: Weatherspark.com.

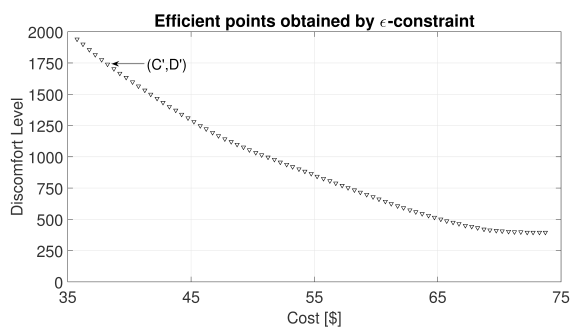

Figure 3: APF and point selected to construct C^d.

4.1.2 Solving SHP^c

For each subset $c \subseteq SHC^-$ defined in Section 4.1, we solved SHP^c. The number of sets is $2^n - 1$ because $c = \varnothing$ represents the existing scenario, which was handled in the first step of the framework.

4.1.3 Payback and investment return

Since some SHCs have life-spans below 25 years, we increased the total cost in proportion. For instance, the 3 kW WT has a life-span of five years, so we need five units to cover 25 years.

For each SHP^c, we found the total investment by summing the total cost of each component of c, as well as the payback and the return on investment. We used the formulas given in Section 3.

4.1.4 BH results

Table 2 summarizes the cost-effective combinations. An interesting finding is the relationship between the renewable generators. The expected synergy does not occur: the sum of their separate investment returns (IRs) is greater than the combined IR.

Table 2: BH results.

Component	Payback (years)	Return on investment (thousand R$)
PVs, 3.5 kW	7.57	40.632
PVs, 6.5 kW	8.59	62.656
PVs, 10 kW	9.13	87.784
WTs, 7 kW	19.58	68.489
WTs, 10 kW	22.60	41.809
SC	11.41	12.513

In this case, batteries are too expensive. Every set c with a battery has an IR lower than that without a battery; sometimes the former value is negative. The price of a Tesla battery pack must decrease to 223.5 USD to pay for itself without renewable generation. Systems composed of a battery and renewable generation have a negative IR. In these systems, the price of a 26 kWh battery must be 1650 USD to match the IR of a 3.5 kW PV system; 100 USD to match that of an SC system; and 1500 USD to match that of a 7 kW WT system.

The price of an EV must be at most 58073 R$ to be cost-effective. If the DM is going to buy a car costing x R$, the price of an EV must be at most $x + 58073$ R$. If we consider a life-span of 10 years for EVs, the price must be at most 116140 R$.

For a more detailed EV investment analysis we calculate the NPV for two scenarios taking into account the maintenance costs. In the first scenario, in the sixth year, after the warranty ends, R$ 1000 is allocated for maintenance and this cost is increased by R$ 300 in each subsequent year. The second scenario is similar until the 14^{th} year, when the EV is sold for R$ 20000 and a new one is bought. The maintenance is then zero until the 21^{st} year, when R$ 1000 is allocated; this cost is increased by R$ 300 in each subsequent year. The NPV is

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_o \tag{8}$$

where T is the number of time periods, C_t is the net cash inflow during period t, C_o is the total initial investment cost, and r is the discount rate. An investment with a negative NPV will result in a net loss. In our scenarios, we fixed the NPV to zero to find r. A project is feasible if the internal rate of return (IRR) is greater than r. For the first scenario, the NPV is zero with an IRR of 6.03%, and for the second scenario, the NPV is zero with an IRR of 2.96%. These IRR are lower than those for conservative investments such as the Brazilian Treasury Prefixed Fund (*Tesouro Prefixado 2029*) Ministério da Fazenda, which offers $r = 11.98\%$ annually. Thus, EVs are not cost-effective.

SC is a better option for water heating because a) WH systems, or b) WH and SC systems, or c) μ-CHP, WH, and SC systems are not cost-effective. μ-CHP is not cost-effective even if its price is halved because of its short life-span; it starts to be profitable if its life-span increases to 13 years. However, the payback could be interesting if a μ-CHP powered by natural gas were available. In an industrial context, Landini and de Mello Sant'Ana (2016) showed a discounted payback in less than five years for a μ-CHP powered by natural gas in a city near BH.

For this customer, the set $\{10\,\text{kW PV}, \text{SC}, 7\,\text{kW WT}\}$ gives the best IR (141.282 thousand R$) with a payback in 17.14 years. The set $\{3.5\,\text{kW PV}\}$ has the smallest positive payback.

4.2 London case

We consider the same SHC^- as for BH. The acquisition price per kWh is that for the tariff *HomeEnergy Fix Mar 2019*, from British Gas. The time of use has two stages: £0.175 from 7:00 a.m. to 10:59 p.m. and £0.0912 otherwise UKPower.co.uk; British Gas. The selling price per kWh is set to £0.0524 following the FIT export tariff in Ofgem. The price of natural gas is £0.0361/kWh from the tariff *Safeguard PAYG* British Gas. The fuel price is set to the average diesel price in April 2018 Petrolprices: £1.25/L. The ground temperature was obtained from WeatherOnline, and the house's heat resistance is based on (Wang et al., 2009, Table 2). The Weibull parameter for wind speed is taken from (Hawkins, 2012, Table 8.5 - London Array I). The nominal power of 5 kW for HVAC is considered to be at least 50% of the measuring heating capacity from GreenMatch. The total daily distance (in km) for EVs is drawn from the uniform distribution U[0,70]. The parameters for the economic analysis are given in Table 3. It is similar to Table 1, but some elements in the column "Price (£)" include the total cost of equipment and installation. Other costs are added in the column "Total Cost (£)." Unless otherwise stated, we do not consider maintenance costs: when the warranty ends, the SHC is replaced. For the solar radiation, we used the percentage of clouds for each month from Weatherspark.com, which is shown in Figure 4. The other parameters are set as in De Souza Dutra et al. (2019).

Table 3: SHC summary for London case.

SHC	Brand and Model	Life-span (years)	Price (USD)	Price (£)	Total Cost (£)
PV 3.5 kW	CS CS5P-250M	25[a]		5906.25 Renewable Energy Hub (a)	5906.25
Battery 26 kWh	2 × Tesla Powerwall	10 Tesla	12500 Tesla	8875[b*]	13312.50
WT 3 kW	3 × Bergey Excel 1 kW	5[a]		15000 Renewable Energy Hub (b)	15000.00
SC	Pure Energy 16	15[a]		4500 Renewable Energy Hub (c)	4500.00
WH	Megaflo Eco Unvented Indirect 300L	2[a]		1319.5* e-tradecounter	1979.25
EV	2018 Nissan Leaf	5[a]		21990 Nissan (b)	21990.00
μ-CHP	BlueGen	10[a]		15500* Renewable Energy Hub (d)	23250.00
PV 6.5 kW	CS CS5P-250M	25[a]		10968.75 Renewable Energy Hub (a)	10968.75
Battery 13 kWh	1 Tesla Powerwall	10 Tesla	6600 Tesla	4686[b*]	7029.00
WT 7 kW	Bergey Excel 1 kW + Bergey Excel 6 kW	5[a]		36000[d]	36000.00
WT 10 kW	Bergey Excel 10 kW	10 Bergey	31770[c]	22556.7[b*]	33835.05

a: According to the manufacturers's datasheet
b: Value converted from USD to GBP
c: Given by the manufacturer
d: Sum of 1 WT 1 kW and 1 WT 6 kW from Renewable Energy Hub (b)
CS: Canadian Solar
*: Does not include installation cost

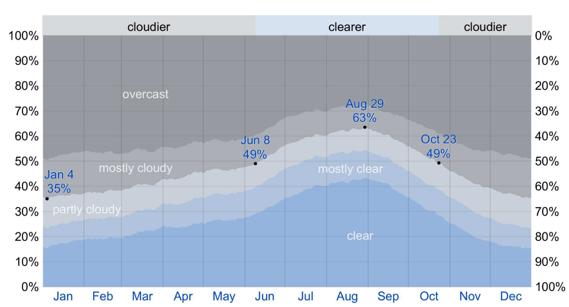

Figure 4: Percentage of time spent in each cloud cover band at London. Source: Weatherspark.com.

4.2.1 London results

Table 4 summarizes the cost-effective combinations. PVs have a payback inversely proportional to the nominal power, and the best IR is for the medium size. Our estimates are worse than Cherrington et al. (2013) and better than Pillai et al. (2014). Compared with Cherrington et al. (2013), our payback is larger by 5–7 years, and the IR is lower by £12–30 k for the 3.5 kW PV. An important difference between our study and Cherrington et al. (2013) is that we do not consider annual inflation of 8%. For a payback of 12 years in our study, the total savings over 25 years increase to £1500, which happens if electricity increases by 8% annually. For Pillai et al. (2014), in London, a 3 kW PV system with FIT has to cost at most £5 k to be self-sustaining. In our case, if the 3.5 kW PV costs £8.6 k, it will still have a positive IR. A difference between our approach and that in Pillai et al. (2014) is that we use a detailed optimization method over a whole year. Thus, the PV energy will be used in an optimal way, which can reduce the payback.

Table 4: London results.

Component	Payback (years)	Return on investment (thousand R$)
PVs, 3.5 kW	17.30	2.789
PVs, 6.5 kW	18.72	3.619
PVs, 10 kW	22.01	2.241
WTs, 10 kW	9.09	98.676

SC would not be cost-effective even if its life-span were 25 years. If its price drops to £2065, it starts to be profitable. A two-year life-span for WH makes it a costly option. It must increase its life-span to 14 years or decrease its price to £192 to become cost-effective.

Only the 10 kW WT has a positive IR. For an annual mean wind speed above 7 m/s, since our 10 kW WT has a cost of £5640/kW, this result is in line with (Sunderland et al., 2016, Table 13) that specifies a viable initial cost below £7548/kW for the generation capacity.

As for BH, batteries are too expensive. Lower battery capacities have lower losses. For the system with a 10 kW WT and a 13 kWh battery, the battery cost must decrease to 1000 USD to match the IR of the corresponding system without a battery. With the exception of systems with a 10 kW WT, every system composed of ESS and PVs or ESS and SC has a negative IR.

Although batteries are not profitable, EV is cost-effective if the life-span is 10 years: the payback is 23.81 years with an IR of £2.731 k. Taking into account the UK plug-in grant Gov.UK of £4500, the payback drops to 18.94 years with an IR of £13.981 k.

BlueGen is unprofitable: the payback is 83 years. It remains unprofitable if the life-span of this μ-CHP increases to 25 years. However, with a life-span of 25 years and the same costs as in Merkel et al. (2015), the payback is 17.52 years, which is in line with the results of Merkel et al. (2015). Given the FIT tariff of £0.1454 in June 2018 for CHP Ofgem, BlueGen is profitable (17.91 years and £22.84 k). If an ICE were used, such as the one in Table 1, the μ-CHP would never be profitable.

The best payback is for {10 kW WT}. With the plug-in grant and an EV lifespan of 10 years, the best set becomes {10 kW WT, EV} (11.34 years and £120.558 k).

4.3 Montreal case

In Montreal, it is generally believed that PV is not profitable because of the low price of electricity. The appliances that are not currently available are PV, EV, battery, and SC. Thus, the set SHC^{-} is composed of PV 3.5 kW, Battery 26 kWh, SC, EV, PV 6.5 kW, and Battery 13 kWh. Although Montreal is cold for almost half of the year, SC is used Transitionenergetique. CHP is discouraged by governmental programs for GHG reductions; even natural gas is considered undesirable La Presse.

The acquisition price per kWh is given in Hydro-Québec (2018). Beyond a fixed price for electricity availability, the tariff can be seen as an inclining block rate (IBR) with two blocks: $0.0591/kWh if the consumption is below 36 kWh per day and $0.0912/kWh otherwise. To represent this, we consider a block with a capacity of 36 kWh and a discount of 35% that can be completely used. Note that the utility does not pay for electricity injected into the grid but gives the customer a credit in kWh that is valid for two years. We consider this to be equivalent to the utility buying electricity at the selling price, but we assume that the compensation can be applied after two years.

The fuel prices are set to the average diesel price in April 2018 Gas Buddy: 1.40 CAD. The nominal power for HVAC is set to 5 kW. The ground temperature is assumed to be between 5^{o}C and 10^{o}C, following (Self et al., 2013, Figure 12). The house's heat resistance is taken from sections 34 and 37 of *Quebec's Regulation Respecting Energy Conservation in New Buildings*. The total daily distance (in km) for EVs is drawn from the uniform distribution U[0,70]. The other parameters are set as in De Souza Dutra et al. (2019).

According to Hydro-Quebec Hydro-Quebec, electricity prices follow the consumer price index (CPI), which varies between 0.5% and 3% annually for 1997 to 2017 Institut de l'statistique du Québec. Ran et al. (Fu et al., 2018, page 23) show that from 2010 to 2017 there was a 61% reduction in the residential PV system cost benchmark and from 2016 to 2017 there was a 6% reduction. We assume that PV prices fall by 6% per year, but, to take into account the effect of learning curves Peinado and Graeml (2007), the percentage is multiplied by 0.98 at the beginning of each year to give a more conservative decrease. Following (International Energy Agency, 2016, page 12), we considered a decreasing cost of 10.3% per year for batteries; this is multiplied by 0.9 each year to give a more conservative decrease. The same value is used for the decreasing cost of EVs, since batteries are considered a key component in terms of overall cost and performance Element Energy Limited (2012). SC technologies are already well developed and can be bought at low prices Raisul Islam et al. (2013), so we did not apply an annually decreasing cost. The parameters for the economic analysis are given in Table 5. The installation costs, a component of the *Total Cost*, were provided by local suppliers.

Table 5: SHC summary for Montreal case.

SHC	Brand and Model	Life-span (years)	Price (USD)	Price (CAD)	Total Cost (CAD)
PV 3.5 kW	14 × CS CS5P-250M	25^a	14 × 225 GoGreenSolar	4533.9^b	10881.3
Battery 26 kWh	2 × Tesla Powerwall	10 Tesla	12500 Tesla	15875^b	23812.50
SC	Heliodyne GOBI 408-001	10^a	1070.99 Ressupply.com	1360.16^b	2040.24
EV	2018 Nissan Leaf	5^a	30000 Nissan (a)	38100^b	38100
PV 6.5 kW	26 × CS CS5P-250M	25^a	26 × 225 GoGreenSolar	8420.1^b	20208.24
Battery 13 kWh	1 Tesla Powerwall	10 Tesla	6600 Tesla	8382^b	12573

a: According to the manufacturers's datasheet
b: Value converted from USD to CAD CS: Canadian Solar

4.3.1 Montreal results

For the solar radiation, we considered the percentage of clouds for each month Weatherspark.com, which is shown in Figure 5.

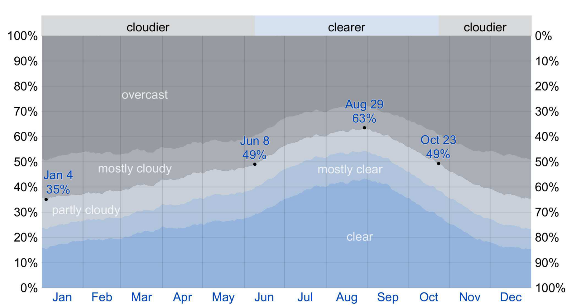

Figure 5: Percentage of time spent in each cloud cover band at Montreal. Source: Weatherspark.com.

The annual savings for some subsets $c \subseteq SHC^-$ are shown in Figure 6. The total savings, for the duration of the project, are given in Figure 7. For example, in Figure 6, each year from 2019 to 2079 has an annual saving for each component. For instance, the 3.5 kW PV has an annual saving of \$297 in 2019, increasing to \$381 in 2079. There is no significant difference between 13 kW and 26 kW batteries.

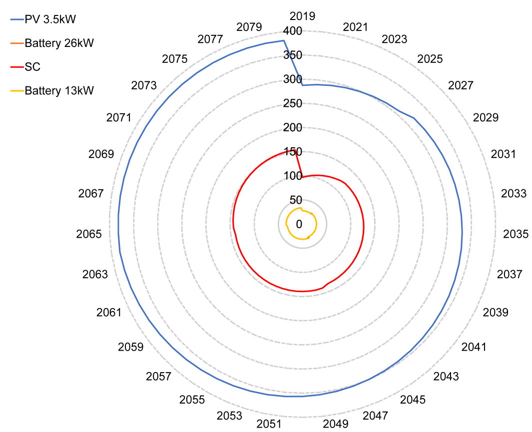

Figure 6: Annual saving ($) for some $c \subseteq SHC^{-}$.

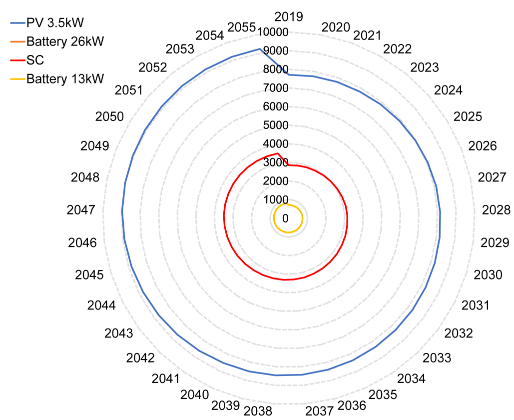

Figure 7: Total savings ($) from the year that project starts for some $c \subseteq SHC^{-}$.

Figure 8 shows the payback for the 3.5 kW PV. In Figures 8 to 12 the x axis gives the start year for the project and the y axis gives the payback in years. The dashed red line indicates the life-span of 25 years. We have three possible scenarios for inflation. If it is 3% for 25 years after the installation year (2019), the expected payback is around 24 years. If it is 0.5% for 25 years after 2024, the payback is 25 years. If it is between 0.5% and 3%, the 3.5 kW PV will have a payback below its life-span between 2019 and 2024. An upper bound (UB) on the start of the project is 2024, since the system starts to be cost-effective for the most conservative value of inflation. A lower bound (LB) is 2019 since the system is cost-effective for 3% inflation.

For a 6.5 kW PV system, the LB is 2019 and the UB is 2025. For a PV 10 kW PV, the LB is 2020 and the UB is 2025.

The SC system will not be profitable until 2028, as shown in Figure 9. With 1.75% inflation, the payback is 38 years if the project starts in 2019. A similar system had a payback above 75 years Hydro-Québec (2012). In our work, the heat-transfer fluid is a closed loop of water with self-draining. In Hydro-Québec (2012), it is a glycol-based coolant with a circulation pump. Our system is around three times less expensive than the glycol-based one, which explains the difference in the payback results.

Batteries are not used since there is a flat tariff so they are not cost-effective. EV is cost-effective after 2037: see Figure 10. The EV payback increases with the price of electricity. This is because the main source of savings is the replacement of fuel by electricity.

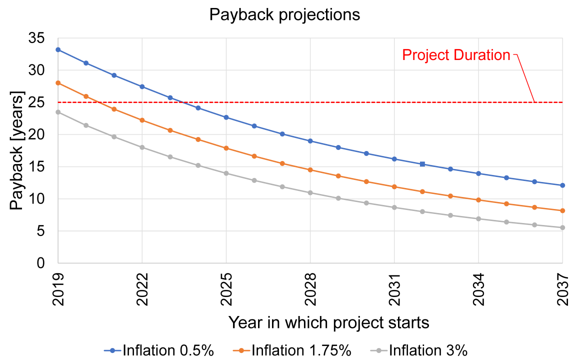

Figure 8: Payback for 3.5 kW PV in Montreal.

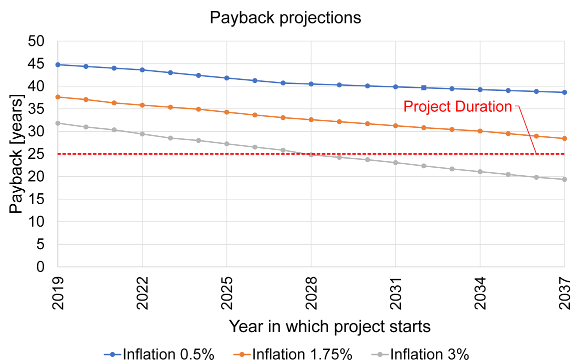

Figure 9: Payback for SC in Montreal.

If the EV life-span is 10 years, the payback is positive after 2021; see Figure 11. If we include the purchase rebate of $8000 from the Drive Electric program of the Quebec government Transition énergétique Québec, the EV payback occurs between 2028 and 2031.

To summarize, in a scenario with higher inflation, the best option is to install a PV system in 2019–2020 and to use an EV after 2028 if the life-span is 5 years. Under conservative inflation, the best option is to install a PV system in 2024–2025 and to use an EV after 2031 if the life-span is 5 years. Batteries and SC should not be used.

5 Conclusions

Transforming a house into a smart home requires considerable investment. We have proposed a framework to guide the transition to smart homes given customized electricity usage. The framework gives a payback analysis of each SHC acquisition combination for a specific user. We tested our framework on examples in Belo Horizonte, London, and Montreal. For BH and London, we considered 1024 systems based on 8760 optimized hours (1 year). For Montreal, we considered 64 systems based on 534360 optimized hours (60 years). The results quantify the dependence of the payback on the site and application, e.g., EV is attractive in London but not BH. The examples illustrate the versatility of our framework.

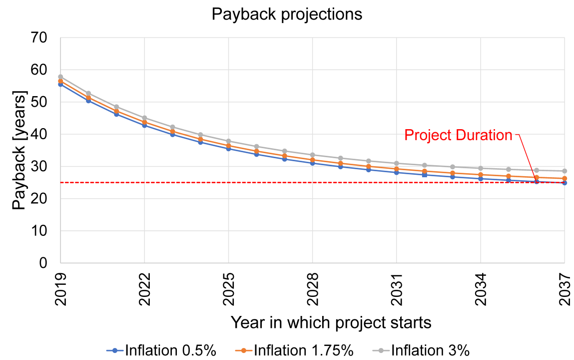

Figure 10: Payback for EV in Montreal.

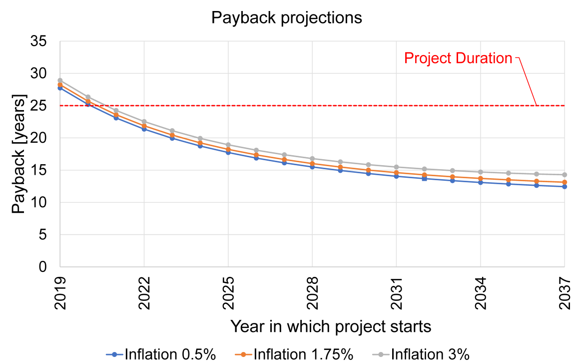

Figure 11: Payback for EV with life-span of 10 years in Montreal.

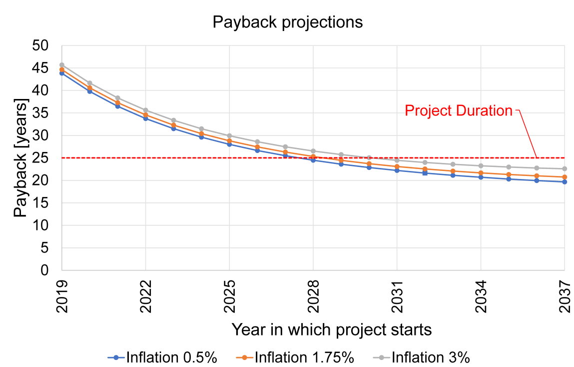

Figure 12: Payback for EV with purchase rebate in Montreal.

References

Yaser Aagreh and Audai Al-Ghzawi. Feasibility of utilizing renewable energy systems for a small hotel in Ajloun city, Jordan. Applied Energy, 103:25–31, 2013. ISSN 03062619. doi: 10.1016/j.apenergy.2012.10.008.

D. O. Akinyele and R. K. Rayudu. Review of energy storage technologies for sustainable power networks. Sustainable Energy Technologies and Assessments, 8:74–91, 2014. ISSN 22131388. doi: 10.1016/j.seta.2014.07.004.

M. N. Akter, M. A. Mahmud, and Amanullah M. T. Oo. Comprehensive economic evaluations of a residential building with solar photovoltaic and battery energy storage systems: An Australian case study. Energy and Buildings, 138:332–346, 2017. ISSN 03787788. doi: 10.1016/j.enbuild.2016.12.065.

Baha M. Al-Alawi and Thomas H. Bradley. Total cost of ownership, payback, and consumer preference modeling of plug-in hybrid electric vehicles. Applied Energy, 103:488–506, 2013. ISSN 03062619. doi: 10.1016/j.apenergy.2012.10.009.

S. Rasoul Asaee, V. Ismet Ugursal, and Ian Beausoleil-Morrison. Techno-economic evaluation of internal combustion engine based cogeneration system retrofits in Canadian houses – a preliminary study. Applied Energy, 140:171–183, 2015. ISSN 03062619. doi: 10.1016/j.apenergy.2014.11.068.

Enrico Saverio Barbieri, Francesco Melino, and Mirko Morini. Influence of the thermal energy storage on the profitability of micro-CHP systems for residential building applications. Applied Energy, 97:714–722, 2012a. ISSN 03062619. doi: 10.1016/j.apenergy.2012.01.001.

Enrico Saverio Barbieri, Pier Ruggero Spina, and Mauro Venturini. Analysis of innovative micro-CHP systems to meet household energy demands. Applied Energy, 97:723–733, 2012b. ISSN 03062619. doi: 10.1016/j.apenergy.2011.11.081.

Bergey. Bergey Excel 10kW. URL http://bergey.com/products/wind-turbines/10kw-bergey-excel. accessed Apr. 2018.

British Gas. British Gas. URL https://www.britishgas.co.uk/. accessed Apr. 2018.

R. Cherrington, V. Goodship, A. Longfield, and K. Kirwan. The feed-in tariff in the UK: A case study focus on domestic photovoltaic systems. Renewable Energy, 50:421–426, 2013. ISSN 09601481. doi: 10.1016/j.renene.2012.06.055.

M. Clemente-Císcar, S. San Matías, and V. Giner-Bosch. A methodology based on profitability criteria for defining the partial defection of customers in non-contractual settings. European Journal of Operational Research, 239(1):276–285, 2014. ISSN 03772217. doi: 10.1016/j.ejor.2014.04.029.

G. Conroy, A. Duffy, and L. M. Ayompe. Economic, energy and GHG emissions performance evaluation of a WhisperGen Mk IV Stirling engine μ-CHP unit in a domestic dwelling. Energy Conversion and Management, 81:465–474, 2014. ISSN 01968904. doi: 10.1016/j.enconman.2014.02.002.

Michael D. De Souza Dutra, M. F. Anjos, and S. Le Digabel. A realistic energy optimization model for smart-home appliances. International Journal of Energy Research, 2019. "To appear".

K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan. A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Transactions on Evolutionary Computation, 6(2):182–197, 2002. ISSN 1089778X. doi: 10.1109/4235.996017.

Rodolfo Dufo-López, José L. Bernal-Agustín, and José A. Domínguez-Navarro. Generation management using batteries in wind farms: Economical and technical analysis for Spain. Energy Policy, 37(1):126–139, 2009. ISSN 03014215. doi: 10.1016/j.enpol.2008.08.012.

e-tradecounter. Megaflo Eco Unvented Hot Water Cylinders. URL http://www.e-tradecounter.co.uk/p-232-megaflo-eco-unvented-hot-water-cylinders.aspx. accessed Apr. 2018.

Mohamed E. El-hawary. The smart grid—state-of-the-art and future trends. Electric Power Components and Systems, 42(3–4):239–250, 2014. ISSN 1532-5008 1532-5016. doi: 10.1080/15325008.2013.868558.

Element Energy Limited. Cost and performance of EV batteries: Final report for the Committee on Climate Change. Report, Element Energy Limited, 2012.

M. Fadaeenejad, A. M. Saberian, Mohd Fadaee, M. A. M. Radzi, H. Hizam, and M. Z. A. AbKadir. The present and future of smart power grid in developing countries. Renewable and Sustainable Energy Reviews, 29:828–834, 2014. ISSN 13640321. doi: 10.1016/j.rser.2013.08.072.

Ran Fu, David Feldman, Robert Margolis, Mike Woodhouse, and Kristen Ardani. U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017. Technical report, National Renewable Energy Laboratory, 2018.

Gas Buddy. Montreal Fuel Prices. URL https://www.gasbuddy.com/GasPrices/Quebec/Montreal. accessed Apr. 2018.

GoGreenSolar. Water heating cost. URL https://www.gogreensolar.com/products/canadian-solar-cs5p-250m-250-watt-solar-panel. accessed Apr. 2018.

Gov.UK. plug-in-car-van-grants. URL https://www.gov.uk/plug-in-car-van-grants. accessed May 2018.

GreenMatch. Central Heating Capacity UK. URL https://www.greenmatch.co.uk/green-energy/central-heating-capacity. accessed Apr. 2018.

Samuel Lennon Hawkins. High resolution reanalysis of wind speeds over the British Isles for wind energy integration. PhD thesis, The University of Edinburgh, 2012.

Hikari. Gerador Diesel 6kW. URL http://www.hikariferramentas.com.br. accessed Apr. 2018.

Hydro-Quebec. Residential electricity rate increases for the past 25 years. URL http://welcome.hydroquebec.com/question/166/what-are-the-residential-electricity-rate-increases-for-the-past-25-years. accessed Apr. 2018.

Hydro-Québec. Performance des chauffe-eau solaires installés au Québec - Rapport final. Report, Laboratoire des technologies de l'énergie d'Hydro-Québec, 2012. Projet pilote sur les chauffe-eau solaires domestiques du Bureau de l'efficacité et de l'innovation énergétiques.

Hydro-Québec. Hydro-Québec's electricity rates for its electricity distribution activities effective April 1, 2018, 2018. URL http://www.hydroquebec.com/data/documents-donnees/pdf/electricity-rates.pdf.

Institut de l'statistique du Québec. L'inflation. URL http://www.stat.gouv.qc.ca/statistiques/economie/comparaisons-economiques/interprovinciales/chap11.pdf. accessed Apr. 2018.

International Energy Agency. Global EV outlook 2016: Beyond one million electric cars. Report, International Energy Agency, 2016.

Anders Frick Johan Fagerberg. Smart homes and home automation. Technical report, Berg Insight, 2015. URL http://www.berginsight.com/ReportPDF/ProductSheet/bi-sh4-ps.pdf.

Jack Kelly and William Knottenbelt. The UK-DALE dataset, domestic appliance-level electricity demand and whole-house demand from five UK homes. Scientific Data, 2:150007, 2015. ISSN 2052-4463. doi: 10.1038/sdata.2015.7.

La Presse. Le gaz naturel. URL http://www.lapresse.ca/environnement/economie/201709/05/01-5130418-le-gaz-naturel-nest-pas-une-energie-de-transition-disent-des-ecologistes.php. accessed May 2018.

Clesio L. Landini and Paulo Henrique de Mello Sant'Ana. Technical, economic, and regulatory analysis of the implementation of micro-cogeneration technology in the Brazilian manufacturing sector. Energy Efficiency, 10(4):957–971, 2016. ISSN 1570-646X 1570-6478. doi: 10.1007/s12053-016-9496-x.

Marco Laumanns, Lothar Thiele, and Eckart Zitzler. An efficient, adaptive parameter variation scheme for metaheuristics based on the epsilon-constraint method. European Journal of Operational Research, 169(3): 932–942, 2006. ISSN 03772217. doi: 10.1016/j.ejor.2004.08.029.

Sina Jahangiri Mamouri and André Bénard. New design approach and implementation of solar water heaters: A case study in Michigan. Solar Energy, 162:165–177, 2018. ISSN 0038092X. doi: 10.1016/j.solener.2018.01.028.

Erik Merkel, Russell McKenna, and Wolf Fichtner. Optimisation of the capacity and the dispatch of decentralised micro-CHP systems: A case study for the UK. Applied Energy, 140:120–134, 2015. ISSN 03062619. doi: 10.1016/j.apenergy.2014.11.036.

Ministério da Fazenda. Tesouro Nacional. URL http://www.tesouro.fazenda.gov.br/tesouro-direto. accessed May 2018.

Chukwuka G. Monyei, Aderemi O. Adewumi, Daniel Akinyele, Olubayo M. Babatunde, Michael O. Obolo, and Joshua C. Onunwor. A biased load manager home energy management system for low-cost residential building low-income occupants. Energy, 150:822–838, 2018. ISSN 03605442. doi: 10.1016/j.energy.2018.03.016.

Nissan. Nissan Leaf 2018, a. URL https://www.nissanusa.com/electric-cars/leaf/versions-specs/version.s.html. accessed Apr. 2018.

Nissan. Nissan Leaf Visia, b. URL https://www.nissan.co.uk/vehicles/new-vehicles/leaf/prices-specifications.html. accessed Apr. 2018.

Ofgem. Feed-in tariff (FIT) rates. URL https://www.ofgem.gov.uk/environmental-programmes/fit/fit-tariff-rates. accessed Apr. 2018.

Jurandir Peinado and Alexandre Reis Graeml. Administração da produção. Operações industriais e de serviços. Unicenp, 2007.

Petrolprices. UK Fuel Prices. URL https://www.petrolprices.com/. accessed Apr. 2018.

Gobind G. Pillai, Ghanim A. Putrus, Tatiani Georgitsioti, and Nicola M. Pearsall. Near-term economic benefits from grid-connected residential PV (photovoltaic) systems. Energy, 68:832–843, 2014. ISSN 03605442. doi: 10.1016/j.energy.2014.02.085.

M. Raisul Islam, K. Sumathy, and Samee Ullah Khan. Solar water heating systems and their market trends. Renewable and Sustainable Energy Reviews, 17:1–25, 2013. ISSN 13640321. doi: 10.1016/j.rser.2012.09.011.

Renewable Energy Hub. Solar panels cost, a. URL https://www.renewableenergyhub.co.uk/solar-panels/solar-panels-cost.html. accessed Apr. 2018.

Renewable Energy Hub. How much is a wind turbine likely to make me and over what period?, b. URL https://www.renewableenergyhub.co.uk/wind-turbines/how-much-are-wind-turbines-likely-to-make-me-and-over-what-period.html. accessed Apr. 2018.

Renewable Energy Hub. How much does a solar thermal system cost?, c. URL https://www.renewableenergyhub.co.uk/solar-thermal-information/how-much-does-solar-thermal-cost.html. accessed Apr. 2018.

Renewable Energy Hub. BlueGen - MicroCHP Fuel Cell System, d. URL https://www.renewableenergyhub.co.uk/product/bluegen-microchp-fuel-cell-system.html. accessed Apr. 2018.

Ressupply.com. Heliodyne-gobi. URL https://ressupply.com/solar-water-heating/heliodyne-gobi-408-001-solar-hot-water-collector. accessed Apr. 2018.

Rheem. Rheem. URL https://www.homedepot.com/p/Rheem-Performance-Platinum-80-Gal-10-Year-Hybrid-High-Efficiency-Electric-Tank-Water-Heater-XE80T10HD50U0/300620269. accessed Apr. 2018.

Stuart J. Self, Bale V. Reddy, and Marc A. Rosen. Geothermal heat pump systems: Status review and comparison with other heating options. Applied Energy, 101:341–348, 2013. ISSN 03062619. doi: 10.1016/j.apenergy.2012.01.048.

D. Six, G. Vekemans, and A. Dexters. Market opportunities for micro-CHP in Flanders (Belgium). 6th International Conference on the European Energy Market, pages 1–6, 2009. doi: 10.1109/eem.2009.5207159.

Keith M. Sunderland, Mahinsasa Narayana, Ghanim Putrus, Michael F. Conlon, and Steve McDonald. The cost of energy associated with micro wind generation: International case studies of rural and urban installations. Energy, 109:818–829, 2016. ISSN 03605442. doi: 10.1016/j.energy.2016.05.045.

TemperSol. Coupled tempersol. URL https://www.tempersol.com.br/produtos/. accessed Apr. 2018.

Tesla. Powerwall. URL https://www.tesla.com/powerwall?redirect=no. accessed Apr. 2018.

Transition énergétique Québec. Drive Electric Program. URL http://vehiculeselectriques.gouv.qc.ca/english/. accessed May 2018.

Transitionenergetique. Solar Hot Water Heater in Québec. URL http://www.transitionenergetique.gouv.qc.ca/en/my-home/helpful-advice/solar-hot-water-heater/#.WujqZogbO71. accessed Apr. 2018.

UKPower.co.uk. Everything you need to know about Economy 7. URL https://www.ukpower.co.uk/home_energy/economy-7#what-is-economy-7. accessed Apr. 2018.

UOL. EV cost estimation. URL https://motor1.uol.com.br/news/184672/nissan-leaf-brasil-2019/. accessed Apr. 2018.

Sander van der Stelt, Tarek AlSkaif, and Wilfried van Sark. Techno-economic analysis of household and community energy storage for residential prosumers with smart appliances. Applied Energy, 209:266–276, 2018. ISSN 03062619. doi: 10.1016/j.apenergy.2017.10.096.

Liping Wang, Julie Gwilliam, and Phil Jones. Case study of zero energy house design in UK. Energy and Buildings, 41(11):1215–1222, 2009. ISSN 03787788. doi: 10.1016/j.enbuild.2009.07.001.

WeatherOnline. London ground temperature. URL http://www.weatheronline.co.uk. accessed Apr. 2018.

Weatherspark.com. Average weather. URL https://weatherspark.com/countries. accessed May 2018.

Y. Xie, M. S. Gilmour, Y. Yuan, H. Jin, and H. Wu. A review on house design with energy saving system in the UK. Renewable and Sustainable Energy Reviews, 71:29–52, 2017. ISSN 13640321. doi: 10.1016/j.rser.2017.01.004.

Zhanbo Xu, Xiaohong Guan, Qing-Shan Jia, Jiang Wu, Dai Wang, and Siyun Chen. Performance analysis and comparison on energy storage devices for smart building energy management. IEEE Transactions on Smart Grid, 3(4):2136–2147, 2012. ISSN 1949-3053 1949-3061. doi: 10.1109/tsg.2012.2218836.