Journal of Energy Storage 26 (2019) 101048

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Optimal Peer-to-Peer energy sharing between prosumers using hydrokinetic, diesel generator and pumped hydro storage

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ARTICLE INFO

Keywords:
Consumer
Diesel generator
Hydrokinetic
Peer-to-Peer energy sharing
Pumped hydro storage
Prosumers, South Africa

ABSTRACT

In this paper, an optimal Peer-to-Peer energy sharing model between two small prosumers is developed and simulated in the south African context. For this purpose, a case study of a commercial type prosumer sharing power with a residential prosumer, both on the same premise, is used to demonstrate the effectiveness of the model. The commercial prosumer owns a small hydrokinetic system operating in conjunction with a pumped hydro storage while the residential prosumer has a diesel generator. The developed model aims to minimize the resulting cost of energy linked to the diesel generator, while optimizing the power flow between the two prosumers. Using actual data, the developed model has been used to simulate and analyze the complex interaction between the different power sources, the energy storage and the demands within the proposed system sizing and operation constraints. The simulation results show that the power flows can be optimally managed, resulting in a substantial reduction in the residential prosumer's operation cost which can now rely not only on its diesel generator but also on the power shared by the hydrokinetic and pumped hydro system of the commercial prosumer.

1. Introduction

In most developing countries, the use of diesel generators (DG) to supply isolated areas is still one of the preferred options [1]. This is due to fact that DGs have low initial costs per produced kW compared to most renewable energy (RE) sources [2]. The other advantages of DGs is that they are easily movable from one site to another and, unlike RE, the output power produced is not linked to the variable magnitude of the resource available at a specific time [3].

However, DGs need continuous supply in fuel to operate. Additionally, the non-linearity of the load supplied result in high specific fuel consumption when the DGs are operating at low loading. These make electricity production using DG very expensive on the long run [4].

The other disadvantage of DG is the negative impact on the environment such as greenhouse gases produced from the exhaust [5].

Considering small-scale RE sources for isolated power supply; hydrokinetic (HKT) energy sources have been investigated and identified as suitable energy sources for area with adequate small streams or rivers. They have high power-to-size ratio and have very competitive cost of energy produced compared to RE sources such as photovoltaic and wind systems of the same size [6].

HKT systems extract kinetic energy from free-flowing water resources, thereby avoiding specific challenges such as important civil infrastructure works linked traditional hydropower [7].

Some research works have been conducted on the use of hybrid DG and HKT in isolated areas based on aspect such as optimal sizing [8], incorporation of pumped hydro storage (PHS) [9] or optimal energy management [10]. Most of these studies have been conducted with the aim of minimizing the operation cost of DG while meeting the load requirements. However, it can be seen that the load demand has been combined as one, and only one prosumer (producer and consumer) was considered.

In the case were several isolated prosumers are considered, the Peer-to-Peer energy sharing concept can be applied to increase the availability of power produced locally in a microgrid scheme [11]. This concept can also lead to the reduction in the storage's size, reduction in the energy wasted when it is not used as well as in the reduction of the cost of electricity when the system is properly managed.

A number of distinct Peer-to-Peer energy sharing schemes have been implemented around the world such as *Piclo* in the UK [12], *Vandebron* in Netherland [13], *PeerEnergyCloud* in Germany [14], Smart Watts also in German [15], *Yeloha* and *Mosaic* in the US [16, 17], SonnenCommunity in Germany [18], *Lichtblick Swarm Energy* in Germany [19], *Community First! Village* in the US [20], *TransActive* Grid in the US [21] and *Electron* in the UK [22]. However; there is a need to investigate this

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https://doi.org/10.1016/j.est.2019.101048
Received 4 August 2019; Received in revised form 1 October 2019; Accepted 28 October 2019

concept for prosumers operating in the South African context.

South Africa has seen an increase in the implementation of micro-generations, in which households or organisations install their private small-scale, renewables-based energy generators to produce and use electricity [23]. These renewable energy sources can play a significant role in South Africa leading to decreasing the carbon emissions and increase the economy.

Currently in South Africa, the household-generators must dump the excess of their energy production because of the Electricity Regulation Act of 2006 that doesn't allow electricity to be fed back to the national grid [24]. Because of the problem above, local researchers at the Central University of Technology have started to investigate the possible 'free trade' between micro-generators in a Peer-to-Peer energy scheme. In such a Peer-to-Peer energy scheme, any two individuals/households (called prosumers) can directly share electricity between each other, without inter-mediating utilities or other third parties. The main aim is to research the feasibility of a 'democratised' Peer-to-Peer energy market where prosumers can decide rather to share the excess generation free of charge to the nearby household instead of dumping it or storing it for later use. The households that produce the energy should have the power to decide on what to do with it. Also, consumers should be able to decide whether getting energy from the grid or from the nearby prosumer who has excess of energy. Similar sharing schemes are already in place in other markets, for example via Airbnb in the hotel industry, or Uber in taxi hire [25].

One of the factors that can negatively affect the development of Peer-to-Peer energy schemes in South Africa is the fact that energy cannot be shared from prosumers that are on different earth numbers through the municipal electrical distribution infrastructures. Electricity can only be shared between prosumers that are on the same land.

Therefore, prosumers on the same municipal earth number and exhibiting different demand profiles, can be connected in a microgrid and use the Peer-to-Peer energy sharing concept [4]. This can lead to the reduction in the storage's size, reduction in the electricity dumped as well as in the reduction on the grid reliance.

Therefore, in this paper, an optimal energy dispatch model that satisfies the need of minimizing the operation cost while satisfying the load demands, is presented for an isolated microgrid consisting of two prosumers operating in a Peer-to-Peer energy sharing scheme. The main purpose of the developed model is to minimize the prosumers' operation costs while optimizing the system's power flow considering the different component's operational constraints. The simulations have been performed using "fmincon" implemented in MATLAB. The model has been applied to a case where the commercial prosumer owns a HKT system with a PHS while the residential prosumer has a DG; the simulation results are analyzed and compared to the case where the DG is used alone to supply the residential prosumer's demand. The results show that using the developed Peer-to-Peer energy sharing model for the proposed prosumers, fuel and cost saving can be achieved on the residential prosumer's side compared to the case where the DG is used alone to supply the same load demand.

2. Model development

2.1. System description

The microgrid under consideration is composed of a commercial prosumer that can generate electricity using a HKT system. It also has a PHS system that can assist in managing the demand by storing the excess energy from the HKT for later use. The residential prosumer, on the other hand, uses power produced by the DG, that needs to be minimised because of the operation cost linked to the fuel consumed.

The different power flows between the two prosumers are shown on Fig. 1. From this figure, it can be seen that the commercial prosumer is mainly supplied by the HKT, from which it has priority. If there is more energy from the HKT than the what is required from the commercial prosumer, the excess is either used to pump water in the PHS reservoir or to supply the load demand of residential prosumer and minimize the DG usage.

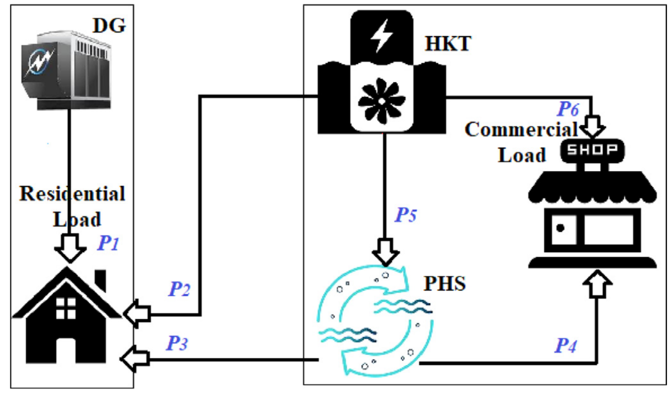

Fig. 1. Proposed Peer-to-Peer energy sharing in the microgrid.

In the case where the HKT power is not enough to provide the required energy to the commercial prosumer, the PHS is used as backup to generate and supply the deficit of energy needed. Fig. 1 also show the different power flow related to the residential prosumer, which owns a DG as main supply option. However, the operation cost linked to the DG has to be minimized. Therefore, the HKT energy produced by the commercial prosumer and the PHS can be used to reduce the reliance from the DG at the residential prosumer's side.

It has to be highlighted that the operation decisions, at any time, depend on both prosumers' instantaneous demands, on the size of different energy sources as well as on the state of potential energy (water level) stored in the PHS's reservoir.

The different power flows from Fig. 1 can be defined as follows:

- P_1: Power from the DG to residential prosumer's demand in kW.
- P_2: Power from the commercial prosumer's HKT used to supply the residential prosumer's load demand in kW.
- P_3: Power from the commercial prosumer's PHS used to supply the residential prosumer's load demand in kW.
- P_4: Power from the commercial prosumer's PHS used to supply its own load demand in kW.
- P_5: Power from the commercial prosumer's HKT used to pump water in the PHS's reservoir in kW.
- P_6: Power from the commercial prosumer's HKT used to supply its own load demand in kW.

2.2. Objective function

The main objective of the proposed energy management model is to minimize the operation cost resulting from the fuel consumed and power generated from the DG while maximizing the power from the commercial prosumer's HKT energy system to supply the commercial demand. In this specific case, the cost of power from the DG to supply the residential prosumer is considered as the sole component carrying operation costs for the considered optimization window. All the other power flows have to be optimised depending on the operation strategy. The objective is to minimize the fuel consumption cost from the DG during the operation time. This can be expressed as:

$$f = \min C_f \times \sum_{j=1}^{N} (aP_{1(j)}^2 + bP_{1(j)} + c)\Delta t + \max(P_6)\Delta t \tag{1}$$

Where f is the function to be minimised; N is the number of sampling intervals within the operation range or period of the system; a, b, c are the fuel cost coefficients of the selected DG; j is the j^{th} sampling interval; C_f is the fuel price per litre.

Additionally, the different internal power flows between the prosumers are not linked to any cost component.

Based on the stated objective function, the power flow from the commercial prosumer's HKT (P_2) and PHS (P_3) to the residential prosumer will be optimised depending on the power generated from the HKT, demands as well as the potential energy in the PHS at the considered sampling interval J.

2.3. Variable constraints

2.3.1. Load balances

The equality constraints available in this system are given by the load power balances for the two prosumers and can be expressed as follows:

$$P_{Residential(j)} = P_{1(j)} + P_{2(j)} + P_{3(j)} \tag{2}$$

$$P_{Commercial(j)} = P_{4(j)} + P_{6(j)} \tag{3}$$

Eq. (2) means that for each sampling time "j" the residential prosumer's load demand can be met by a combination of the power from the DG, HKT or PHS.

Eq. (3) means that for each sampling time "j" the commercial prosumer's load demand can be met by a combination of the HKT or PHS power.

2.3.2. HKT and PHS output power

At any sampling time (j), the sum of HKT power for supplying both prosumer demands for pumping water in the PHS's reservoir must be less or equal to the maximum HKT power generated in the considered specific sampling interval (depending on the size and available resources). This can be expressed as:

$$P_{2(j)} + P_{5(j)} + P_{6(j)} \leq P_{HKT(j)}^{\max} \tag{4}$$

In addition, for each sampling interval (j), the sum of powers from the PHS to supply the both prosumers must be less than the maximum power of the turbine of the PHS. This can be expressed as:

$$P_{3(j)} + P_{4(j)} \leq P_{PHS}^{Max} \tag{5}$$

2.3.3. PHS energy dynamic

As show on Fig. 1, in the considered set-up, the PHS's reservoir can only be supplied from the HKT. Therefore, at any given sampling interval (j), the PHS's volume of water stored (Similar to a state of charge SoC) can be expressed as follows:

$$SoC_{(j)} = SoC_{(0)} + \frac{\Delta t}{C_n} \times \left(\eta_{Pump} \times \sum_{j=1}^{N} (P_{5(j)}) - \frac{\sum_{j=1}^{N} P_{3(j)} + P_{4(j)}}{\eta_{Gen}} \right) \tag{6}$$

Where $SoC_{(0)}$ is the initial state of charge at the beginning of every sampling time; C_n is the nominal energy storage capacity of the PHS system in kWh; η_{Pump} and η_{Gen} are the PHS's pump and generator's efficiencies respectively.

2.3.4. Variable boundaries

The different power generator can only operate within their respective size or rating constraints. For all the control variables linked to the prosumers, these boundariess can be expressed as:

$$0 \leq P_{i(j)} \leq P_{i(j)}^{\max} \tag{7}$$

Where P_i represents all the different control variables from P_1 to P_6; $P_{i(j)}^{Max}$ is the maximum power that is produced by the HKT generators and which depend on the resource. However, the maximum power can also be expressed as $P_{i(j)}^{Max}$ in the case where the control variables linked to the DG and PHS; knowing that their maximum outputs are linked to the design, not to the resource.

As the volume (SoC) is the only considered state variable, the boundaries linked to this variable can be written as:

$$SoC_0 \leq SoC_j \leq SoC^{\max} \tag{8}$$

2.3.5. Exclusive power flows

Since the PHS system cannot operate in pumping and generating mode at the same time, the exclusive power flow constraint can be expressed as:

$$(P_{3(j)} + P_{4(j)}) \times (P_{5(j)}) = 0 \tag{9}$$

2.3.6. Fixed-final state condition

In order to repeatedly implement the optimal control of the Peer-to-Peer energy model between prosumers, the water level at the end of the control horizon should be equal to the one at the beginning of the control horizon. This can be mathematically expressed as:

$$\sum_{j=1}^{N} (P_{3(j)} + P_{4(j)} - P_{5(j)}) = 0 \tag{10}$$

2.4. Solver selection

Because Eqs. (1) and (9) are non-linear, the whole model can be seen as a nonlinear optimization problem. Therefore, solvers such as "*fmincon*" with the interior-point algorithm from MATLAB optimization toolbox can be selected to deal with the optimization problem [23]. This can be expressed as:

$$\min_x f(x) \text{Subject to: } \begin{cases} c(x) \leq 0 \\ c_{eq}(x) = 0 \\ Ax \leq b \\ A_{eq}x = b_{eq} \\ l_b \leq x \leq u_b \end{cases} \tag{11}$$

Where: x, b, b_{eq}, l_b, and u_b are vectors; A and A_{eq} are matrices; $c(x)$ and $c_{eq}(x)$ are functions that return vectors and $f(x)$ is a function that returns a scalar.

3. Case study description

3.1. System sizing

The methodology for sizing the DG, PHS and HKT are described in reference [26–28] respectively. The size of the considered power generator as well as storage on both prosumer sides can be found in Table 1.

For the same kW rating, different DGs from different manufacturers present different fuel consumption curves. For this case, a 1.5 kW DG manufactured by "*Cummins power*" has beed selected with its respective fuel consumption parameters given in Table 1 [3].

Table 1
Simulation parameters.

Item	Figure
Sampling time (Δt)	30 min
HKT rated power	2 kW
PHS nominal capacity	9.6 kWh
DG rated power	1.5 kW
a	0.0074 L/h.kW^2
b	0.2333 L/h.kW
c	0.4200 L/h
$SoC_{(0)}$	100%
SoC^{max}	100%
SoC^{min}	20%
η_{Gen}	70%
η_{Pump}	75%
C_f	1.2 US$

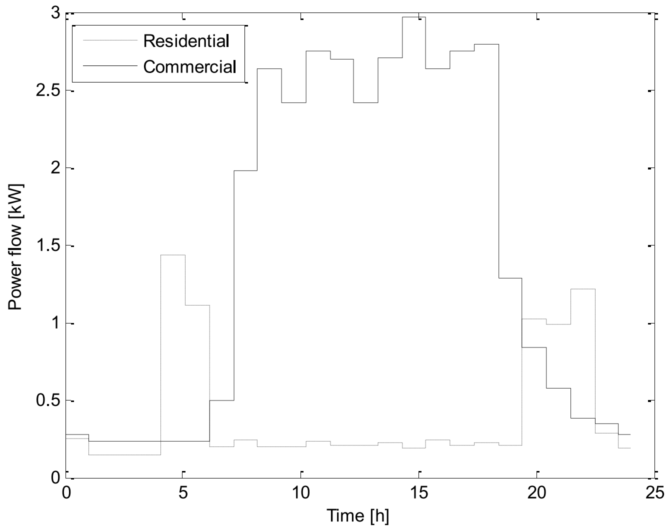

Fig. 2. Residential and commercial prosumers' load profiles.

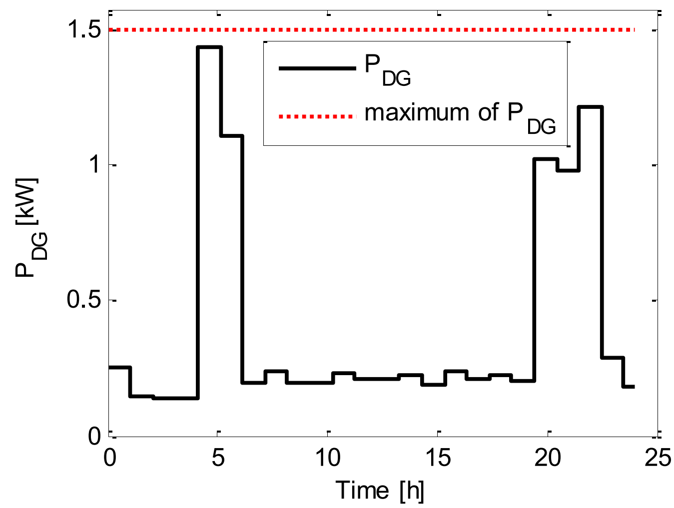

Fig. 3. Residential load supplied by DG only.

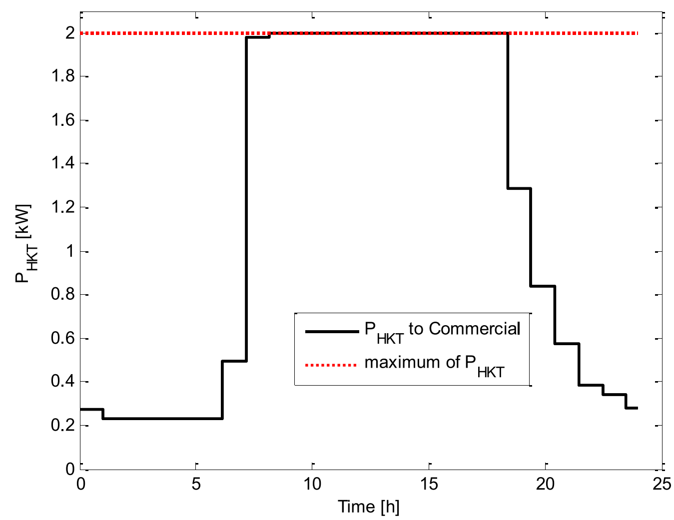

Fig. 4. Optimal power sharing from HKT to commercial load.

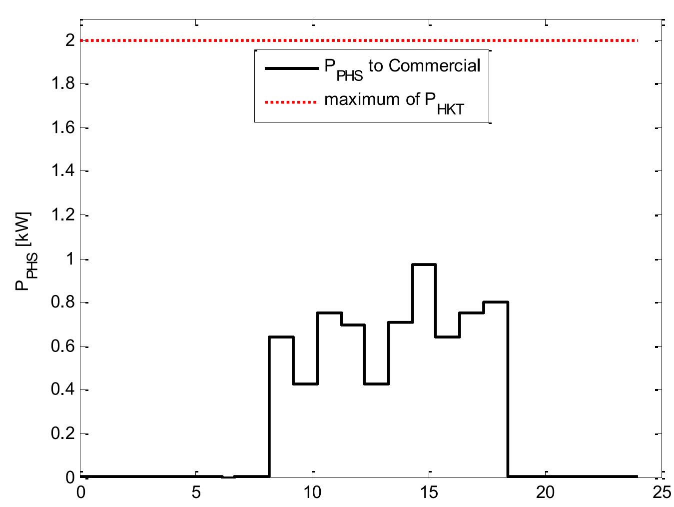

Fig. 5. Optimal power sharing from PHS to commercial load.

3.2. Load profiles and resources

For the proposed case study, the two prosumer demand profiles can be seen on Fig. 2. It can be noticed that the residential profile has a peak demand in the morning from 06h00 to 07h00 as well as in the evening between 19h00 and 22h00. On the other hand, the commercial profile is low for the whole night and quite high and steady during the day, from 08h00 to 18h00.

Detailed info on the water resources used for the HKT system can be found in Ref. [26].

These HKT resources and load data are collected for the worst case in winter where the water flow is low while the load demands are high.

4. Simulation results and discussion

In this section, the simulation results from the proposed system running under the developed optimal energy management model are discussed. The results will be discussed based on the behaviors linked to the power flow from the HKP, PHS as well as the DG in different periods within the simulation time horizon.

The DG alone is used as baseline for comparison purposes when the residential prosumer cannot be supplied by the HKP and PHS energy shares from the commercial prosumer.

4.1. Baseline: DG alone to supply the residential demand

In this case, the DG power is used as the only option to supply the residential demand. Fig. 3 illustrates the case in which the DG is used as the only supply option. It can be clearly seen that the DG operates in a load following manner. Later, the operation cost incurred using the DG alone will be compared to the resulting costs where the DG is used in conjunction with the HKT and PHS of the commercial prosumer in the developed peer to peer energy sharing model.

4.2. Optimal Peer-to-Peer energy sharing between the prosumers in the microgrid

Figs. 4–6 show how the maximum and optimal output power flows from the HKT and PHS perform on the commercial prosumer's side while Figs. 7–9 are related to the HKT, PHS and DG, respectively, on the residential prosumer's side during the selected simulation horizon. It has to be highlighted that the HKT and the PHS belong to the commercial prosumer who is optimally sharing power with the residential prosumer when both are operated under the objective function and constraints of the developed optimization model.

From 00h00 to 04h00, the commercial load demand is low; therefore, it is successfully met by the HKT only (Fig. 4); and this goes up to

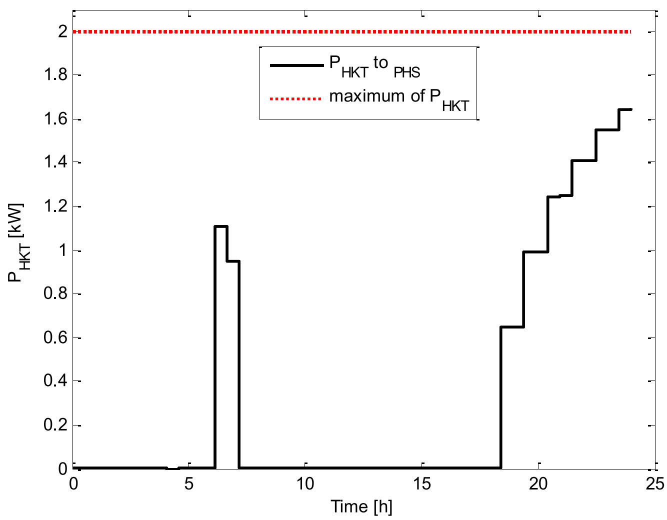

Fig. 6. Optimal power from HKT to PHS.

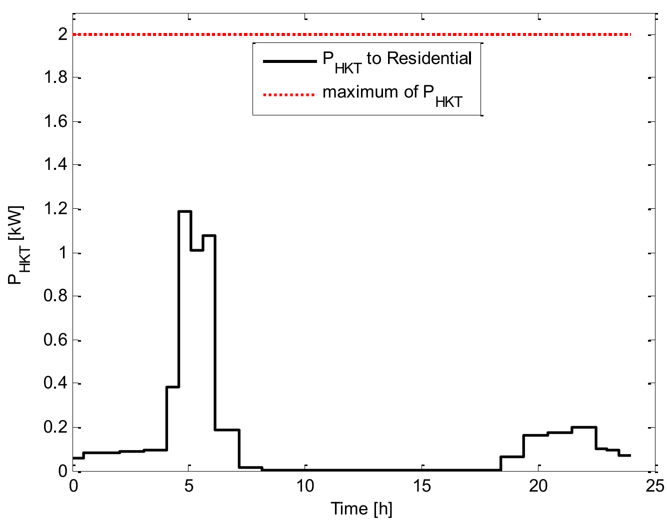

Fig. 7. Optimal power sharing from HKT to residential load.

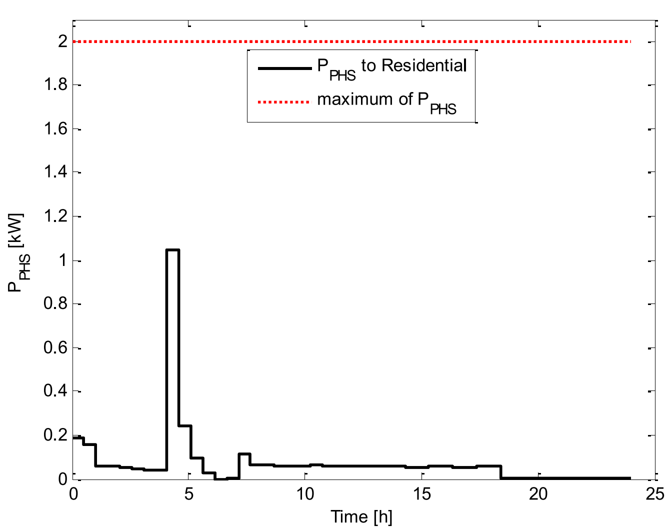

Fig. 8. Optimal power sharing from PHS to residential load.

07h00.

It can also be seen that the residential load demand is low, therefore it is successfully met by a contribution of the HKT (Fig. 7) and PHS

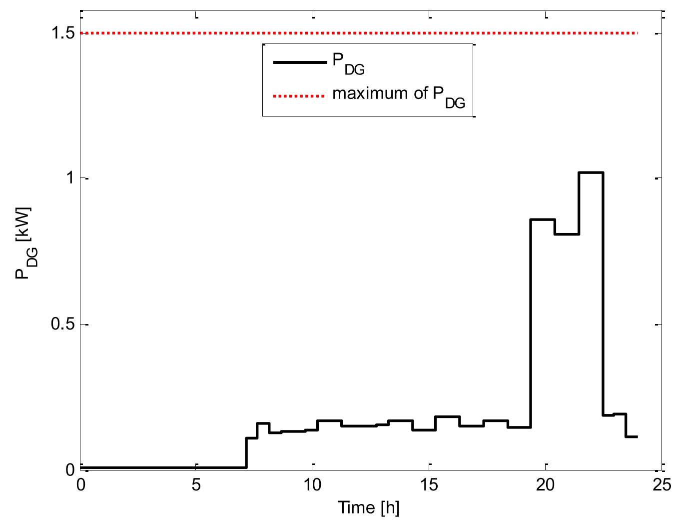

Fig. 9. Power from DG to residential load.

(Fig. 8) from the commercial prosumer. The DG is not used to supply the residential load during this period (Fig. 9).

Between 04h00 and 05h00, the residential load is mainly supplied by the PHS (with a contribution of close to 1 kW), and complemented by the HKT (with a contribution of 0.4 kW). The DG is still not used to supply the residential load during this period. Between 05h00 and 06h00, the residential load is mainly supplied by the HKT with a small contribution from the PHS, while the DG is still off.

Between 06h00 to 07h00 the HKT is used alone to supply the residential load demand. It has to be noted that between 06h00 and 07h00 the HKT is also used to pump water into the reservoir of the PHS (Fig. 6) and the corresponding state of water stored is increased (Fig. 10). Therefore, the PHS cannot operate in generation mode to supply any of the load demands. The optimal operation strategy in this period is still to keep the DG off for cost saving.

Between 07h00 and 18h00, the commercial load demand is high; therefore, the HKT system is operating at its maximum generation capacity (2 kW) to supply, in priority, the commercial load. This is complemented by the PHS's contribution (Fig. 9). On the other side, the residential demand is supplied by the PHS with a contribution from the DG. Because of its size constraint, the HKT does not supply the residential demand in this period. Therefore, the residential demand is supplied by the PHS complemented by the DG.

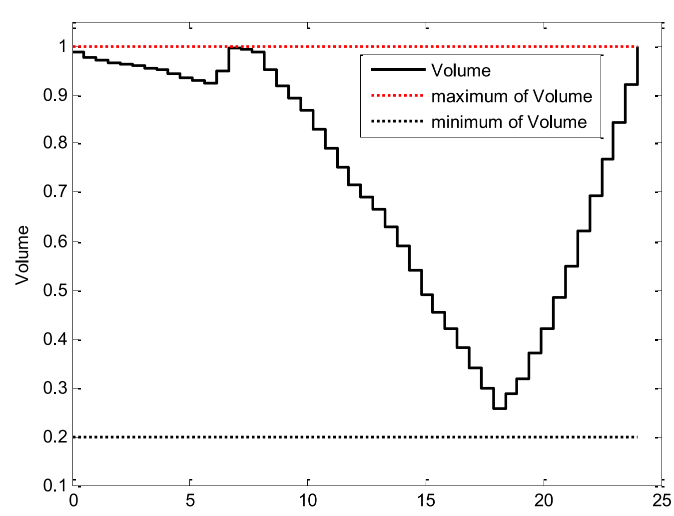

Fig. 10. Dynamic of the water volume (SoC) in the PHS reservoir.

Table 2
Costs comparison.

Supply option	Daily operation cost ($)
Load exclusively supplied by the DG	$6.24
Peer-to-Peer energy sharing	$2.65
savings	$3.59

From 18h00 to 24h00, there is enough power from the HKT to supply the commercial load demand as well as to pump water in the PHS's reservoir to satisfy the final-state condition that needs to be met at the end of the simulation horizon.

Because the final-state condition constraint and the exclusive power flow, the reservoir is being refilled; therefore, there is no output power from the PHS in this considered interval to supply any of the load demands (Figs. 5 and 8). The residential demand is supplied with a small contribution from the HKT power not used to supply the commercial prosumer or to pump water in the reservoir (Fig. 7) while the major share is from the DG as it is the last available supply option (Fig. 9).

4.3. Daily economic analysis

Table 2 gives a summary on the cost saving that can be realized on the residential consumer' s side when the Peer-to-Peer energy sharing scheme is implemented with proposed optimal energy management model instead of using the DG alone.

5. Conclusion and recommendations

In this paper, an optimal energy dispatch model that satisfied the need of minimizing the operation cost while satisfying the load demands, was presented for an isolated microgrid consisting of two prosumers. The main purpose of the developed model is to minimize the prosumers' operation costs while optimizing the system's power flow considering the different component's operational constraints. The simulations have been performed using "fmincon" implemented in MATLAB. The model has been applied to a case where the commercial prosumer owns a HKT system with a PHS while the residential prosumer has a DG. The simulation results were analyzed and compared to the case where the DG is used alone to supply the residential prosumer's demand. The results show that using the developed Peer-to-Peer energy sharing model for the proposed, fuel and saving can be achieved on the residential prosumer's side compared to the case where the DG is used alone to supply the same load profile.

In this work, the internal power flow between the two prosumers were considered to be free. For future work, a contracted cost component should be allocated to the internal power flows from the HKT and PHS from the commercial prosumer to the residential consumer. This may assist the commercial prosumer in maximizing its return on investment while giving to the residential prosumer the opportunity to compute the total cost acquired from the different power source. These cost components may also influence the operation decision and strategies linked to the different power flow.

Declaration of Competing Interest

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

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