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Dynamic programming for optimal operation of a biofuel micro CHP-HES system

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Abstract: Combined heat and power systems (CHPs) have received much attention in recent years due to increasing use of bio-fuels and distributed generation (DG). Conventionally, they are connected to the power grid to balance electrical demands and supplies. This research investigated an off-grid (stand-alone) biofuel micro CHP system with hybrid energy storage (HES) (including battery banks and super-capacitors) by developing an energy management strategy based on dynamic programming (DP). DP is an optimization strategy which has been applied to energy systems in recent years. However, they suffer from dimension problems when the number of variables increases. This work is the first attempt to apply the decision tree (DT) to multi-dimension DP solutions in energy systems. The energy efficiency is improved from 45.77% to 57.97% using diesel- biofuels and the system has a potential for commercial applications. The experimental test results validate its feasibility and effectiveness.

Keywords: Combined heat and power; dynamic programming; decision tree; hybrid energy storage; optimal energy management.

1. Introduction

Over the last ten years, there has been an increase in the use of combined heat and power (CHP) systems as part of distributed generation (DG) primarily owing to their energy savings, high energy efficiency, as well as reduced carbon dioxide emissions and other environmental benefits [1, 2]. CHPs adopt cascaded utilisation of energy to provide both heat and electricity. Generally, they are connected to power grid. On the other side, off-grid CHPs that feature decentralization can improve energy efficiency by using waste heat directly over production, which could save 80% of the primary energy input as reported [3]. Domestic CHPs can transform waste heat to multi-energy to end-users onsite. With these advantages, this type of CHPs has the potential to be of commendable energy systems in household.

Bio-fuels as renewable energy resources are generally used with CHP. These applications due to their sustainability have attracted considerable interest from the research community. For the CHPs applied in domestic sectors, a noticeable research focus is how to improve their dynamic

Nomenclature

CHP	combined heating and power
DG	distributed generation
DP	dynamic programming
DT	decision tree
HES	hybrid energy storage
K	the number of switching the engine
$p_{cl}(t, p_{elec})$	heat power recovered from coolant system at time t with electric power output p_{elec} (kW)
$p_{exs}(t, p_{elec})$	heat power recovered from exhaust gas at time t with electric power output p_{elec} (kW)
$p_{rcv}(t, p_{elec})$	heat power recovered from exhaust gas at time t with electric power output p_{elec} (kW)
Q_{exs}	heat energy recovered from exhaust gas (kWh)
Q_{cl}	heat energy recovered from coolant system (kWh)
Q_{rcv}	total heat energy recovered (kWh)
T_{eng}	engine operational duration (s)
T_{HES}	HES operational duration (s)
T_i	engine operation time during i (s)
T_{tgt}	peak hour (s)
η_{eng}	mean electric efficiency of the engine
η_{HES}	mean electric efficiency of the HES
$\eta_{ch}(t)$	mean charging efficiency of the HES
η_{st}	overall electric efficiency of the system
$\xi_{ch}(t, p_{elec})$	charging efficiency of the HES at time t with electric power output p_{elec}
$\xi_{\frac{ch}{disch}}(t, p_{elec})$	electric efficiency of the HES over charging/discharging at time t with electric power output p_{elec}
$\xi_{eng}(t, p_{elec})$	electric efficiency of the engine at time t with electric power output p_{elec}

performance when energy demands fluctuate. It is believed that a CHP combined with an energy storage system could improve dynamic performance, with [4, 5] demonstrating an increase in performance. A similar conclusion was pointed out in [6-8] and the work also emphasized that energy management strategies are the key factor in actual operation. References [9-12] explored the methods of CHP operation, especially in building-related applications. However, such work did not focus on the relationship between dynamic

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performance of the units and real-time energy demands during operation.

In the literature, considerable work has been undertaken on the operational optimisation of CHPs. References [13-15] adopted fuzzy logic theory for power energy management in CHPs. However, they may require selecting regions empirically which may result in sub-optimal decisions in practice. References [16, 17] discussed droop control in the optimal operation of the CHPs with an energy storage technology. But the selection of decent droop coefficients is a main challenge for these applications. CHPs developed in references [18, 19] developed a particle swarm algorithm to find the best options over the system's operation. However, both iteration calculation and premature convergence are the barriers for practical applications of such systems. Overall, these methods are effective but require either empirical coefficients or pre-determined parameters.

On the contrary, dynamic programming (DP) as an optimisation method has recently attracted lots of interest by researchers in the area of energy systems.

Generally, DP can solve nonlinear dynamics with constraints in simple a way when the problems can be discretized with time, state and decision variables. In other words, DP solves the problems by dividing the whole process into different stages. These stages interact and interconnect

with decision (or control) variables. The states including one or multi components (variables) refer to the objective conditions at the beginning of each stage. Essentially, the target of DP is to find the best decision set over the whole searching trajectory. Therefore, stages, decision and states consist of the basic factors for solving problems under DP frame. DP does not require either empirical coefficients or pre-determined parameters.

Research has been undertaken to try to realise energy flux splitting to achieve integrated optimization under the objective function. Reference [20] investigated an energy generation system where the fuel-cells, batteries and super-capacitors were included in. Other examples are also found in the energy-related studies in [21-22]. However, due to dimensional problems are still the barriers to multi-source energy systems, DP has not been recognized as the best way to optimize energy management in this area. In CHPs applications, reference [23] employed DP to make decisions on CHP operation. A daily load profile was used for all the year to reduce the complexity of the optimization problem and iterative calculations were minimised. DP was also used in a CHP system in reference [24] to find the proper switching policy between the CHP and thermal energy storage under a Monte Carlo framework. The effectiveness of this method was strongly dependent on the specific the CHP structure.

Fig. 1. Schematic diagram of a CHP-HES system.

This study attempts to apply DP to solve real-time energy management in a multi-source system. Different to the previous research, the main purpose of this work is to make the decision for each real-time operation without iterative calculations. DP solution finds the optimal power distribution among the suppliers (primary mover, batteries and super-capacitors) as demands fluctuate with respect to time. Therefore, optimal energy efficiency as target is achieved. The techniques proposed in this study overcome the multiply dimension problem that typically occurs in DP applications by reducing the dimension in the calculation. Decision tree (DT) is developed in a simple way which might be easily implanted into other more energy-related research in the future. First of all, the experimental bench of a domestic CHP-HES system is introduced followed by the challenge of domestic energy demands. Following this, detailed analysis of the characteristics of a household electricity profile is carried out before connecting a DP solution where the state variables, the decision variables and the outcomes are selected. Also, a daily electric load profile was chosen to verify the effectiveness of this CHP-HES system under DP frame by analyzing the outcomes and evaluating with relevant criteria.

Fig. 2. Daily electricity consumption for domestic households [29].

2. System construction and domestic energy demands

2.1 System construction

In an off-grid CHP system, both energy and their dynamics should be taken into account. This research adopts an energy storage system to assist engine based power generation and accommodate energy demand variations. For enhancement of system dynamics, the storage system includes both batteries and super-capacitors for improvement of high power delivery and energy capability as pointed out in [25]. Fig. 1 illustrates the complete system

proposed. The bio-diesel engine-based system generates both heat and electricity locally. The engine primarily satisfies basic electricity demand; waste heat is recovered from both coolant source and exhaust gas; heat is then used for hot water or space heating. Low-temperature water also obtains heat from exhaust gas before it goes into the water heat exchanger for a third heat exchange. The HES system includes battery packs and super-capacitor module. The DC output from them is integrated into the power from diesel engine/generator. Therefore, three electrical sources as three vectors will be operated over electrical supplies to the domestic utilities. An energy management unit is the crucial part in terms of dynamic power allocation among these three energy supplies according to energy needs where DP strategy is programmed into controller to select optimal operational mode and also calculate power for each of them.

Fig. 3. Flowchart for the decision making procedure.

2.2 Household energy demands

References [26-28] explored domestic energy consumption and proposed several possible solutions to satisfy energy demands electrically and thermally. In most of cases, their investigations were based on hourly data. However, domestic electricity demands varied relatively quicker over heat demands due to different physical properties [4]. As stated in investigation executed by Wood [29], electrical energy in domestic varied from several watts to thousands watts in transient period. Fig. 2 gave a daily electricity profile for a selected house. As can be seen, the usage of several appliances (kettles, ovens and tumble dryers) taking place at the same time would incur a peak demands (up to 10 kW). On the other side, the electricity demands over the most of time plunged into less than 1kW. The curves in Fig. 2 featured frequent and dramatic fluctuation. Reasonably, this investigation take electricity needs for the prime consideration for energy management.

3. Dynamic programming for energy management

3.1. The operational target in CHP-HES

The purpose of system operation in this research is to find out the best decision candidate for the real-time power supply among multi sources. Fig. 3 demonstrates the design thought for this application. First of all, instantaneous electricity demand is detected and meanwhile state variables in current stage are processed by DP-DT. And then, the optimal decision candidate is selected to decide power needs for each power source (generator, batteries and super-capacitors) and new variables is then recalculated for next step.

DP, as an attractive optimization method, has been applied in various research areas, including landing aircraft, managing blood inventories, scheduling vehicles flow or

other economics etc. DP-based strategies also have been applied over the energy-related researches [30-33].

3.2. DP algorithm and challenge of this application

Typically, state space, outcome space and decision space are required in DP optimization process. When any variables in these three space increase, DP algorithms would suffer from “curses of dimensionality” and the problem would become extremely difficult to resolve or irresolvable [34].

Fig. 4 illustrates the general process by applying DP to solve optimization problem. The idea behind DP optimization follows this way: suppose State (k) as the current state, it should take decision variable into account to transmit to next state, namely State (k+1). In this case, decision selection should satisfy certain criteria. For our cases, decision candidates should be the option which leads to the optimal energy efficiency over searching trajectory at each stage.

The CHP-HES proposed in this investigation had three different energy sources which led to multi-degree of freedom when they are in variable space. The aim of the operational strategy in this study is to decide the best operational mode for each stage and thereafter to decide power amount provided by the energy sources (generator, batteries and super-capacitors) to accommodate the continuous load needs, which would be considered as decision variables in decision space. If these decision variables are considered as time-related variables directly, there would be massive amount of values as consequences. In other words, the optimization process would become irresolvable.

Then, we consider the variable classification of DP process in this application. We classify load demands into three different level, low demand, medium demand and high demand. Therefore, load level would situate within these

Fig. 4. State transition under dynamic programming.

three situations when the load fluctuated. In the following section, we will provide detailed statement for DP-DT solution for this investigation.

3.3. Variables definition and calculation

State classification

This investigation employs a dynamic programming for electrical power dispatch. In each stage, the state variables include s_1, s_2, s_3 referring to engine load ratio, the SOC of the batteries and the super capacitor module respectively where $s_1, s_2, s_3 \in \{0, 1\}$. Table 1 provides their information and equation (1) to (4) gives their calculation as followed.

$$s_1(t) = \beta = \frac{P_{out}}{P_N} \times 100\% = \sqrt{\frac{i_{gen}(t)^2 - I_0^2}{I_N^2 - I_0^2}} \quad (1)$$

$$I_0 = \lambda[(1 - \cos \phi_N) \cdot \sqrt{1 - \cos^2 \phi_N}] \cdot I_N \quad (2)$$

$$s_2(t) = SOC_{bat} = \frac{1}{Q_{bat}} \int_0^t i_b(t) dt + SOC_{0,bat} \quad (3)$$

$$s_3(t) = SOC_{sc} = \frac{1}{Q_{sc}} \int_0^t i_{sc}(t) dt + SOC_{0,sc} \quad (4)$$

where soc_{bat} and soc_{sc} refer to the state of charge of batteries and super-capacitors; $soc_{0,bat}$ and $soc_{0,sc}$ are of the initial SOC of them; Q is the capacity; i_{gen} is load ratio of the generator; I_0, I_N refer to stator current and nominal current of the generator, respectively. In this study, $s_1(t)$ can be acquired via generator power/ current while soc_{bat} ($s_2(t)$) and soc_{sc} ($s_3(t)$) can be obtained directly by SOC detector to reduce the complexity of controller.

Table 1 State variables.

State variable	Symbol	Definition	Range
s1	β	Engine load ratio	{0 1}
s2	SOC_{bat}	SOC of batteries	{0 1}
s3	SOC_{sc}	SOC of super-capacitors	{0 1}

Decision variables

Decision variables d_1, d_2, d_3 in decision space can be described as switching on/off engine, charging/discharging batteries, charging/discharging super-capacitors, respectively.

The basic principle of the energy management strategy is in consonance with energy balance equation as starting point of this research, as followed.

$$P_{eng} - P_{load} + P_{bat} + P_{sc} = 0 \quad (5)$$

Three decision variables (diesel engine, batteries and super capacitors) are responsive to three states in each stage as a function of time (power distributed for each step).

3.4. Decision process for a optimization target

As aforementioned, decision tree is employed to solve the optimization problem in this investigation. In previous investigation, fast response of the super-capacitors was found and they followed the change of batteries [35]. It is reasonable believed that the soc_{sc} can track soc_{bat} simultaneously. Therefore, soc_{sc} is ignored in decision process for simplification. That is, the supercapacitor module and the battery bank are simultaneously controlled. Fig. 5 illustrates the decision tree for this investigation where optimal decision searching at each stage followed the similar way as depicted in this figure.

Decision candidates

There are three components which need to be controlled on and off so as to manipulate the power flow within the system. These are the engine, the battery bank and the supercapacitor module. Their on/off actions are defined by 1/0 in the decision variables, as illustrated in Table 2. Because the batteries and the supercapacitors are controlled simultaneously, the actions for supercapacitor operation are eliminated so that d_3 is the same as d_2 .

Decision nodes and outcome nodes

Table 2 Decision variables.

Decision variable	Definition	Range	Decision
d_1	Engine operation	0	Turn off
		1	Turn on
d_2	Battery operation	0	Charging
		1	Discharging
d_3	Supercapacitor operation	0	Charging
		1	Discharging

There are two levels of decision nodes. The first level decision nodes include 4 options. The second level includes 12 nodes with 2 possible options for each node (satisfied, unsatisfied). Also, 2 level outcome nodes are needed in the process. Each outcome node contains parameter ($\xi_{i,j}$) and the last outcome nodes receive the value v_m where $\xi_{i,j}$ and v_m stand for possibility degree at level i with route j and profit at the end nod. For instance, the parameter $\xi_{1,2}$ places on node level 1. In this case, the possibility of engine load ratio with soc_{bat} 100% is of $\xi_{1,2}$.

Objective function

The optimization objects through this process is expressed as follows.

$$OPT = \max_{d_k \in D_k} \prod \{\xi_{i,j}(s_k, d_k) \cdot v_k\} \quad (6)$$

Decision selection

Fig. 5. Decision tree in the DP optimization process.

Through the decision tree, optimal decision candidate is selected with maximized contribution value of the route.

For instance, in some stage, the demand goes high where the engine load is of 95% and the batteries are fully charged. Therefore the possibility coefficient vector are obtained as follows,

$$\begin{aligned}\xi(1, j)_{j=1 \sim 4} &= \{0.5, 0.3, 0.1, 0.1\}, \\ \xi(2, k)_{k=1 \sim 12} &= \{1, 0, 0, 0, 1, 0, 0, 0, 1, 0, 1, 0\}, \\ \xi(3, l)_{l=1 \sim 24} &= \{0.6, 0.4, 0.5, 0.5, 0.5, 0.5, 0.5, 0.5, 0.4, 0.6, 0.5, \\ &0.5, 0.5, 0.5, 0.5, \dots, 0.6, 0.4, 0.5, 0.5, 0.6, 0.4, 0.5, 0.5\}, \\ v(m)_{m=1 \sim 24} &= \{0.8, 0.6, 0.4, 0.3, 0.2, 0.1, 0.1, 0.1, \\ &0.8, 0.6, 0.4, 0.3, 0.2, 0.1, 0.1, 0.1, \\ &0.8, 0.6, 0.4, 0.3, 0.8, 0.6, 0.4, 0.2\}\end{aligned}$$

Therefore, the value vector is calculated with outcome vectors:

$$\begin{aligned}out(m)_{m=1 \sim 24} &= \{0.24, 0.12, 0, 0, 0, 0, 0, 0, 0.096, 0.108, 0, 0, \dots, \\ &0.048, 0.024, 0, 0, 0.012, 0.004, 0, 0\}\end{aligned}$$

Fig. 6 demonstrates the calculation process for this instance. The maximum value in the outcome vector is 0.24

a. Output electrical power vs engine load

$$p_{eng} = p_{max} \quad (7)$$

which decides the optimal decision being of “gen-set on & EES discharge” by backward derivation. In this case, the power allocated among these sources are calculated,

$$p_{eng} = p_{max} \quad (7)$$

$$p_{EES} = p_{load} - p_{eng} \quad (8)$$

4. Performance analysis

4.1 Types of biofuel

Fig. 7 shows the electrical performance of the CHP system with four different biofuels, including biodiesel, sunflower oil, rapeseed oil and croton oil. In Fig. 7(a), the figure illustrates that the evaluated indicators increase with the engine load nearly proportionally. Fuel consumption of Rapeseed oil, sunflower oil and croton oil is almost the same at each test point. Biodiesel displays the lowest consumption among these fuels as shown in Fig. 7(b). Fig. 7(c) shows a comparison of their energy efficiency. It is clear that biodiesel has better energy efficiency than others and thus is chosen for the following analysis.

4.2 Performance of the biofuel micro CHP-HEES

This research is focused on a typical UK household energy demand. The specific requirements are given in [36]. Two peak demands occur in Fig. 8. The first one began at 8:20 am with the highest demand 5.74 kW while the second

b. Biofuel consumption vs engine load

c. Biofuel electrical efficiency vs engine load

Fig. 7. Electrical performance of the micro-CHP with four different biofuels.

started at 6:34 pm with a 5.33 kW power demand. The rest 20.88 hours experienced lower demands. According to the household energy needs, the specific engine-based CHP are selected with continuous mechanical output 7.72 kW and 6.5 kW alternative electrical power at full-load. 6 Gel batteries (12V/120Ah each unit) combine with super-capacitors (40V/60F). The details of the device parameters for CHP-HES are summarized in Table 1.

Figs. 9 and 10 show the dynamic response of both the engine and HES. As can be seen in Fig. 9, engine/generator started twice at 8:20 am and 6:34 pm where corresponding power outputs were the maximum at 6.5 kW. As illustrated in Fig.9, the engine ran the limit period with relative high load rate.

Both charging and discharging power from the HES could be seen in Fig. 10 where the positive values are discharging power while the negative represents charging. The HES received surplus power from the engine as it was running. Compared to the engine, the HES worked over the most of time within the 24-hour test. Fig. 8 saw the scenarios for both batteries and super-capacitor modules. It is obviously that super-capacitors play as energy buffer, which assists batteries at the demands suddenly changed. It is therefore that HES system can deal with abrupt change properly while batteries were protected. Based on the outcomes, the following performance indicators are analysed.

4.3 Waste heat recovery

Meanwhile, new state variables can be achieved as the basis for derivation calculation at next stage. Heat obtained was recovered from the cooling system and the exhaust gas of the engine/generator. Therefore, heat energy recovered was equal to the sum of them over the whole engine operation which was calculated by the series of equations below.

The thermal energy recovered from the exhaust gas Q_{exs} is equal to the integration of the recovered the heat power from the exhaust gas $p_{exs}(t, p_{elec})$ over the engine duty time $\{T_1, T_2, \dots, T_K\}$. Similarly, the thermal energy recovered from the coolant system Q_{cl} is equal to the integration of the recovered heat power from the exhaust gas $p_{cl}(t, p_{elec})$ over the engine duty time $\{T_1, T_2, \dots, T_K\}$. The total heat energy recovered Q_{rcv} is equal to the integration of the total recovered heat power $p_{rcv}(t, p_{elec})$ over the engine

$$Q_{exs} = \int_0^K [\int_0^{T_i} p_{exs}(t, p_{elec}) dt] di \quad (9)$$

$$Q_{cl} = \int_0^K [\int_0^{T_i} p_{cl}(t, p_{elec}) dt] di \quad (10)$$

duty time $\{T_1, T_2, \dots, T_K\}$. Therefore,

So,

$$Q_{rcv} = \int_0^K [\int_0^{T_i} p_{rcv}(t, p_{elec}) dt] di \quad (11)$$

with

$$p_{rcv}(t, p_{elec}) = p_{exs}(t, p_{elec}) + p_{cl}(t, p_{elec}) \quad (12)$$

The total heat energy recovered from the engine during the 24h test is 15.98kWh, while the heat consumption for the day is 15.36 kWh [36]. The heat recovered is 4% more than the demand. Furthermore, due to the engine being operated at high loads, heat at higher temperature can be obtained for use. Therefore, the practical heat recovered in the test can fully satisfy the requirement for the house in the 24 h. The heat recovered is 37.3% of the fuel input.

4.4 system efficiency

Generally, energy efficiency can be calculated by the equation as follows,

$$\eta = \frac{\text{Energy output}}{\text{Energy input}} \text{ or } \eta = \frac{\text{Power output}}{\text{Power input}} \quad (13)$$

In reference [37], biofuel consumption, equivalent energy amount of the bio-engine, equivalent power input/output of the bio-engine were investigated by physical tests. Reference[38] also provided the result for HES (batteries and supercapacitor) efficiencies over charging/discharging via several trial tests. Efficiencies calculation in this study employs these outcomes, including $\xi_{eng}(t, p_{elec})$ (engine efficiency versus power output), $\xi_{ch}(t, p_{elec})$ (HES charging efficiency versus power input), $\xi_{\frac{ch}{disch}}(t, p_{elec})$ (efficiency via charging/discharging).

Engine electric efficiency refers to the mean efficiency over its operation. Let $\xi_{eng}(t, p_{elec})$ be the real-time electric efficiency at engine output power p_{elec} . The total value is equal to the integration of the efficiency over the engine duty time $\{T_1, T_2, \dots, T_K\}$. The overall duty period is equal to the integration of the duty time series $\{T_1, T_2, \dots, T_K\}$. So the mean electric efficiency is calculated as follows:

$$\eta_{eng} = \frac{\int_0^K [\int_0^{T_i} \xi_{eng}(t, p_{elec}) dt] T_i di}{\int_0^K T_i di} \quad (14)$$

By considering the loss from both charging and discharging processes, HES efficiency η_{HES} hereby is equal to its mean charging efficiency $\eta_{ch}(t)$ times its transferring efficiency from charging to discharging $\xi_{\frac{ch}{disch}}(t, p_{elec})$. The electrical efficiency η_{HES} can be expressed as

$$\eta_{HES} = \frac{\int_0^K [\int_0^{T_i} \eta_{ch}(t) \times \xi_{\frac{ch}{disch}}(t, p_{elec}) dt] di}{\int_0^K T_i di} \quad (15)$$

$$\eta_{ch}(i) = \frac{\int_0^{T_i} \xi_{ch}(t, p_{elec}) dt}{T_i} \quad (16)$$

By considering the sum of the mean efficiency of the each component dividing the overall operational time, the mean efficiency of the system η_{st} can be calculated by:

$$\eta_{st} = \frac{\eta_{eng} \times T_{eng} + \eta_{HES} \times T_{HES} + 0.5 \times (\eta_{eng} + \eta_{HES}) \times T_{tgt}}{T_{eng} + T_{HES} + T_{tgt}} \quad (17)$$

For comparison, a conventional engine-based CHP system without specific control strategies is compared. The CHP is supposed to have a maximum power output 6.5 kW, to meet the maximum electricity demand; and it has similar electric efficiencies at different loads as the engine/generator

Fig. 9. Power profile of the engine.

in the CHP-HES system.

The calculated results for this CHP system are also listed in Table 4. From the results, it can be seen that the average electric efficiency of the CHP system only 3.84% over 24-hour continuous operation. And meanwhile, the engine ran with relative low efficiency during most of duty time. Furthermore, engine generated excessive heat due to its long-term operation. The heat recovered from the engine is of 118.87 kWh by calculation, more than 7 times over the heat requirement (15.36 kWh) for the day. That means there is 103.51 kWh of heat wasted.

On the other side, CHP-HES can also satisfy dynamic domestic energy needs where real-time operational mode was selected according to the DP-DT at each step to the end of the test. All of the test results are listed in Table 4. Discharging efficiency of the storage system, engine efficiency and overall electric efficiency are 20.56%, 20.79% and 20.68% respectively, as seen in Table 4.

Fig. 8. Electrical demand profile in a household application [27].

Fig. 10. Power profile of the HES.

Obviously, the CHP-HES system has much better performance with higher electric efficiency, 20.68% in overall, which is 5 times more than that of conventional engine-based CHP. Furthermore, the overall efficiency of CHP-HES system increased from 45.77% to 57.97% where the improvement of the overall system efficiency is 26.7%, as shown in Table 4. Also, it is found that the engine generator supplied 33.6% of the electric energy in 24 hours; the HES system contributed 66.4% electricity needed with DP-DT strategies. Fig. 11(a) shows the percentage of electricity supplied from the engine/generator and the HES system. Fig. 11(b) shows the allocation of the operational duration of the engine/generator and the HES. By comparison, the engine's duty time decreased from 24 hours to 3.12 hours while its efficiency increased dramatically from 3.84% to 20.79%. In other words, the engine/generator in CHP-HES system ran with relatively high duty rate, which benefit its lifetime in favor of the system cost.

Table 3 Specification summary for the CHP-HES.

Engine		Generator		Batteries		Super capacitors	
Type	Yanmar TF120M	Model	YTG6.5S	Type	Gel batteries	Cell	1000F/2.7V
Speed	2400 rpm	Alternator model	MR2-160/2	Number of unit	6	Number of unit	24
Cooling system	Radiator	Capacity	6.5 kVA	Voltage	12V	Capacity	40F
Continuous power output	10.5 hp/7.72 kW	Current Output	29.5 A	Capacity/unit	120Ah	voltage	60V

Fig. 11(a) Energy contribution.

Fig. 11(b) Operational duration (hours).

5. Conclusions

This paper has presented a new energy management strategy for a combined heat and power (CHP) system with hybrid energy storage (HES). It is derived from dynamic programming (DP) with a new decision tree method. The main contributions are as follows:

- An off-grid multi-source energy system consisting of bio-fuel engine/generator, batteries and super-capacitors has been built.
- This is the first attempt to apply dynamic programming (DP) with decision tree (DT) in energy management system which simplifies the multi-dimensional problems.
- The effectiveness of the proposed method was validated by the experimental results of case study. Dynamic performance of the system was improved due to the integration of batteries and supercapacitors.
- Overall energy efficiency increased to 57.97% with improvement by 26.7% under the DP-DT strategy and so did its dynamic response.

The developed system is suitable for household applications and has a potential to be commercially utilised. However, a major uncertainty is that the biofuel may deteriorate the engine performance in the long term, which needs more research work.

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Table 4 Summary of performance indicators.

Performance Indicator		With DP-DT	Without DP-DT
Energy (kWh)	Discharging energy from HES	8.90	NA
	Electric energy from engine	9.59	11.96
	Engine energy to load	3.06	33.63
	Energy for charging energy storage system	6.05	NA
	Electricity consumed by load	11.96	11.96
	Thermal energy recovered	15.98	118.87
Duration (hours)	HES discharging time	20.88	NA
	Engine operating time	3.12	24
	Charging period for HES	3.03	NA
	Duration of peak generation	3.12	3.12
Power (kW)	Power from HES	3~3.52	NA
	Power from engine	0~6.50	0~5.74
	Load power	0~5.74	0~5.74
Efficiency (%)	HES electric efficiency	20.56	NA
	Engine electric efficiency	20.79	3.84
	Thermal efficiency	37.29	41.93
	System electric efficiency	20.68	3.84
	System overall efficiency	57.97	45.77

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