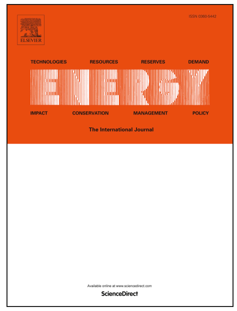

Energy and uncertainty management through domestic demand response in the residential building

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Energy and uncertainty management through domestic demand response in the residential building

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Abstract

An optimal energy management is addressed in the residential building. The residential building is equipped with renewable energies including wind turbines and solar panels. The uncertainty of renewable energies is modeled by stochastic programming. The demand response program is simultaneously adopted to handle such uncertainty and reducing the energy cost. In this respect, four different loads are modeled in the building including interruptible, constant energy, constant power, and uninterruptible loads. The aforementioned loads are properly adjusted and dispatched for minimizing the energy cost as well as to deal with renewable energy intermittency. The bidirectional operation is modeled for the building and it can send energy to the grid or receive it from the upstream network. The results verify that the introduced model can efficiently harvest all possible energy of the wind-solar system, handle the uncertainty, minimize the cost, and operate as off-grid. All of these purposes are achieved by optimal dispatching and adjusting of the loads through the proposed demand response program.

Keywords:

Demand Response; Energy Management; Hybrid Power Generation; Renewable Energy Intermittency; Residential Building;

Nomenclature

Parameters and Symbols	Definitions
C_{E}^{t}	Price of energy ($/kWh)
$Daily_{\cos t}$	Daily cost of energy ($/day)
$EL2$	Energy of load 2 (kWh)
K_{Load1}^{t}	Binary variable for load 1
K_{Load4}^{t}	Binary variable for load 4
L_{Cap}^{r}	Line capacity (kW)
LP_{Load3}^{t}	Profile of power for load 3 (%)
$NL1$	Number of time periods the load 1 needs to operate
$NL4$	Number of consecutive time periods the load 4 needs to operate
$P_{Grid}^{s,t}$	Power between grid and building (kW)
P_{Load}^{t}	Total power of load (kW)
$P_{Solar}^{s,t}$	Power of solar system (kW)
$P_{Wind}^{s,t}$	Power of wind system (kW)
P_{Load1}^{t}	Power of load 1 (kW)
P_{Load2}^{t}	Power of load 2 (kW)
P_{Load3}^{t}	Power of load 3 (kW)
P_{Load4}^{t}	Power of load 4 (kW)
P_{Load1}^{r}	Rated power of load 1 (kW)
P_{Load2}^{r}	Rated power of load 2 (kW)
P_{Load3}^{r}	Rated power of load 3 (kW)
P_{Load4}^{r}	Rated power of load 4 (kW)
R_{Pr}^{s}	Probability of scenario
s,S	Index of scenarios, set of scenarios
t,T	Index of time periods, set of time periods
T_{Period}^{t}	Duration of time period (Hour)

1. Introduction

The hybrid power generation from renewable energy resources (RESs) is one of the interesting problems in the electrical networks. In this regard, the coordination of renewable and non-renewable energy resources has been broadly modeled [1]. In practice, the RESs like wind, solar, hydro, and hydrogen may be installed on the electrical grids [2] or off-grid systems [3]. It is therefore useful to study the hybrid power generation by these resources. This problem has been addressed in different ways such as correlation of hydro-thermal-wind-solar [4], wind-solar [5], wind-solar-hydro [6], and thermal-wind-solar [7]. The studies demonstrate that such correlation makes significant influences on the problem and should be considered [8].

The correlation of RESs can also be studied in home energy management problem [5]. This problem manages the energy consumption in the homes and building [9]. The home energy management has been properly addressed including various renewable and nonrenewable energy types such as wind [10], solar [11], biomass [12], and geothermal [13]. Furthermore, the home energy management has been studied from various perspectives, for instance the wireless operation and management [14], demand response analysis [15], and electrical-thermal loading [16]. The energy storage systems are also one of the useful technologies that can be properly utilized in the building for managing the energy [17, 18].

The demand response (load control) is one of the efficient methods to manage energy in the building [19]. The demand response is a broad term defining various methods to improve operation of the system through controlling the loading side rather than the generating side. The loads and their models are one of the major parts of demand response. There are various loading models such as interruptible-curtailable loads [20], constant power and constant energy loads

[21], and uninterruptable loads [22]. A demand response program optimally adjusts and changes the loads to manage energy and minimize energy cost.

1.1. Contributions and innovations of the current paper

The current paper presents an optimization programming to minimize energy cost in the residential building. The building is connected to the grid and equipped with wind and solar generating systems. The building has bidirectional operation and it can send its surplus of energy to the utility grid. The demand response program is also considered in the building including interruptible load, constant power load, constant energy load, and consecutive operative load (uninterruptible load). The intermittency of wind-solar energies is investigated by proper load adjustment through demand response program. The main innovations of current paper are listed as follows;

- The residential building is supported by the various energy capacity resources including wind unit, solar generating system, and demand response program at the same time.
- The bidirectional operation is considered for the residential building and the building is able to operate disconnected from the grid. In such state, the energy of the building is supplied by the available capacity resources (i.e., wind, solar, and demand response program).
- Various load models are considered through demand response program including interruptible loads, constant power loads, constant energy loads, and uninterruptible loads.

- The uncertainties of wind, solar, and load are incorporated by the stochastic programming. The demand response program is also optimized to deal with the uncertainties.

2. The proposed model

Figure 1 shows structure of the given model. The building is powered by wind and solar energies and it is also connected to the electric utility grid. There is a meter between the building and the grid in order to record the receiving and sending energies. The building can send its surplus of energy to the grid [8]. The energy management in the building is carried out through adjusting the loads. There are different loads in the building and the developed method can properly adjust the loads to manage energy and minimize energy cost in the building. The problem is expressed as an optimization programming that minimizes the energy cost. The problem utilizes energy of the wind and solar and manages the loads to minimize the cost. The extra energy is sent to the grid and make profit for the building [9].

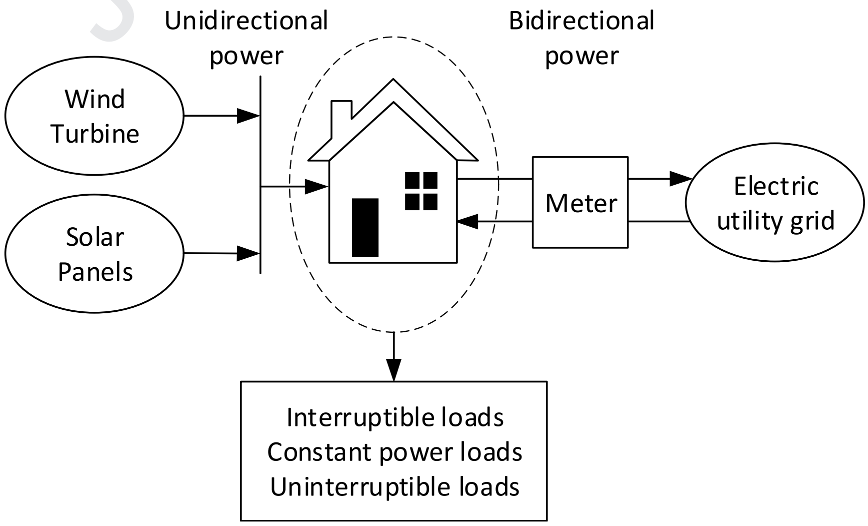


Figure 1: Structure of the given model for energy management in the building

3. Mathematical model

In this section, the mathematical model is developed for all components and parts of the model.

3.1. The grid operation modelling

The given energy management tool in the residential building minimizes daily energy cost in the building as defined by (1). The objective function introduced in (1) calculates the expected value of the cost under all scenarios of performances related to the wind-solar uncertainty. The probability of each scenario is less than one as shown by (2) and sum of all probabilities is equal to one as specified by (3) [23].

$$Daily_{\cos t} = \sum_{s \in S} \sum_{t \in T} \left(P_{Grid}^{s,t} \times R_{Pr}^{s} \times C_{E}^{t} \right) \quad (1)$$

$$0 \le R_{Pr}^{s} \le 1 \quad \forall s \in S \quad (2)$$

$$\sum_{s \in S} \left(R_{Pr}^{s} \right) = 1 \quad (3)$$

The traded power between building and grid is calculated by (4). It is demonstrated by (5) that the load is a positive variable shown by (6) and the load modeled by four different loading types from *Load 1* to *Load 4*. These loads are modeled and discussed in the subsections 3.2 to 3.5. The building can send energy to the grid or receive it from the grid. As a result, the traded power between building and grid may be positive or negative as shown by (7). However, the capacity of line between building and grid limits this power as indicated by (8) and (9).

$$P_{Grid}^{s,t} = P_{Load}^{t} - P_{Solar}^{s,t} - P_{Wind}^{s,t} \quad \forall s \in S, t \in T \quad (4)$$

$$P_{Load}^{t} \ge 0 \quad \forall t \in T \quad (5)$$

$$P_{Load}^{t} = P_{Load\,1}^{t} + P_{Load\,2}^{t} + P_{Load\,3}^{t} + P_{Load\,4}^{t} \;\forall t \in T \tag{6}$$

$$-\infty \le P_{Grid}^{s,t} \le +\infty \;\forall s \in S, t \in T \tag{7}$$

$$P_{Grid}^{s,t} \le L_{Cap}^{r} \;\forall s \in S, t \in T \tag{8}$$

$$P_{Grid}^{s,t} \ge \left(-L_{Cap}^{r}\right) \forall s \in S, t \in T \tag{9}$$

3.2. Interruptible load

The consumed energy by the interruptible loads is not necessary to be continues. Their consumed energy can be interrupted several times and then they can continue to operate again. Such operation can be defined for some appliances such as electric motors. The *Load 1* is an interruptible load and a positive variable as shown by (10). A binary variable is defined as (11) and it is fixed as (12). Then the loading profile for the interruptible load is modeled by (13) [5].

$$P_{Load\,1}^{t} \ge 0 \;\forall t \in T \tag{10}$$

$$0 \le \left| K_{Load\,1}^{t} \right| \le 1 \;\forall t \in T \tag{11}$$

$$\sum_{t \in T} \left(K_{Load\,1}^{t} \right) = NL1 \tag{12}$$

$$P_{Load\,1}^{t} = K_{Load\,1}^{t} \times P_{Load\,1}^{r} \;\forall t \in T \tag{13}$$

3.3. Constant energy load

The constant energy loads need fixed energy level during day hours regardless of the operation time. Such procedure can be considered as operation of chargeable devices. They can be charged at intermittent time periods with different powers. The *Load 2* is a constant energy load and a positive variable as shown by (14). The energy of the load is defined by (15) and its power limited by (16).

$$P_{Load\,2}^{t} \geq 0 \;\forall t \in T \tag{14}$$

$$\sum_{t \in T} \left(P_{Load\,2}^{t} \times T_{Period}^{t} \right) = EL2 \tag{15}$$

$$P_{Load\,2}^{t} \leq P_{Load\,2}^{r} \;\forall t \in T \tag{16}$$

3.4. Constant power load

The constant power loads follow a constant profile during day hours such as lighting demand. The *Load 3* is a constant power load and a positive variable as shown by (17). Its energy profile is defined by (18).

$$P_{Load\,3}^{t} \geq 0 \;\forall t \in T \tag{17}$$

$$P_{Load\,3}^{t} = LP_{Load\,3}^{t} \times P_{Load\,3}^{r} \;\forall t \in T \tag{18}$$

3.5. Uninterrupted loads

Some loads need consecutive and uninterrupted operation such as washing machine. It means that the operation of these devices cannot be interrupted until finishing their tasks. The *Load 4* is modeled as a load with consecutive operation. It is a positive variable as (19). A binary variable is defined as (20) and the consecutive operation is modeled by (21). The loading profile for this load is modeled by (22).

$$P_{Load\,4}^{t} \geq 0 \;\forall t \in T \tag{19}$$

$$0 \leq \left| K_{Load\,4}^{t} \right| \leq 1 \;\forall t \in T \tag{20}$$

$$K_{Load\,4}^{t} + K_{Load\,4}^{t+1} + \cdots + K_{Load\,4}^{t+NL4-1} = NL4 \quad (21)$$

$$P_{Load\,4}^{t} = K_{Load\,4}^{t} \times P_{Load\,4}^{r} \;\; \forall t \in T \quad (22)$$

3.6. Optimization programming

The final model is expressed as standard optimization programming. The model includes binary and integer variables. As a result, the mixed integer linear programming (MILP) is formed. This MILP is expressed as follows;

Minimize (Equation (1))

Subject to

Equations (2) to (22)

Where the objective function is given by (1) and the constraints are modeled through (2) to (22). This standard optimization programming is solved by GAMS/ CPLEX.

This paper applied conventional scenario-generation and scenario-reduction techniques to model the uncertainties. In the given model, the scenarios of performance are generated based on the uncertain parameters of the model (wind, solar, and load powers). A large set of scenarios is formed. The scenario reduction technique is then applied to reduce number of scenarios to the desired level. This paper utilizes backward scenarios reduction technique and its detail can be found in [24]. The details of conventional stochastic programming including scenario-generation and scenario-reduction techniques can also be found in [24].

3.7. Flowchart of the model

A simple flowchart of the given model is depicted in Figure 2. The model starts with getting input data from the user. A large set of scenarios is then generated based on the uncertain parameters of the model. The model including all constraints and objective function is implemented in GAMS software and solved by CPLEX solver. If the constraints are not satisfied, the model is revised to fix the problems. The model is then solved again to get the final solution that is the global optimal solution of the planning.

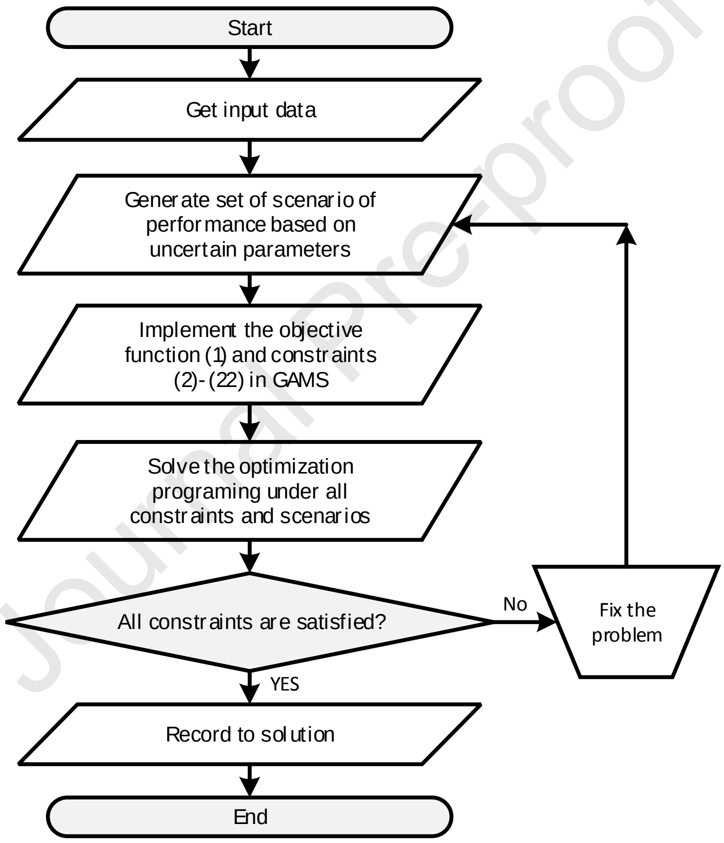


Figure 2: Flowchart of the given model

4. Data and setting of problem

Figure 1 shows structure of the residential building. It is installed with 20 kW wind turbine and 20 kW solar system. Parameters of the wind turbines and solar panels are listed in Table 1 [25] and Table 2 [26] accordingly.

The capacity of the line between grid and building is 42 kW. Table 3 shows the electricity price and wind-solar energy profile. The data are taken from [9]. The energy of the load can be curtained by 11 kWh if necessary (load shedding strategy).

Table 1: Parameters of wind turbine

Parameter	Value
Cut-in wind speed (m/s)	2.3
Rated wind speed (m/s)	10
Cut-out wind speed (m/s)	25
Rated power (kW)	2
Number of blades	3
Size (m)	Diameter 2.2 m
Changing blade angle	±40 degree
Changing position of turbine nacelle	±10 degree
Number of turbines	10

Table 2: Parameters of solar module

Parameter	Value
Nominal voltage (v)	24
Maximum power point (MPP) (W)	150
Rated current IMPP (A)	4.4
Rated voltage VMPP (V)	34
Short circuit current (A)	4.8
Open circuit voltage (V)	43.4
Nominal operation temperature (ºC)	25

Table 3: Electricity price, wind-solar energy profile, and energy profile for Load 3

Electricity Price ($/kWh)	Wind Power (%)	Solar Power (%)	Power of Load 3 (%)
0.12	0.8	0	0.05
0.12	0.85	0	0.05
0.12	0.9	0	0.05
0.12	0.95	0	0.05
0.12	0.9	0	0.05
0.12	0.85	0	0.05
0.12	0.8	0.1	0.1
0.2	0.75	0.15	0.25

0.2	0.7	0.2	0.45
0.2	0.8	0.45	0.65
0.2	0.75	0.8	0.85
0.2	0.6	1	0.8
0.2	0.5	1	0.85
0.2	0.45	0.95	0.75
0.2	0.35	0.9	0.65
0.2	0.4	0.75	0.55
0.25	0.45	0.45	0.6
0.25	0.55	0.35	0.7
0.25	0.65	0.1	0.85
0.25	0.75	0.05	1
0.25	0.85	0	0.9
0.25	1	0	0.7
0.12	0.95	0	0.5
0.12	0.85	0	0.3

4.1. Demand response program

The building is modeled by four loads. Table 4 lists the demand response program model for the loads. The first and second loads are the interruptible loads, the third load is the constant power load, and the fourth load is the uninterruptible load that needs consecutive operation [5].

Table 4: Demand response program

	Load type	Power (kW)	Energy (kWh)	Operation pattern
Load 1	Interruptible load	20	160	At least 8 non-consecutive hours in day
Load 2	Interruptible load	5	50	At least 10 non-consecutive hours in day
Load 3	Constant power load	25	293.75	Constant operation pattern as given in Table 3
Load 4	Uninterruptible load	15	90	Six consecutive hours in day

The interruptible load can stop its operation and then continue again like electric vehicle charging process. The Uninterruptible load (or shift-able load) needs to operate over consecutive hours to finish its duty and its operation cannot be interrupted until finishing the duty like a laundry machine. But its operation can be shifted from day to night or vice versa. The constant power load operates according to a pattern during 24-hour like a refrigerator or air conditioning system.

4.2. Simulation software and model

The proposed model for energy management in the residential building is expressed as mixed integer linear programming in GAMS software. The model is solved by CPLEX solver in GAMS. The absolute gap tolerance is set on 1E-5. The simulations are carried out on the PC with following details: CPU 2.4 GHz Core i5, RAM 4 GB.

The proposed model is expressed as mixed integer linear programming. In order to avoid high computational time, all the nonlinear equations (e.g. the absolute values) are linearized to form the linear programming. The linear programming solution takes less time and its convergence is guaranteed. The proposed model takes about 5-minute which is acceptable. The approach is therefore computationally efficient to be used in a real system to be deployed.

5. Numerical results

The introduced model is simulated on the given residential building. Table 5 lists the energy cost of building with and without the energy resources. The wind-solar reduce the energy cost from 98.68 ($/day) to 14.21 ($/day). The solar system alone reduces the cost by 27.87 ($/day) and the wind energy alone reduces the cost by 56.59 ($/day). Both of them together reduce the cost by 84.47 ($/day). It is obvious that the wind system is more effective to reduce the energy cost. The proposed model can properly harvest all possible energy of wind and solar systems and manage the energy through the given demand response program. Such operation reduces the energy cost by about 85%.

Table 5: Energy cost for building with and without renewable resources

	Energy cost ($/day)

Without wind and solar	98.68
With solar and without wind	70.08
With wind and without solar	42.08
With wind and solar	14.21

The traded power between building and grid is depicted in Figure 3 for two cases with and without renewable resources. The building receives total energy from the grid when the renewable resources are not installed. On the other hand, when the renewable resources are connected, the profile of power is significantly changed. The plan harvests all energy of the wind-solar system to minimize the energy cost. As well, the planning sends energy to the grid at high-cost time periods such as 8 to 18 and such operation reduces energy cost in the building. The results verify that the energy is received from the grid during low-cost time periods and the surplus of energy is send to the upstream network at high-cost time intervals.

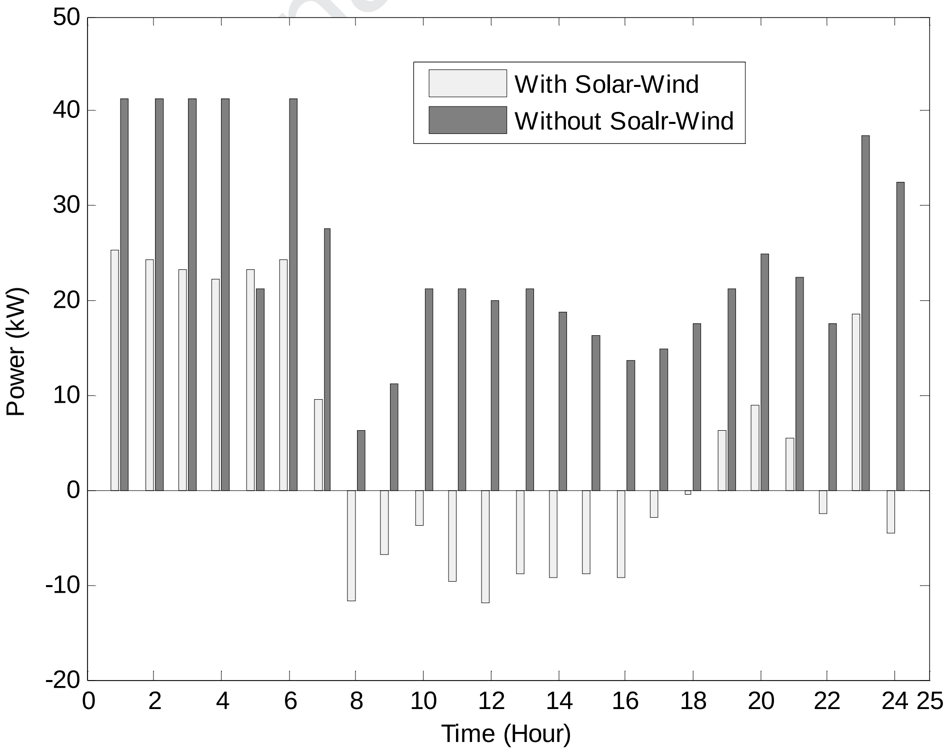


Figure 3: Traded power between building and grid with and without renewable resources

Figure 4 shows the contribution of wind and solar in the traded power. It is clear that significant part of the power is supplied by wind and solar systems. When the produced power by wind and solar systems is less than the load, the power is received from the grid. On the other hand, when the produced power by these resources is more than the load, the excess of power is transferred to the grid.

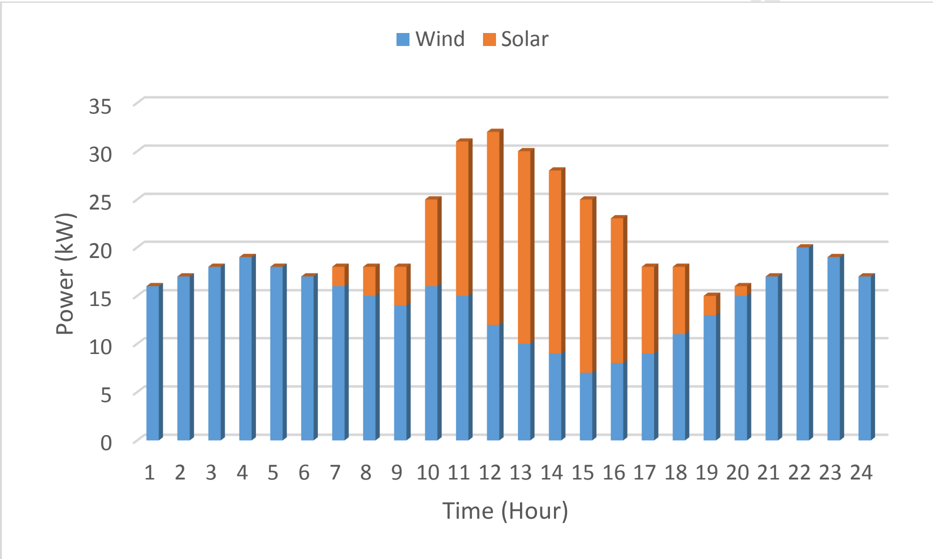


Figure 4: Contribution of wind and solar in the traded power

The results of demand response program are listed in Table 6. The optimal dispatch for all four loads is achieved by the programming and listed as below. The *Load 1* is an interruptible load and has some interruptions in the operation. The planning runs the load under low-cost hours to minimize the operational cost. The *Load 2* is the constant energy load and its operation is optimized while its required energy (50 kWh) is achieved. The *Load 3* is constant power load and follows its defined pattern. The *Load 4* has 6 hours of consecutive operation and is powered by the planning under low-cost hours. The planning optimizes the dispatch of all loads to minimize energy cost in the building and maximizing the utilization of renewable energy.

Table 6: Optimal dispatch of loads at different hours of the day

Time (Hour)	Load 1 (kW)	Load 2 (kW)	Load 3 (kW)	Load 4 (kW)
1	20	5	1.250	15
2	20	5	1.250	15
3	20	5	1.250	15
4	20	5	1.250	15
5	20	5	1.250	15
6	20	5	1.250	15
7	20	5	2.500	0
8	0	0	6.250	0
9	0	0	11.25	0
10	0	5	16.25	0
11	0	0	21.25	0
12	0	0	20.00	0
13	0	0	21.25	0
14	0	0	18.75	0
15	0	0	16.25	0
16	0	0	13.75	0
17	0	0	15.00	0
18	0	0	17.50	0
19	0	0	21.25	0
20	0	0	25.00	0
21	0	0	22.50	0
22	0	0	17.50	0
23	20	5	12.50	0
24	0	5	7.500	0

5.1. Line capacity analysis

The capacity of line between grid and building is important and makes influences on the outputs and results. In order to confirming this point, two line capacities including nominal capacity (capacity of line 42 kW) and limited capacity (capacity of line 32 kW) are simulated and discussed. The results for these two cases are listed in Table 7. Decreasing line capacity increases energy cost and cost about 50%.

Table 7: Energy cost under different line capacities

	Capacity of line (kW)	
	42	32
Energy cost ($/day)	14.21	22.34

The traded power between building and grid under different line capacities is depicted in Figure 5. Line capacity decreasing forces the building to receive energy from the grid under high-cost hours such as time periods 8,9,10,15,16,24 and resulting increasing of the energy cost for the building. On the other hand, greater line capacity lets the building to supply its energy under low-cost hours. The building does not receive energy from the grid at the mentioned high-cost hours, but also sends energy to the upstream network and makes profit.

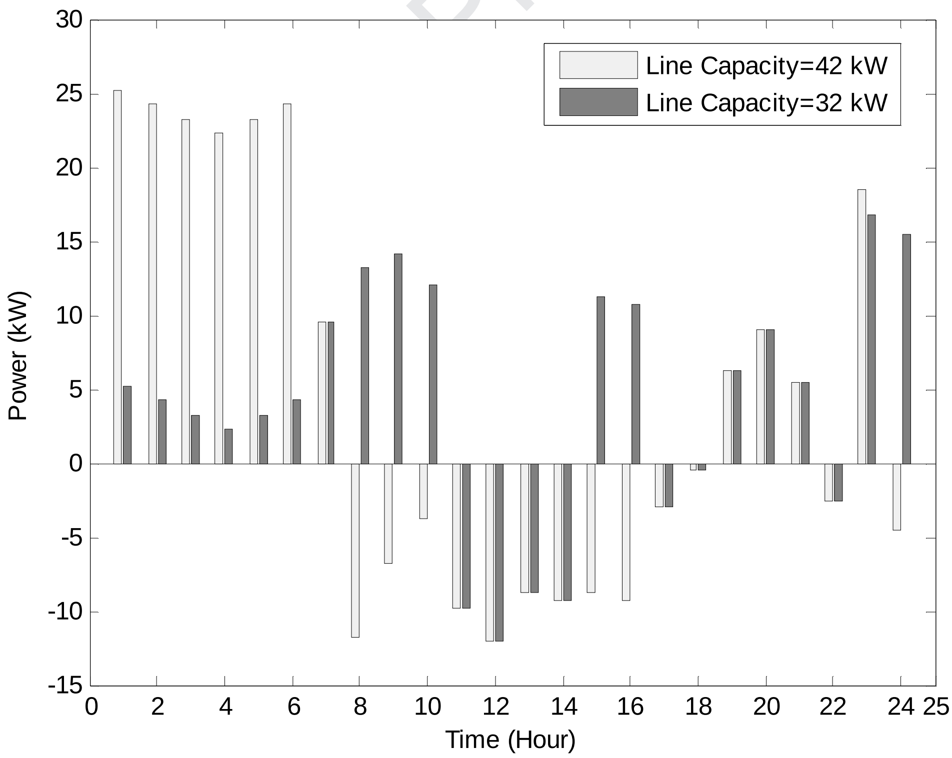


Figure 5: Traded power between building and grid under different line capacities

Table 8 summarizes the optimal dispatch of loads under 32 kW line capacity. The interruptible operation of *Load 1* is optimized. The required energy of *Load 2* is also met while its operation is optimized. The *Load 3* follows its constant pattern and the *Load 4* shows 6 consecutive hours of operation.

Table 8: Optimal dispatch of loads under 32 kW line capacity

Time (Hour)	Load 1 (kW)	Load 2 (kW)	Load 3 (kW)	Load 4 (kW)
1	0	5	1.250	15
2	0	5	1.250	15
3	0	5	1.250	15
4	0	5	1.250	15
5	0	5	1.250	15
6	0	5	1.250	15
7	20	5	2.500	0
8	20	5	6.250	0
9	20	0.95	11.25	0
10	20	0.75	16.25	0
11	0	0	21.25	0
12	0	0	20.00	0
13	0	0	21.25	0
14	0	0	18.75	0
15	20	0	16.25	0
16	20	0	13.75	0
17	0	0	15.00	0
18	0	0	17.50	0
19	0	0	21.25	0
20	0	0	25.00	0
21	0	0	22.50	0
22	0	0	17.50	0
23	20	3.3	12.50	0
24	20	5	7.500	0

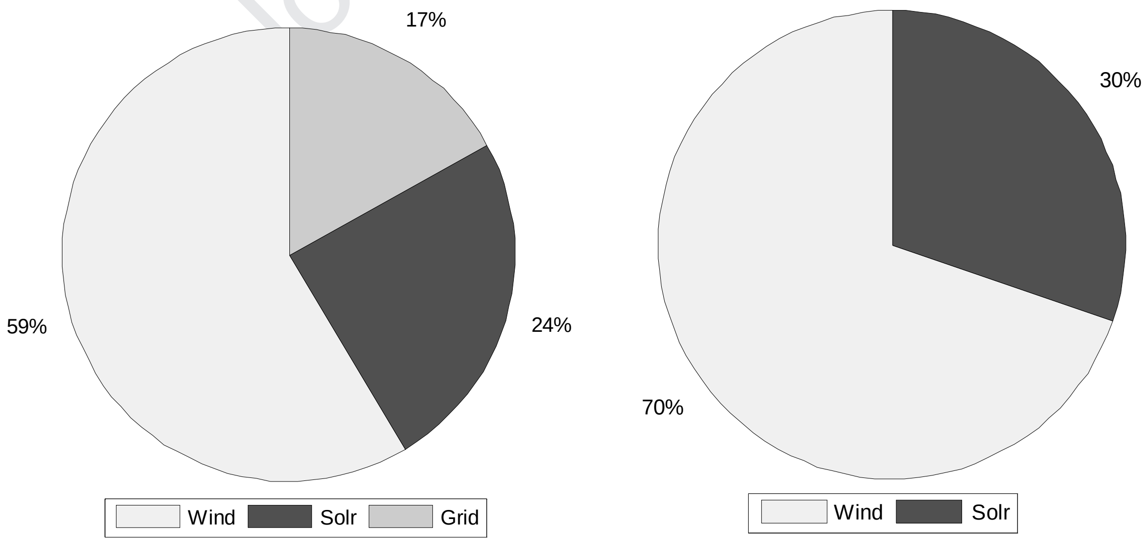
5.2. Uncertainty analysis and off-grid operation

In the planning, the intermittency of wind and solar energies is handled by the proposed demand response program. The loads are properly adjusted by the program to cope with such uncertainty. Table 9 presents the energy cost with and without renewable energy intermittency. The network with renewable energy intermittency needs to adjust the loading to cope with such uncertainty and the energy cost is increased as a result. On the other hand, when the renewable energy intermittency is not included, the loads are not adjusted to cope with renewable energy intermittency but they are adjusted to minimize the energy cost. As a result, the energy cost is reduced beyond the level achieved by the case including renewable energy intermittency.

Table 9: Energy cost with and without renewable energy intermittency

	without renewable energy intermittency	with renewable energy intermittency
Energy cost ($/day)	7.60	14.21

The off-grid operation of the building needs greater wind and solar systems. In order to show the off-grid operation, wind and solar energies are increased to 24 kW and 25 kW respectively. Figure 6 shows the energy of building under grid-tied and off-grid operations. In the grid-tied operation, most of the energy is supplied by the wind and a small portion is taken from the gird. In the off-grid operation, wind supplies 70% and solar 30% of the loads. The energy of wind system is more than solar system.



A: grid-tied operation **B**: off-grid operation

Figure 6: Energy of building under grid-tied and off-grid operations

5.3. Temperature effect on the solar system

The temperature effect on the solar Photovoltaic is an important parameter and it needs to be incorporated in the modeling. In this section, a brief investigation is conducted on this issue to signify its impacts on the outputs. The solar panel efficiency is reduced by increasing the temperature. The Photovoltaic panels are often tested at a temperature of 25 degrees centigrade and the heat may reduce their efficiency by about 10 to 25%. In order to show the impacts of the temperature on the solar Photovoltaic, several cases are simulated and listed in Table 10. It is clear that increasing the heat reduces the efficiency of solar system and results more energy cost for the system. In the proposed model, it is assumed that the heat reduces output efficiency of the solar system.

Table 10: Temperature effect on solar Photovoltaic

Case	Energy cost ($/day)
Normal temperature resulting in 100% efficiency	14.21
Increasing temperature resulting in 90% efficiency	16.97
Increasing temperature resulting in 80% efficiency	19.73

5.4. System operation under contingency

In the proposed model, the building is not a net zero energy building and it is connected to the upstream grid. As a result, it receives some portion of its energy from the grid. However, the building is able to operate disconnected from the grid. It does not mean that the building is working as off-grid at all hours of the day. It is only able to operate at some hours when the upstream grid is not available because of the power outage. The upstream grid outage is a contingency situation and may take time from minutes to hours. During this period, the building can continue its operation.

In this paper, only one contingency (N-1 contingency) is studied. It means that if one of the components (wind unit, solar unit, or upstream grid) is not available, the load can be supplied by the other capacity resources. As a result, if the building is disconnected from the grid (i.e., one contingency), the energy of the building is supplied by the other capacity resources including wind, solar, and demand response program. However, if another contingency is occurred at the same time when the first contingency is underway (N-2 contingency), some portions of load may be unsupplied because the proposed model has not been designed for operation under N-2 contingency. Considering N-2 or N-3 contingency increases the system reliability and availability but it also increases the system cost significantly. The operation under N-2 contingency or N-3 contingency (i.e., outage of upstream network, wind, and solar) needs to install extra energy resources (e.g., diesel generator) resulting in more investment cost. There are two options to deal with such situation, either accepting such unavailability of energy for building or investing more cost to install extra energy resources.

In order to demonstrate such points, the contingency analysis of the model is addressed in Table 11. The building successfully operates under N-1 contingency but it cannot supply the demand under N-2 and N-3 contingencies. Under N-3 contingency, all of the load demand is unsupplied. The building needs further energy resources to handle such situation. In this regard, one 43 kW diesel generator is installed on the building and the contingency analysis is carried out again as listed in Table 12. It is obvious that the building can supply the demand under N-3 contingency. However, it is impossible to supply the load under N-4 contingency.

Table 11: The contingency analysis of the proposed model

Contingency	Unavailable components	Unsupplied energy of load (kWh)
N-1	Wind	0
	Solar	0
	Upstream network	0
N-2	Wind and Solar	0
	Wind and Upstream network	448.75
	Solar and Upstream network	245.75
N-3	Wind, Solar, and Upstream network	593 .75 kWh (All of load)

Table 12: The contingency analysis when 43 kW diesel generator is installed

Contingency	Unavailable components	Unsupplied energy of load (kWh)
N-1	All configurations	0
N-2	All configurations	0
N-3	All configurations	0
N-4	Wind, Solar, Upstream network, and diesel generator	593 .75 kWh (All of load)

5.5. Scalability of the proposed method

The scalability shows the ability of the building to handle a growing amount of the load by adding new resources or by optimal utilization of available resources. From this point of view, the building is able to handle the load growth by about 900 kWh per day by optimal utilization of available resources. In other words, the building comprises proper adequacy to supply non-estimated load growth and it does not need to add new resources to supply such load growth.

The proposed energy management system can also be applied on the other buildings with different energy resources and loads. The proposed model is a planning-package to manage energy in the building. This package gets input data from the planner and solves the problem. It can be applied to design the building including different load powers, solar-wind powers, upstream network capacity or even new energy resources.

5.6. Operational cost of wind turbines and PVs

In the non-renewable electrical generating systems like gas or coal fired power plants, the operational cost is significant because of fuel cost. But in the renewable generating systems like wind and solar units, the operational cost is very low because the fuel cost does not exist. In order to show this point, the operational cost of wind and solar systems is assumed in Tables 13-14 [27] and the results including the operational costs are listed in Table 15. It can be seen that the network with solar-wind reduces the cost whether the operational cost is included or not. However, the operational cost increases the total cost from 5186 ($/year) to 7986 ($/year).

Table 13: Operational costs of 20 kW solar system

Parameter	Level ($)
Annual electricity of inverter	100
Annual Maintenance	400
Annual Solar panel cleaning	300
Annual Liability insurance	100
Annual Photovoltaic-insurance	400
Total operational annual cost	**1300**

Table 14: Operational costs of 20 kW wind system

Parameter	Level ($)
Annual electricity of interface devices	100
Annual Maintenance	900
Annual Liability insurance	100
Annual Turbine-insurance	400
Total operational annual cost	**1500**

Table 15: Total cost with and without operational cost

	Without wind-solar	With wind-solar excluding operational cost	With wind-solar including operational cost
Total annual cost ($/year)	36018	5186	7986

6. Conclusions

This paper simulates the building with different energy and capacity resources to manage energy. The simulation results demonstrate that the wind energy reduces the cost by 56.59 ($/day), solar energy reduces the cost by 27.87 ($/day), and both of them together reduce the energy cost by 84.47 ($/day) that shows about 85% reduction in the cost. The building without RESs receives energy from the grid during all 24 hours, while the building with renewables can send energy to the grid at high-cost hours such as hours 8 to 18. The proposed demand response program successfully adjusts all four loads of the building in order to minimizing the energy cost and smoothing the renewable intermittency. The demand response program shows that load 1 operates at hours 1-7 and 23 where the energy price is low. The second load is also supplied during low cost hours including 1-7, 10, 23-24. The third load follows its defined pattern and operates over all 24-hour. The load 4 operates over 6 consecutive hours from 1 to 6 that are the off-peak hours. The results show that decreasing capacity of the line between grid and building from 42 kW to 32 kW increases the cost by about 50 %. Under such condition (limited line capacity), the building has to receive energy from the grid under high-cost hours such as time periods 8,9,10,15,16,24 resulting in more energy cost. The renewable energy intermittency increases the cost by 50% because the network needs further infrastructures and load regulation services to deal with such uncertainty. The off-grid operation of the building needs larger wind and solar power as 24 kW and 25 kW, respectively. The contingency analysis shows that the building successfully operates under N-1 contingency but it cannot supply the demand under N-2 and N-3 contingencies. The building needs further energy resources such as 43 kW diesel generator to operate under N-3 contingency. It is also demonstrated that the network with solar-wind reduces the cost whether the operational cost is included or not. However, the operation cost increases the total cost from 5186 ($/year) to 7986 ($/year).

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Research Highlights

- Building is supported by coordination of various energy capacity resources.
- Energy capacity resources are wind, solar, and demand response program.
- Bidirectional and off-grid operations are admitted for building.
- Demand response program includes different loading models and operations.
- Uncertainty is incorporated by stochastic programming and demand response program.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: