Cost Allocation Model for Net-Zero Energy Buildings under Community-Based Reward Penalty Mechanism

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Abstract – The introduction of financial incentives for net-zero energy building/community (ZEB/ZEC) is a potential strategy that facilitates the development of sustainable buildings. In this study, a reward-penalty mechanism (RPM) is firstly proposed for a community that aims to achieve the target of annual zero energy balance. In order to investigate the cost allocated for each building in the community, a cost allocation model by considering the load of these buildings and the levels of zero energy building achieved is further proposed, based on which four typical types of the model is selected and investigated. The economic performance of a building under the four types of allocation model is then compared for a community that consists of 20 family houses in Ireland. By considering the possible ZEB level ranges in each building, two Cases are conducted (Case 1 – the range is between 0.0 and 1.0; Case 2 – the range is between 0.5 and 1.0). The results show that the 1st model is the simplest one that allocates cost evenly. By contrast, the cost of a building depends on its load in the 2nd model and depends on the ZEB level it achieved in the 3rd model, while it considers the two factors evenly in the 4th model. The proposed cost allocation model is expected to provide a basic guide for the designers of financial incentives as well as experts in the fields of net-zero energy buildings.

Keywords – Cost allocation model; economic performance; net-zero energy building/community; reward-penalty mechanism

1. INTRODUCTION

Net-zero energy buildings (ZEB/NZEB) has been widely recognized as a potential solution to address the challenges of the increasing environmental and energy problems [1], [2]. Various regulations and legislatives have been proposed to promote ZEB practical applications, which can be observed from the task 40 “Towards net zero energy solar buildings” under the umbrella of international energy agency (IEA) [3], and the goal of

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‘nearly net zero energy buildings’ for all the new buildings from 2020 under the Directive on Energy Performance of Buildings [4].

In general, passive design strategy (i.e., building envelope, orientation) [5], [6] high efficiency energy-consuming system (e.g. heating, ventilation and air-conditioning system) [7] and renewable energy system (e.g. solar photovoltaic, wind turbine system) [8], [9] are the three key approaches for the design of ZEB. Basically, Energy consumption in building sectors and industry sectors is a vital factor to be much concerned, based on which carbon dioxide emissions can be forecasted [10] and the relative effect of main parameters on energy consumption can be identified [11]. In perspective of building owners, the economic performance of ZEB is a vital factor that has been widely investigated by optimal design and control of renewable energy systems in buildings. In order to minimize the overall initial investment of renewable energy systems an exhaustive search approach was employed by Sun [12] for optimal sizing the renewable energy system and storage system in a ZEB. To treat uncertainty for robust system sizing of ZEB, Zhang and Sun [13] further proposed a response-surface-model-based system sizing method that can substantially reduce the number of Monte Carlo simulations, and the design option with the maximal overall performance (i.e., annual energy match ratio, self-consumption ratio and initial investment) is finally selected. In the study conducted by Hassoun et al. [14], various power design options were compared in order to achieve the least total net present cost and maximum renewable energy fraction for a standalone net zero energy house located in Lebanon. Besides, a model predictive control using nonlinear algorithm [15] and using mix-integer nonlinear algorithm [16] were proposed by Lu et al. to minimize system operation costs of low/zero energy buildings based on day ahead electricity prices.

The application of renewable energy systems in buildings plays a vital role in the promotion of net-zero energy buildings, however, the cost of ZEB is usually much higher than that of a traditional building mainly due to the high investment of renewable energy systems [17]. A range of incentive policies (i.e. investment subsidies, feed-in tariff (FIT), net metering schemes) can be found on the application of renewable energy sources in [18] and [19], and FIT is one widely applied incentives in numerous countries. Many studies have investigated how feed-in-tariff (FIT) affects homer users’ decision in terms of: economic aspect [20], investment behaviour for PV selection [21] and WT selection [22], as well as different incentive schemes [23]. For instance, the government firstly introduced a unified feed-in tariff and then determined a sub-regional feed-in tariff (FIT) policy in 2013 for solar power in China [24]. Malaysia introduced the FIT scheme for grid-connected electricity generated by renewables in its 2011 Renewable Energy Act [25]. In 2018, the UK government has announced the new feed-in tariffs for small scale renewable and low carbon electricity, tariff level for new installations of PV (≤ 10 kW) and Wind (≤ 50 kW) is 3.79 p/kWh and 8.24 p/kWh respectively [26]. The Emissions Trading Scheme has also been proved to be of profound significance for achieving low-cost emission reduction and renewable energy goal [27], [28].

In our previous study, a reward-penalty mechanism has been proposed which focuses on building level [29], [30]. It is recognized that a fundamental role has been increasingly assigned to ‘energy communities’ in which energy production is based on renewable sources [31]. However, no specific financial incentives have been identified for the promotion of achieving zero energy community and the benefits of its building users until now. This study is therefore conducted to investigate the potential effect of cost allocation model for the buildings in a community under the proposed reward-penalty mechanism based on community level.

2. METHODOLOGY AND PROBLEM FORMULATION

A reward-penalty function (1) is proposed for a community that aims to achieve the target of zero energy community. It is developed with the ability of adjusting the cost-effective system selection for a community. As the proposed reward-penalty function follows a quadratic concave curve, a lower ZEC selection will cause a heavier financial penalty for the building owners, and a higher RES integration will bring a greater bonus. A general schematic diagram is shown in Fig. 1, the first step is to identify the building load, its renewable generation and the main key parameters (e.g., RES price, electricity price) for developing the reward-penalty mechanism for this community. Secondly, the initial cost (C_{io}) and reward/penalty cost (C_{rp}) can be calculated for each level of zero energy community (ZEC). Thus, the corresponding total cost of the community can be derived. Finally, the total cost will be allocated to each building users based on the proposed cost allocation model.

Fig. 1. Schematic diagram of allocation model for community-based RPM.

2.1. Development of Community-Based RPM

In this study, PV array and the grid are the two power systems for the community. PV generation has considered the effect of temperature, as calculated in Eq. (1). The PV efficiency is 18 % under the standard test condition and its derating factor is selected to be 0.9.

$$E_{pv,i} = f_{pv} \frac{I_{T,i}}{I_S} [1 + k_p (T_{C,i} - T_{STC})], \quad (1)$$

where

$E_{pv,i}$ PV generation per kW at the hour i ;

f_{pv} PV derating factor, %;

I_S The radiation under standard test conditions, 1 kW/m^2 ;

$I_{T,i}$ Solar radiation on the surface of the PV array (kW/m^2) at the time i ;

k_p The temperature coefficient of power, $\%/^{\circ}\text{C}$;

$T_{C,i}$ PV module temperatures in the current hour, $^{\circ}\text{C}$;

T_{STC} PV module temperatures under standard test conditions, 25°C .

Based on the installation of PV system, a zero-energy level for the community (R_{zec}) is defined as the ratio of its renewable generation (E_{pv}) to its load (E_{cl}), as formulated in Eq. (2). A value of 0.0 for R_{zec} represents no renewable generation in this community, and a value of 1.0 for R_{zec} means the community achieved its zero-energy target.

$$R_{zec} = \frac{\sum_{i=1}^{8760} E_{pv,i}}{E_{cl}} \quad (2)$$

During application, the grid-connected community is supplied by the power from either PV system or the grid, as shown in Eq. (3). Where, i represents the time from 1 h to 8760 h, and the electricity price from grid (i.e., the case of non-sufficient RES generation) and to grid (i.e., the case of excess RES generation) is assumed to be an equal value of 0.1 \$/kWh.

$$E_{cl,i} = E_{res,i} + E_{grid,i} \quad (3)$$

The annual initial cost of the community (C_{io}) generally consists of the capital cost of RES and building operation cost, it can be fitted as a linear fitting formula in Eq. (4). Then, the community-based RPM is developed based on the method proposed by Lu et al. [32], and the reward/penalty cost (C_{rp}) can be formulated in Eq. (5). The parameters a , b , and c in Eq. (5) can be determined by the total cost (TC) in Eq. (6) if given three conditions. In this study, the total cost of the community is assumed to be twice of its initial cost for a selection of 0.0ZEC design, and it is only half of its initial cost for a selection of 1.0ZEC design. In addition, the most economical selection is set to be 1.0ZEC design under the application of RPM.

$$C_{io} = b_1 \cdot R_{zec} + c_1 \quad (4)$$

$$C_{rp} = a \cdot R_{zec}^2 + b \cdot R_{zec} + c \quad (5)$$

$$TC = C_{io} + C_{rp} \quad (6)$$

2.2. Development of Cost Allocation Model.

As illustrated in section 2.1, the total cost of the community is derived for different levels of ZEC design, and it is actually the accumulated total cost of the entire buildings in the community. The total cost is required to be undertaken by the building users in this community, and thus an important step is to develop a cost allocate model. Generally, the building load and the level of zero energy target the building achieved are two key factors that affects the total cost of the community. Therefore, the allocation model can be developed based on the two factors in Eq. (7).

$$TC(k^{th} B) = TC \cdot \left(\alpha \times \frac{E_{bl}(k)}{E_{cl}} + \beta \cdot \frac{\frac{1}{R_{zeb,k}}}{\sum_{l=1}^n \frac{1}{R_{zeb,k}}} \right), \quad (7)$$

where, $k = 1, 2, \dots, n$, $\alpha + \beta = 1.0$.

Actually, the simplest method is to evenly allocate the total cost for each building, i.e., the 1st model as formulated in Eq. (8). Based on the developed allocation model (7), there are another three typical model types, i.e., the 2nd model concerning only the building load in Eq. (9), the 3rd model concerning only the level of zero energy target it achieved Eq. (10), and the 4th model concerning the two factors evenly in Eq. (11).

$$1^{\text{st}} \text{ Model: } TC1(k^{\text{th}} B) = TC \cdot \frac{1}{n} \quad (8)$$

$$2^{\text{nd}} \text{ Model: } \alpha = 1.0, \beta = 0.0, TC2(k^{\text{th}} B) = TC \cdot \frac{E_{bl}(k)}{E_{cl}} \quad (9)$$

$$3^{\text{rd}} \text{ Model: } \alpha = 0.0, \beta = 1.0, TC3(k^{\text{th}} B) = TC \cdot \frac{\frac{1}{R_{zeb,k}}}{\sum_{k=1}^n \frac{1}{R_{zeb,k}}} \quad (10)$$

$$4^{\text{th}} \text{ Model: } \alpha = 0.5, \beta = 0.5, TC4(k^{\text{th}} B) = TC \cdot \left(0.5 \cdot \frac{E_{bl}(k)}{E_{cl}} + 0.5 \cdot \frac{\frac{1}{R_{zeb,k}}}{\sum_{k=1}^n \frac{1}{R_{zeb,k}}} \right) \quad (11)$$

3. DESCRIPTION OF CASE STUDY

The proposed RPM strategies and cost allocation models are investigated based on a community that consists of 20 family-houses randomly selected in Ireland [33]. The electricity consumption data of these buildings are collected by the smart meter with half-hourly records for more than one year [34]. As shown in Fig. 2, the annual electricity loads of these buildings range from 1 476 kWh/yr to 11 191 kWh/yr.

In this study, solar resource and ambient temperature in Dublin, Ireland are selected to evaluate the potential of PV generation. The longitude of Dublin is 53°26'10", and the latitude is 6°15'53". As displayed in Fig. 3, the average annual temperature is identified to be 10.2 °C and solar irradiation on optimally inclined plate is 3.020 Wh/m²/day.

Fig. 2. The annual electricity load of 20 buildings in the community.

Fig. 3. Average temperature and irradiation on optimally inclined plate in Ireland [35].

4. RESULT ANALYSIS

4.1. Effect of RPM on Total Cost

A comparison of the economic performance is presented for the community under the case without RPM (C_{i0}) and the case with RPM (TC), as shown in Fig. 1. As indicated in section 2.1, the ratio of the total cost to the initial cost is given 2.0 for a 0.0ZEC design and it is 0.5 for a 1.0ZEC design, while the minimum total cost is expected to be at 1.0ZEC design. Under

this condition, the reward-penalty function is solved, i.e., $C_{rp} = 19180.8x^2 - 36171x + 12057$. It can be observed that there is not much benefit for the community with a higher ZEC level if no financial incentive is applied. However, a significant cost reduction can be achieved under the developed RPM. More specifically, the minimum total cost of 4 934 \$/yr is located at 1.0ZEC design. By contrast, the maximum total cost of 24 114 \$/yr is located a 0.0ZEC design, and it is twice time of the community without RES integration. Consequently, a selection of lower ZEC level will cause a heavier fine whilst a great profit can be expected for a community at a higher RES integration.

Fig. 4. The total cost of the community under RPM.

4.2. Cost Allocated for Buildings – Case 1

As the level of the community to be ZEC is determined by its building users, and the installation of PV system is actually a willing determined by building users. In Case 1, a random probability between 0.0 and 1.0 is assumed as ZEB level achieved by each building. Then, Monte Carlo method is employed to generate a sample of 100 ZEB levels for each building. Finally, the distribution of ZEC level and the total cost of the community are identified as shown in Fig. 5. It is found that the ZEC level and the corresponding total cost are expected to vary between 0.31 and 0.68, between 6 875 \$/yr and 14 084 \$/yr, respectively. In addition, the cumulative probability of 50 % is observed for ZEC level to be 0.52, and it is 50 % for the total cost to be 9 419 \$/yr.

Fig. 5. (a) Distribution of ZEC level; (b) total cost of the community.

In order to further investigate the benefit for building owners, the total cost of the community is allocated based on four typical types of allocation model as proposed in Eq. (8)–(11). The average cost of each building as well as the community is summarized in Table 1. Under the selection of the 1st allocation model, the total cost is the same for each building with an annual cost of 481 \$/yr. Under the selection of the 2nd allocation model, a lowest total cost is required for a lowest building load while a highest total cost is required for a highest building load. This can be found from the 1st Building (load of 1 476 kWh) with an annual cost of 118 \$/yr and the 20th Building (Load of 11 191 kWh) with an annual cost of 892 \$/yr. Under the selection of the 3rd allocation model, a slight difference is found in the cost of each building. This is because the ZEB levels of these buildings are all randomly selected from 0.0 to 1.0, and the average values under 100 samples are identified between 0.478 and 0.547. Under the selection of the 4th allocation model, the cost allocated for each building is the mean value of that in the 2nd and the 3rd model.

TABLE 1. AVERAGE COST OF EACH BUILDING AND THE COMMUNITY (100 SAMPLES)

20 Buildings	BL, kWh/yr	ZEB level	TC1, \$/yr	TC2, \$/yr	TC3, \$/yr	TC4, \$/yr
B1	1.476	0.504	481	118	500	309
B2	2.403	0.494	481	192	464	328
B3	2.503	0.498	481	200	455	327
B4	3.319	0.497	481	265	464	364
B5	3.412	0.501	481	272	656	464
B6	4.312	0.536	481	344	467	406
B7	4.761	0.491	481	380	455	417
B8	5.275	0.529	481	420	604	512
B9	5.278	0.527	481	421	362	391
B10	5.704	0.478	481	455	466	460
B11	6.261	0.499	481	499	690	595

B12	6.404	0.526	481	510	352	431
B13	6.960	0.547	481	555	361	458
B14	7.595	0.496	481	605	417	511
B15	7.692	0.524	481	613	489	551
B16	8.157	0.502	481	650	401	526
B17	8.406	0.519	481	670	382	526
B18	9.154	0.505	481	730	484	607
B19	10.305	0.520	481	821	555	688
B20	11.191	0.509	481	892	586	739
Community	120 568	0.512	9 611	9 611	9 611	9 611

Fig. 6. Distribution of ZEB level for 10th Building.

Fig. 7. The cost allocated for 10th Building under four cost allocation models *TC1*, *TC2*, *TC3*, *TC4*.

A detail distribution of ZEB level and the allocated cost are presented for 10th Building (B10) as shown in Fig. 6 and Fig. 7. In terms of the selection of ZEB level, the cumulative probability of 50 % is observed to be 0.45 for this building. In terms of the cost allocated for this building, a distribution is presented for the four typical types of allocation model. It is interesting to find that the distribution pattern and range of the 10th building cost is similar under the 1st allocation model and the 2nd allocation model. In addition, a little bit low probability is observed for the building users to pay several thousand dollars under the 3rd allocation model and the 4th allocation model.

4.3. Cost Allocated for Buildings – Case 2

In Case 2, a random probability between 0.5 and 1.0 is considered as the range of ZEB level for each building. Based on 100 samples simulation, the distribution of ZEC level and the total cost of the community are identified as shown in Fig. 8. It is found that the ZEC level and the corresponding total cost are expected to vary between 0.65 and 0.84, between 5 421 \$/yr and 7 259 \$/yr, respectively. In addition, the cumulative probability of 50 % is observed for ZEC level to be 0.74, and it is 50 % for the total cost to be 6 201 \$/yr.

Fig. 8. (a) Distribution of ZEC level; (b) total cost of the community $TC(C)$.

Similarly to the Case 1, the total cost of the community is allocated based on the four allocation models, as summarized in Table 2. Under the selection of the 1st allocation model, the same annual total cost is found for each building (307 \$/yr). Under the selection of the 2nd allocation model, the building with low load will be distributed with a low annual cost from the 1st Building (i.e., load of 1.476 kWh and cost of 75 \$/yr). By contrast, the building with high load will be distributed with a high annual cost from the 20th Building (Load of 11.191 kWh and cost of 571 \$/yr). Under the selection of the 3rd allocation model, the costs of the 20 buildings range from 298 \$/yr to 321 \$/yr with the average ZEB levels range from 0.72 to 0.77. Under the selection of the 4th allocation model, the cost of each building is also seen to be the mean value of that in the 2nd and the 3rd model.

TABLE 2. AVERAGE COST OF EACH BUILDING AND THE COMMUNITY (100 SAMPLES)

20 Buildings	BL, kWh/yr	ZEB level	TC1, \$/yr	TC2, \$/yr	TC3, \$/yr	TC4, \$/yr
B1	1 476	0.764	307	75	302	189
B2	2 403	0.734	307	123	314	218
B3	2 503	0.752	307	128	305	216
B4	3 319	0.739	307	169	312	241
B5	3 412	0.746	307	174	306	240
B6	4 312	0.751	307	220	305	263
B7	4 761	0.759	307	243	305	274
B8	5 275	0.727	307	269	318	294
B9	5 278	0.715	307	269	321	295
B10	5 704	0.756	307	291	304	297
B11	6 261	0.757	307	319	304	312
B12	6 404	0.761	307	326	303	315
B13	6,960	0.765	307	355	302	329
B14	7 595	0.770	307	387	298	343

B15	7 692	0.753	307	392	305	349
B16	8 157	0.717	307	416	321	369
B17	8 406	0.751	307	429	308	368
B18	9 154	0.764	307	467	302	384
B19	10 305	0.748	307	525	309	417
B20	11 191	0.764	307	571	301	436
Community	120 568	0.750	6 147	6 147	6 147	6 147

Fig. 9. Distribution of ZEB level for 10th Building.

Fig. 10. The cost allocated for 10th Building under four cost allocation models *TC1*, *TC2*, *TC3*, *TC4*.

A detail distribution of ZEB level and the allocated cost are presented for 10th Building (B10) in Case 2, as shown in Fig. 9 and Fig. 10. The cumulative probability of 50 % is observed to be 0.75 for ZEB level of this building. In addition, although the cost of the building is more centralized in the range of 250 \$/yr and 450 \$/yr under the 1st and the 2nd allocation model, the cost differences among the four model are reduced under this case.

5. CONCLUSION

This study aims to develop cost allocation model for the buildings under community-based reward-penalty mechanism, which is conducted based on a community consisting of 20 family houses in Ireland. The economic performance of the community is firstly investigated under the proposed reward-penalty mechanism (RPM). Since the load of these buildings and the levels of zero energy building achieved are two main factors determining the total cost of the community, four typical types of allocation model are proposed for building users in this community.

Since the level of the community to be ZEC is actually determined by its building users, two cases are investigated considering a different ranges of ZEB level, i.e., in case 1, the range of ZEB level is set between 0.0 and 1.0; In case 2, the range of ZEB level is set between 0.5 and 1.0. A similar trend is observed for the cost allocated for each building under the four types of allocation model. Under the selection of the 1st allocation model, the total cost is the same for each building. Under the selection of the 2nd allocation model, a lower building load

will be allocated with a lower cost, and a higher building load will be allocated with a higher cost. Under the selection of the 3rd allocation model, the costs of these building don't show much differences. Under the selection of the 4th allocation model, the cost allocated for each building is the mean value of that in the 2nd and the 3rd model since it considers the two main factors evenly.

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