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Economic Performance of Net-Zero Energy Community under Reward-Penalty Mechanism Considering PV System Reliability

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Abstract **– Economic performance of net-zero energy building/community (ZEB/ZEC) is an important factor that affects potential investors' decision on installing renewable energy systems (RES). A reward-penalty mechanism (RPM) is proposed for accelerating the development of zero energy communities, which is developed without considering the reliability effect from RES generation. However, an investigation is deserved for the reliability effect of RES on building economic performance. A case study is therefore conducted based on an assumed community consisting of 20 family houses, in which the electricity load was collected by the smart meter for more than one year. The results show that the proposed RPM works efficiently under an ideal condition, while the costs of the community and its buildings are greatly increased when the effect of PV system reliability is considered. Specifically, the total cost of the community under 1.0ZEC design is 5 005 USD/yr in the first year, which increases to 11 341 USD/yr in the 25th year. By contrast, the total cost of the community under 1.2ZEC design is 5 243 USD/yr in the first year and increases to 9 607 USD/yr in the 25th year. It is believed that the results of this study can provide a progressive perspective for scheme makers and building owners in terms of its economic benefit. Development of enhanced RPM by considering system reliability will be investigated in our future work.**

Keywords **– Economic performance; PV system; reliability; reward-penalty mechanism; net-zero energy building/community**

Nomenclature		
PV	Photovoltaic	
RES	Renewable energy system	
RRM	Reward-penalty mechanism	
ZEB/ZEC	Net-zero energy building/community	
$E_{bec,n}$	Energy consumption of building of building n	kWh/yr

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E_{cec}	Energy consumption of a community	kWh/yr
C_{io}	Initial cost and operation cost	USD/yr
C_{rp}	Reward-penalty value	USD/yr
T_C	PV module temperatures in the current hour	°C
T_{STC}	PV module temperatures under standard test conditions	°C
TC	The total cost of a community	USD/yr
TC_n	The total cost of building *n*	USD/yr
R_{zec}	The level of zero energy community	
λ_r	Failure rate	1/h
μ_r	Repair rate	1/h
λ_F	Degradation rate of the component	1/h
T_W	Life time of the component	year (yr)
f_{pv}	Derating factor of PV system	%
k_p	The temperature coefficient of PV generation	%/°C
I_T	Solar radiation on the surface of the PV array	kW/m^2
I_S	Solar radiation under standard test	kW/m^2
i	The time of a year, $1 \le I \le 8760$	h

1. INTRODUCTION

The increasing electricity consumption is a significant contributory factor associated with problems both in the areas of energy conservation and environmental protection [1], [2]. In this context, the construction sector has been recognized to be responsible for the high energy consumption and environmental degradation [3], [4]. To solve this problem, sustainable buildings, e.g., green buildings and low/net-zero energy buildings, have been advocated as a guiding paradigm to sustainable development [5], [6].

Two questions, i.e., how to motivate owners to renovate their homes and increase energy efficiency and what business models should be used to implement economically viable and high-quality projects, were proposed based on a survey study of buildings in Latvia [7]. Incentive policy is a promising method that has been established worldwide to encourage the development of green buildings as project owners are driven to adopt green building practices. Generally, incentives can be defined as something that influence people to act in certain ways [8]. Usually, the government is responsible for administering the external incentives, in which the beneficiaries are handed a forced choice of meeting a specified green building related condition or requirement so as to benefit from this type of incentives [9]. The external incentive involves direct financial incentives and non-financial incentives, and the tax incentive is a popular financial incentive offered by the government, especially in the USA [10]. Although no direct costs are involved in non-financial incentives, they are actually financially rewarding because it saves owners' time by mitigating risk and process issues [11], [12]. The internal incentives involve human well-being related incentive, demand related incentive, gratifying incentive, persuasion and inspirational incentive, and this kind of incentives is a forced choice and beneficiaries are required to fulfil specified conditions or requirements before benefitting [13]. The gratifying incentives are an effective way of assessing the achievement of green buildings. The certification provides the owners with a feeling of gratification since their image and reputation are increased. For instance, the Green Builder logo of the Austin Green Building Program, Texas, US, helps participants increase their reputation and competition [14]. In the USA, the level of LEED certification (e.g. LEED Platinum, LEED Silver) is highly important for a new project in the Real Estate industry since it helps participants differentiate themselves from their competitors [15], [16]. A further investigation and comparative analysis of LEED projects can be identified in the literatures [17], [18].

For green society construction and sustainable development, the use of renewable energy resources has been accepted as a positive solution. A survey of current statues, problems and prospects was conduct on renewable energy development in Malaysia [19]. Substantial financial incentive policies, i.e. investment subsides, net metering schemes, and feed-in tariff, etc., mainly contribute to the widespread of renewable energy application [20], [21]. For instance, in the study of Banovac et al. [22], four most important regulatory functions ((licensing, monitoring, tariff setting and implementation, and customer protection) were used to define the regulatory mechanism with sufficient fidelity. The authors estimated that these functions together account for more than 80 % of all regulatory activity. Li et al. [23] established a two-level decision sub-game led by the national government and compares the cost-saving effect before and after the application of Chinese Certified Emission Reduction scheme. A survey of impact models underlying 60 agri-environmental schemes in seven EU member states was conducted by Primdahl et al. [24], based on which the role of impact models at different stages in the agri-environmental schemes policy process can be identified. Although a growing body of research were identified to focus on how to make and adjust incentive mechanisms in the context of the technical innovation of renewables and the curtailment of incentive rates, few incentives are developed specifically for net zero energy building [25]. To address these problems, Lu et al. [25] introduced a penalty cost to ensure that a minimum total cost is located within a safety factor of 1.0 (i.e., 1.0ZEB). The results show that ZEB owners would pay only half of the original cost. And then they further investigated the effective of penalty cost using two segmented functions, which was demonstrated to work successfully in the case of Hong Kong zero carbon building [26].

However, no reward-penalty mechanism has been developed at a community level that aims to achieve zero energy community. In addition, the reliability of generation system can affect the power generation which may result in a great difference on expected economic performance for building owners. This study is therefore conducted to investigate the influence of the reliability of PV system on the economic cost of a community and its buildings under the developed reward-penalty mechanism.

2. DEVELOPMENT OF REWARD-PENALTY MECHANISM FOR A COMMUNITY

Fig. 1 shows the main procedure for developing and applying community-level RPM. In general, a community load level and the level of zero energy community are two key factors for the development of community-level RPM. Firstly, the hourly energy consumption profile from a community is required based on its historical energy consumption data. Then, PV system-driven zero energy community (ZEC) are divided into several levels, based on which the required PV system, annual initial cost as well as annual operation cost could be derived. Thus, the traditional annual cost of the community (i.e., C_{io}, initial cost and operation cost) can be fitted as a linear fitting formula, as shown in Eq. (1). A reward-penalty function Eq. (2) is introduced to follow a quadratic concave curve, enabling the cost-effective system selection for a community where a high PV system should be expected. Therefore, the total cost can be calculated in Eq. (3) based on Eq. (1) and Eq. (2). Given three conditions (i.e., the preference of scheme makers' decision, like Eq. (4)–(6)), the reward-penalty function can be solved. For instance, the ratio (ε_1, ε_2) of the total cost to the initial & operation cost at 0.0ZEC design and 1.0ZEC design, respectively; and the level of ZEC corresponding to the lowest total cost. Finally, the total cost (*TC*) for the community under RPM is the sum of traditional annual cost (C_{io}) and reward-penalty value (C_{rp}).

$$C_{\mathrm{io}} = b_1 \cdot R_{\mathrm{zec}} + c_1 \,, \tag{1}$$

$$C_{\mathrm{rp}} = a_2 \cdot R_{\mathrm{zec}}{}^2 + b_2 \cdot R_{\mathrm{zec}} + c_2 \,, \tag{2}$$

$$TC = C_{\mathrm{io}} + C_{\mathrm{rp}} \,, \tag{3}$$

$$R_{\mathrm{rez}} = 0.0,\; TC = \varepsilon_1 \cdot C_{\mathrm{io}} \,, \tag{4}$$

$$R_{\mathrm{rec}} = 1.0,\; TC = \varepsilon_2 \cdot C_{\mathrm{io}} \,, \tag{5}$$

$$TC_{\mathrm{min}} = TC(R_{\mathrm{zec}} = 1.0) \,. \tag{6}$$

Thirdly, apply the RPM to the community and then obtain the corresponding total cost for different levels of zero energy community (R_{zec}). Therefore, the total cost is the accumulated cost of the entire buildings in the community. The last step is to allocate the cost to each building based on its load level, as shown in Eq. (7). Where, TC_n is the allocated cost for building *n*, $E_{\mathrm{bec,n}}$ and E_{cec} are the energy consumption of building *n* and energy consumption of the community, respectively. It is assumed that the cost is allocated based on the level of building energy consumption.

$$TC_n = TC \cdot \frac{E_{\mathrm{bec},n}}{E_{\mathrm{cec}}} \,. \tag{7}$$

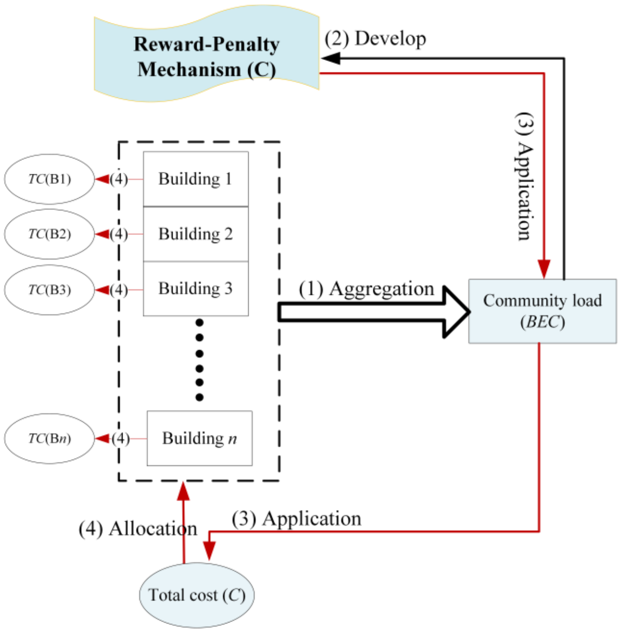


Fig. 1. Schematic diagram of community-level RPM.

3. RELIABILITY ANALYSIS OF PV SYSTEM

The representation of all possible states in a space state diagram is called Markov chain [27]. The states employed to define the reliability model of each generation unit are: “1” operating, “2” repairable failure and “3” obsolescence. The transitions rates are defined as: failure λ_r, repair μ_r and degradation λ_F. Fig. 2 shows the model developed by Alvarez-Alvarado and Jayaweera [28], which is employed for PV system reliability analysis in this study. The degradation rate can be calculated by Eq. (8).

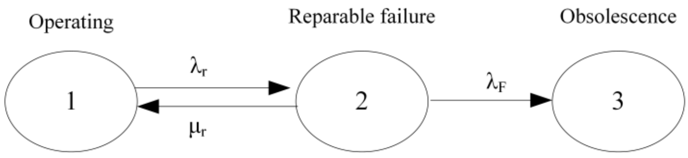


Fig. 2. Markov chain model considering aging effect [28].

$$\lambda_F = \frac{\lambda_r + \mu_r}{T_W \cdot \lambda_r - 1}. \tag{8}$$

The probability of being in each state can be mathematically determined from the stochastic matrix of transition states *H*. This matrix is the infinitesimal generator of dimensions $z \cdot z$, where *z* is the total number of states [29].

$$H = \begin{pmatrix} -\lambda_r & \lambda_r & 0 \\ \mu_r & -\mu_r & \lambda_F \\ 0 & 0 & 0 \end{pmatrix}. \tag{9}$$

Then, the probability vector of all possible states is determined by Eq. (10), where υ is the eigenvalues of H^T, v is the eigenvectors of H^T and k is a constant given by the initial state; T indicates the transpose of the matrix [30], [31].

$$P(t) = \sum_{i=1}^{z} k_i v e^{-v_i t}, \tag{10}$$

where

$$k_1 = 1;\ k_2 = \frac{\lambda_r + \lambda_F + \mu_r - a}{2a};\ k_3 = \frac{-\lambda_r - \lambda_F - \mu_r - a}{2a};\ a = \sqrt{-4\lambda_r\lambda_F + (\lambda_r + \lambda_F + \mu_r)^2}, \tag{11}$$

$$v_1 = 0;\ v_2 = \frac{-\lambda_r - \mu_r - \lambda_F - a}{a};\ v_3 = \frac{-\lambda_r - \lambda_F - \mu_r + a}{a}, \tag{12}$$

$$v = \begin{pmatrix} 0 & \frac{(\lambda_r - \lambda_F - \mu_r + a)(\lambda_r + \lambda_F + \mu_r + a)}{4\lambda_F\lambda_r} & \frac{(-\lambda_r - \lambda_F - \mu_r - a)(\lambda_r + \lambda_F + \mu_r - a)}{4\lambda_F\lambda_r} \\ 0 & \frac{-\lambda_r - \lambda_F - \mu_r - a}{2\lambda_F} & \frac{-\lambda_r - \lambda_F - \mu_r + a}{2\lambda_F} \\ 1 & 1 & 1 \end{pmatrix}. \tag{13}$$

A measure of reliability is the availability of the component, and it is defined as the sum of the probabilities of being in operating state, as shown in Eq. (14). By considering the aging effect of PV system, the availability of PV system is reduced as time passes, as displayed in Fig. 3 and Table 1.

$$A(t) = k_1 v_{11} e^{-v_1 t} + k_2 v_{12} e^{-v_2 t} + k_3 v_{13} e^{-v_3 t}. \tag{14}$$

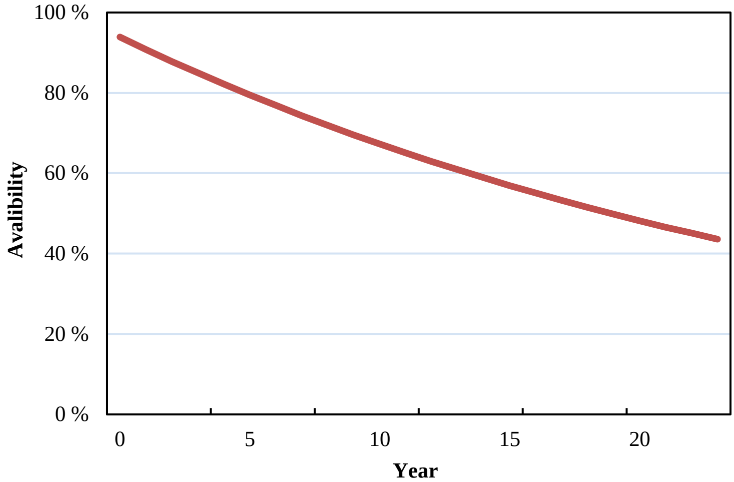


Fig. 3. The effect of operation year on availability of PV system.

TABLE 1. AVAILABILITY OF PV SYSTEM FOR 25 YEARS

Year	**1**	**3**	**5**	**7**	**9**	**11**	**13**	**15**	**17**	**19**	**21**	**23**	**25**
Availability	0.939	0.878	0.822	0.769	0.719	0.673	0.629	0.589	0.551	0.515	0.482	0.451	0.422

4. CASE STUDY AND RESULT ANALYSIS

4.1. Description of Case Study

The proposed RPM strategies are investigated based on the electricity consumption of a community consisting of a randomly selected 20 family-houses in Ireland [32]. The data set are collected from the smart meter data with half-hourly records for more than one year [33]. In this study, the temperature and solar energy in Dublin, Ireland are used to evaluate PV generation. The average temperature and irradiation on optimally inclined plate in Dublin (longitude is 53°26'10", latitude is 6°15'53") are displayed Table 1, where, the average annual temperature and available irradiation on optimally inclined plate are identified to be 10.2 °C and 3 020 Wh/m^2/day. The range of the annual building electricity load is observed to between 1 476 and 11 191 kWh/yr, and the 20 buildings are arranged according to its load as shown in Fig. 4. A summary of the entire community electricity load is presented in Fig. 5, it is observed that the load of the entire community ranges from 8 000 to 12 000 kWh/month, and it is 120 567 kWh for a year.

PV array is assumed for supplying power to the grid-connected community, which takes into account the effect of temperature as calculated in Eq. (15), where $E_{pv,i}$ is the PV generation per kW at the hour i, f_{pv} is the PV derating factor (%) and is selected to be 0.9, $I_{T,i}$ is the solar radiation on the surface of the PV array (kW/m^2) at the time i, and I_S is the radiation under standard test conditions (1 kW/m^2). The temperature coefficient of power is represented by k_p (%/°C), T_C and T_{STC} are the PV module temperatures in the current hour (°C) and under standard test conditions (25 °C). The PV efficiency is 18 % under the standard test condition.

$$E_{pv,i} = f_{pv} \frac{I_{T,i}}{I_s} \left[1 + k_p (T_{C,i} - T_{STC}) \right]. \tag{15}$$

The zero-energy level of a community (R_{zec}) is defined as the ratio of on-site PV energy generation (E_{pv}) to its energy consumption, as shown in Eq. (16), a higher value of R_{zec} represents a higher zero energy level of the community.

$$R_{zec} = \frac{E_{pv}}{E_{cec}}. \tag{16}$$

TABLE 2. AVERAGE TEMPERATURE AND IRRADIATION ON OPTIMALLY INCLINED PLATE IN IRELAND [34]

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
I_{opt}, Wh/m^2/ /day	1 200	1 810	2 870	4 100	4 820	4 620	4 710	3 920	3 450	2 320	1 420	887	3 020
T, °C	5.7	6.0	7.1	8.5	11.1	13.7	15.7	15.8	14	11.2	8.1	6.0	10.2

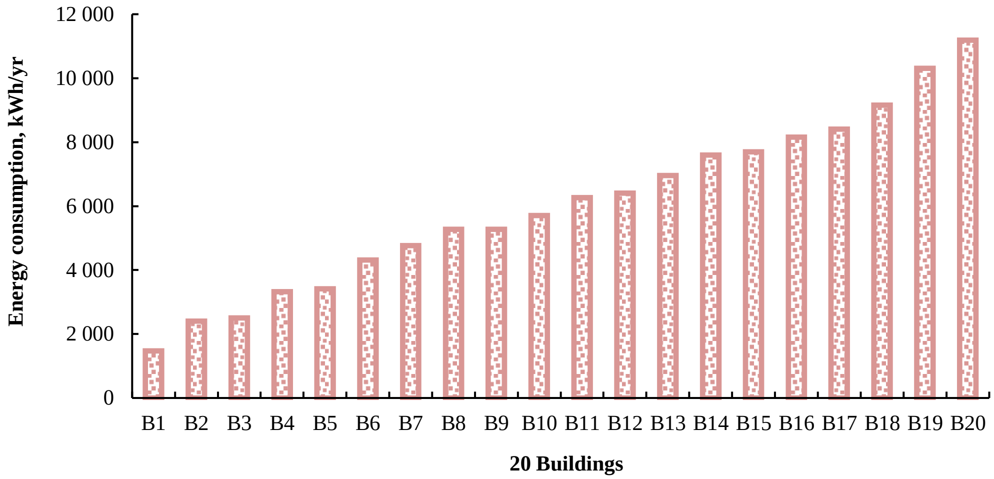


Fig. 4. The annual electricity load of 20 buildings in the community.

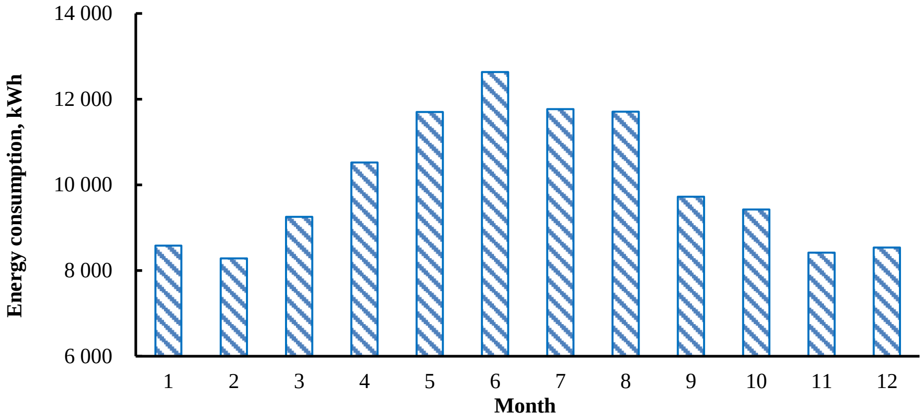


Fig. 5. The electricity load of the entire community in each month.

4.2. Economic Cost under RPM

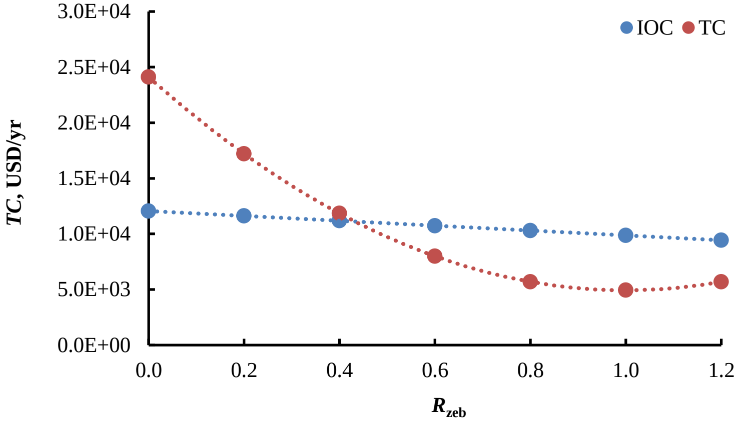


Fig. 6. The total cost of the community under ZEC level selected.

Based on the electricity consumption data of 20 family-houses, the reward-penalty function at community level is solved, i.e., $C_{rp} = 191.801 \cdot R_{zec}^2 - 36.171 \cdot R_{zec} + 12.057$. The total cost is therefore represented as: $TC = 19.181 \cdot R_{zec}^2 - 38.361 \cdot R_{zec} + 24.114$. The effect of applying community-level RPM on the total cost of the community is reflected as shown in Fig. 6. It can be observed that the developed RPM reshapes the original cost curve into a significant descending concave curve. The maximum value of the total cost is 24 114 USD/yr under a selection of 0.0ZEC design, which is twice time of the traditional buildings without RES system. By contrast, the minimum value of the total cost is 4 934 USD/yr under a selection of 1.0ZEC, which is only half of that in traditional community without RES system. The developed RPM for the community is demonstrated efficient from the reshaped total cost of the community. That is to say, a great profit can be expected for a community at 1.0ZEC design whilst a significant fine will be paid at a lower ZEC level design.

4.3. Economic Cost under 1.0ZEC Design

Under ideal condition, the annual total cost of the community is 4 934 USD/yr at a selection of 1.0ZEC design, which considers PV reliability of 1.0 as time passes. However, this is not the real case and the reliability of PV system is usually decreased with time. Since the reliability of PV system has a great impact on power generation, the level of zero energy community is changing year by year, resulting in an increasing total cost as shown in Fig. 7. The total cost of the community at 1.0ZEC design is observed to be 5 005 USD/yr in the first year, which increases to 6 718 USD/yr in the 10th year, 9 767 USD/yr in the 20th year and 11 341 USD/yr in the 25th year, and the average annual cost is supposed to be 7 774 USD/yr.

Accordingly, the total cost is then allocated for each building, as shown in Fig. 8 and Table 3. The cost of each building also increases with years. For instance, the cost of 1st Building (B1) is 61 USD/yr in the 1st year and increases to 139 USD/yr in the 25th year, its average annual cost is identified to be 95 USD/yr. By contrast, the cost of 20th Building (B20) is 465 USD/yr in the 1st year and increases to 1 053 USD/yr in the 25th year, its average annual cost is identified to be 722 USD/yr. In general, the total cost of each building in the 25th year is more than twice that in the 1st year.

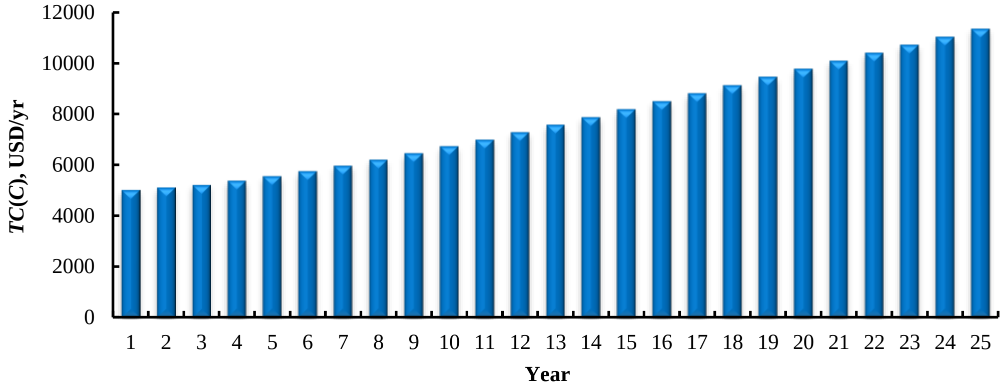
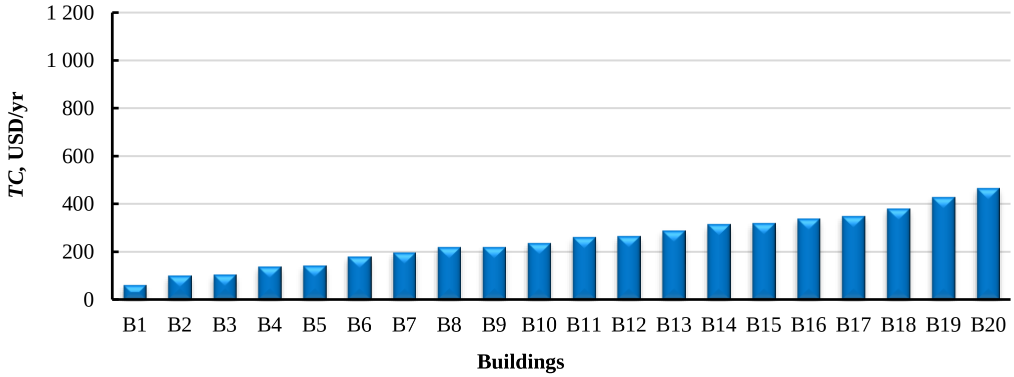
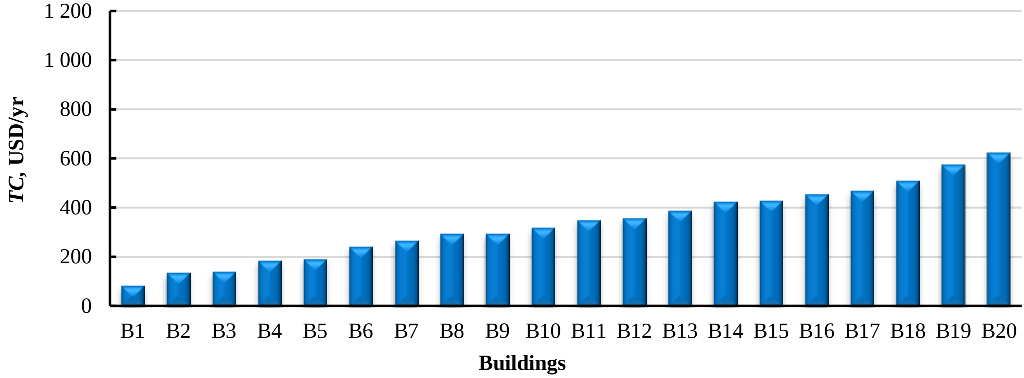


Fig. 7. The total cost of the community under 1.0ZEC design considering PV reliability.



(a)



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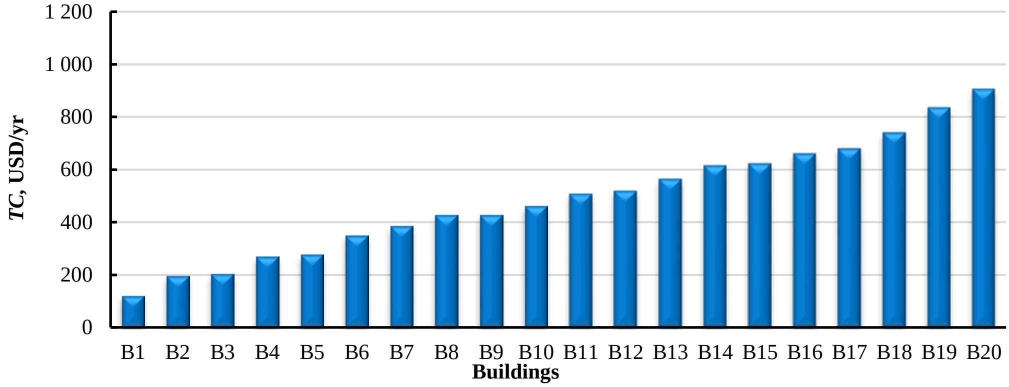

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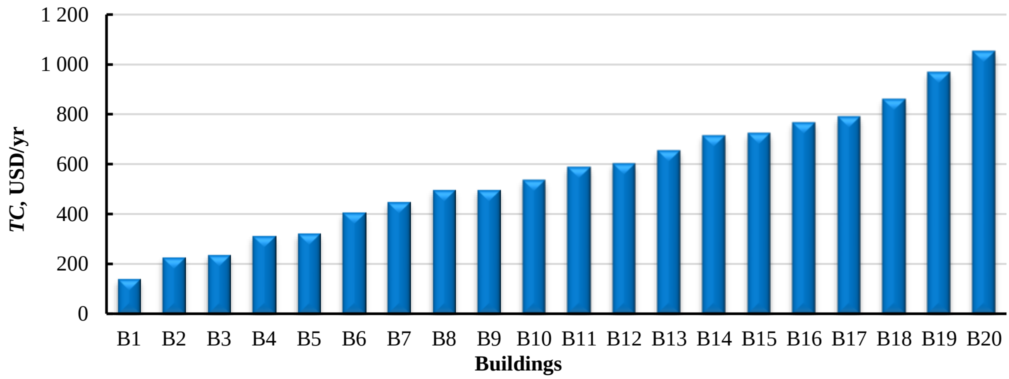


(d)

Fig. 8. The cost allocated for each building in (a) 1st year, (b) 10th year, (c) 20th year and (d) 25th year considering PV reliability.

TABLE 3. THE COST ALLOCATED FOR EACH BUILDING UNDER 1.0ZEC DESIGN (UNIT: USD/YR)

20 Buildings	**Load, kWh/yr**	**1st**	**5th**	**9th**	**13th**	**17th**	**21st**	**25th**	**Average**
B1	1 476	61	68	79	93	108	123	139	95
B2	2 403	100	110	128	151	175	201	226	155
B3	2 503	104	115	134	157	183	209	235	161
B4	3 319	138	153	177	208	242	277	312	214
B5	3 412	142	157	182	214	249	285	321	220
B6	4 312	179	198	231	271	315	360	406	278
B7	4 761	198	219	255	299	348	398	448	307
B8	5 275	219	242	282	331	385	441	496	340
B9	5 278	219	243	282	332	385	441	496	340
B10	5 704	237	262	305	358	416	477	537	368
B11	6 261	260	288	335	393	457	523	589	404
B12	6 404	266	294	343	402	467	535	602	413
B13	6 960	289	320	372	437	508	582	655	449
B14	7 595	315	349	406	477	554	635	714	490
B15	7 692	319	354	411	483	561	643	724	496
B16	8 157	339	375	436	512	595	682	767	526
B17	8 406	349	386	450	528	614	703	791	542
B18	9 154	380	421	490	575	668	765	861	590
B19	10 305	428	474	551	647	752	862	969	664
B20	11 191	465	514	599	703	817	936	1 053	722
Community	120 568	5 005	5 542	6 448	7 574	8 800	10 080	11 341	7 774

4.4. Economic Cost under 1.2ZEC Design

Since the reliability of PV system decreases with time, a selection of ZEC level is expected to be higher than 1.0ZEC for a community. Therefore, the economic cost under 1.2ZEC design is further investigated and compared with the case under 1.0ZEC design. As shown in Fig. 9, the total cost of the community is first seen to decrease and then increase as time passes. For instance, the total cost is observed to be 5 243 USD/yr in the first year, which increases to 5 462 USD/yr in the 10th year, 8 039 USD/yr in the 20th year and 9 607 USD/yr in the 25th year. The average annual cost is supposed to be 6 548 USD/yr, which is reduced by 15.8 % compared with that under 1.0ZEC design (7 774 USD/yr).

Similarly, the total cost allocated for each building is also increased with time, as shown in Fig. 10 and Table 4. For instance, the cost of 1st Building (B1) is 64 USD/yr in the 1st year and increases to 118 USD/yr in the 25th year, and the average annual cost is identified to reduce from 95 USD/yr under 1.0ZEC design to 80 USD/yr under 1.2ZEC design. By contrast, the cost of 20th Building (B20) is 487 USD/yr in the 1st year and increases to 892 USD/yr in the 25th year, and the average annual cost is identified to reduce from 722 USD/yr under 1.0ZEC design to 608 USD/yr under 1.2ZEC design. In general, the total cost of each building, as well as the community, is less than that under 1.0ZEC design.

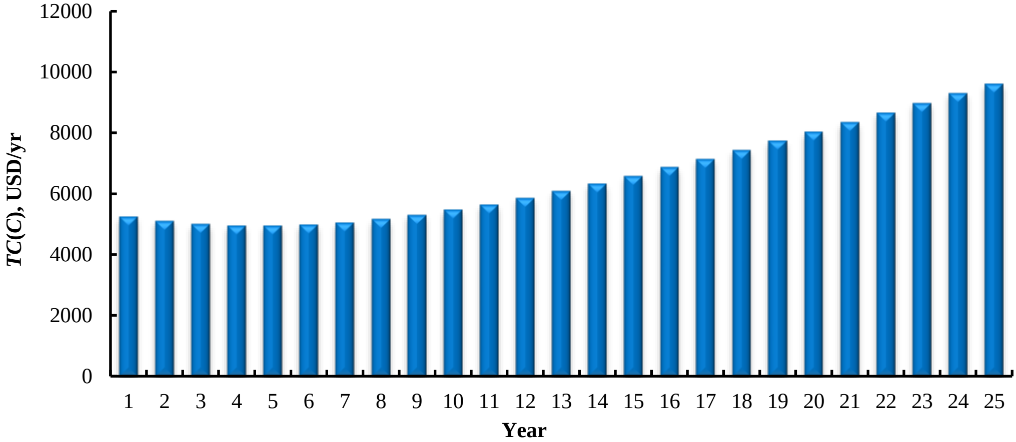
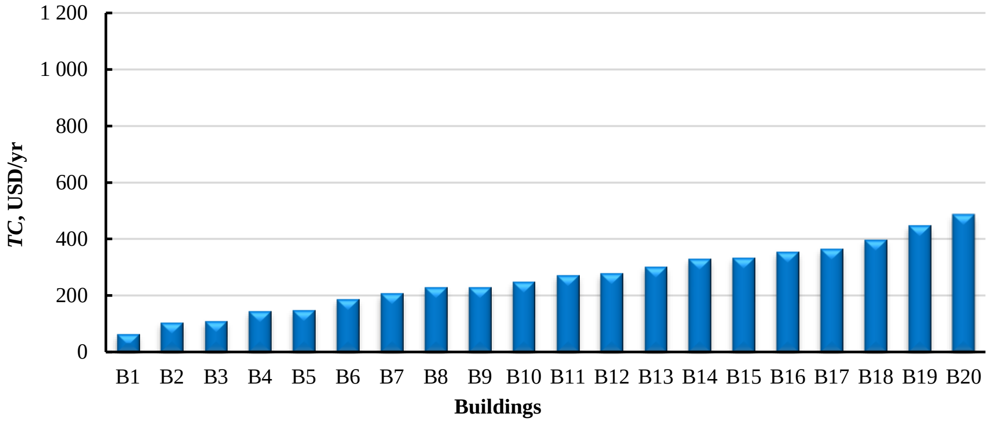


Fig. 9. The total cost of the community under 1.2ZEC design considering PV reliability.



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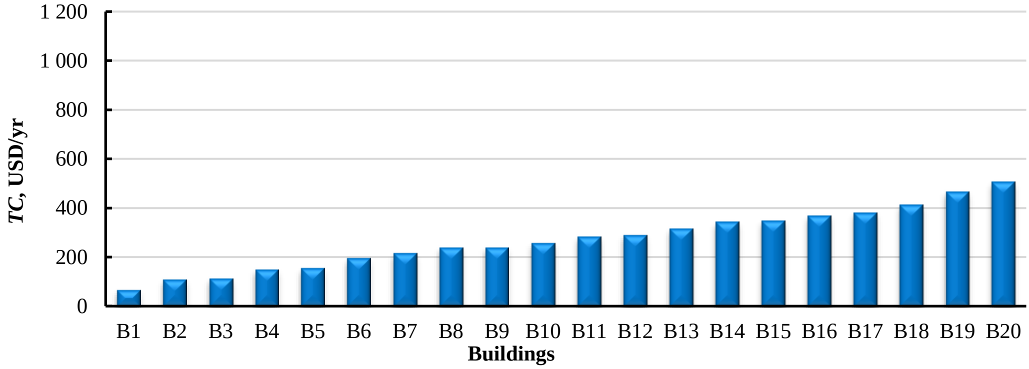

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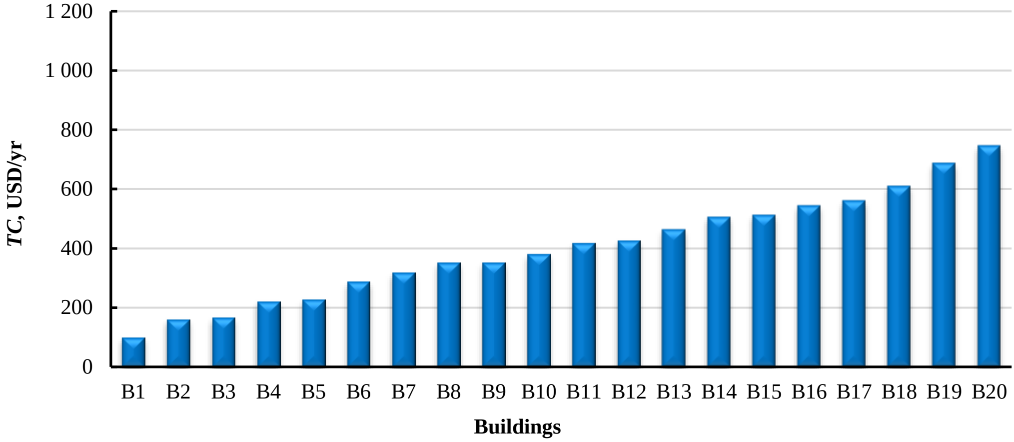

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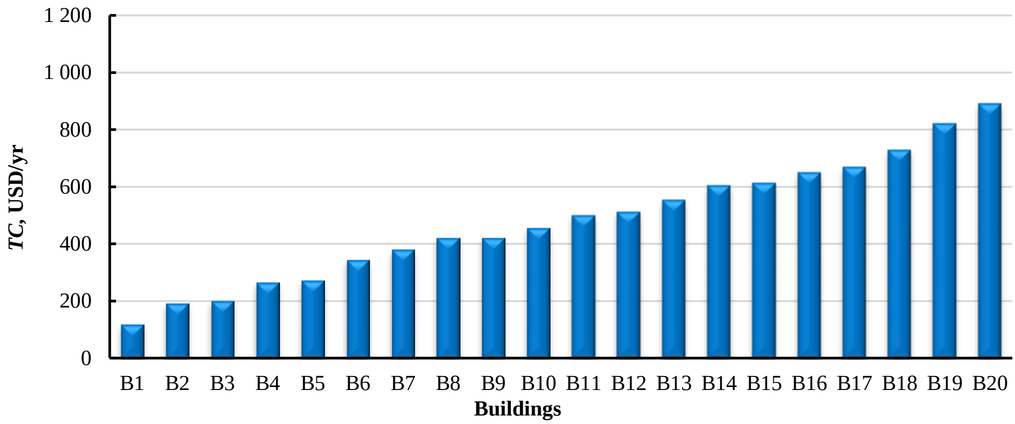

(d)

Fig. 10. The cost allocated for each building in (a) 1st year, (b) 10th year, (c) 20th year and (d) 25th year considering PV reliability.

TABLE 4. THE COST ALLOCATED FOR EACH BUILDING UNDER 1.2ZEC DESIGN (UNIT: USD/YR)

20 Buildings	**Load, kWh/yr**	**1st**	**5th**	**9th**	**13th**	**17th**	**21st**	**25th**	**Average**
B1	1 476	64	60	65	75	87	102	118	80
B2	2 403	104	98	106	121	142	166	191	130
B3	2 503	109	102	110	126	148	173	199	136
B4	3 319	144	136	146	168	196	230	264	180
B5	3 412	148	140	150	172	202	236	272	185
B6	4 312	187	177	189	218	255	298	344	234
B7	4 761	207	195	209	240	282	329	379	259
B8	5 275	229	216	232	266	312	365	420	287
B9	5 278	229	216	232	266	312	365	421	287
B10	5 704	248	234	251	288	338	395	455	310
B11	6 261	272	256	275	316	371	433	499	340
B12	6 404	278	262	281	323	379	443	510	348
B13	6 960	303	285	306	351	412	482	555	378
B14	7 595	330	311	334	383	449	526	605	412
B15	7 692	334	315	338	388	455	532	613	418
B16	8 157	355	334	358	412	483	564	650	443
B17	8 406	366	344	369	424	497	582	670	457
B18	9 154	398	375	402	462	542	633	729	497
B19	10 305	448	422	453	520	610	713	821	560
B20	11 191	487	458	491	565	662	774	892	608
Community	120 568	5 243	4 938	5 295	6 087	7 135	8 343	9 607	6 548

5. CONCLUSION

This study investigates the economic performance of a net-zero energy community (ZEC) under the proposed reward-penalty mechanism (RPM) by considering PV system reliability. A case study is conducted based on a community consisting of 20 family houses in Ireland. The proposed RPM can bring a great profit for the community under a selection of a higher zero energy level, while a heavy fine will be required for the community with a selection of a lower zero energy level.

The aging effect of PV system is observed to have a significant negative impact on total cost for both the community and its buildings. In terms of 1.0ZEC design, the total cost of the community is 5 005 USD/yr in the first year and increases to 11 341 USD/yr in the 25th year, while the average annual cost is supposed to be 7 774 USD/yr. In terms of 1.2ZEC design, the total cost of the community is 5 243 USD/yr in the first year and increases to 9 607 USD/yr in the 25th year, while the average annual cost is supposed to be 6 548 USD/yr. Thus, further investigation will be conducted on the development of enhanced RPM by considering system reliability.

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