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Evolutionary Game Analysis of Energy-Saving Renovations of Existing Rural Residential Buildings from the Perspective of Stakeholders

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Abstract: To promote the orderly development of energy-saving renovations of existing rural residential buildings, it is necessary to coordinate the interests of various stakeholders. This study selects three key stakeholders—the government, energy-saving service enterprises and rural residents—as the research subjects and analyzes their interests and rights. In the meantime, a tripartite evolutionary game model is constructed to analyze the evolutionary rules and evolutionary stable strategies of tripartite behaviors, on the basis of which the influencing factors are analyzed. The research results show that: (1) as the supervisor and advocate of energy-saving renovations in existing rural residential buildings, the government, by adopting subsidies and fines, effectively fosters enthusiasm about energy-saving service enterprises among rural residents, encouraging them to participate in energy-saving renovations of existing rural residential buildings; (2) when the income of energy-saving renovations exceeds their cost, changes in the initial willingness ratio of the stakeholders, the government subsidies and fines only affect the evolution of the system so that it reaches a balanced and stable state, without changing the three parties' behavioral strategy choices in the game; (3) when the income from energy-saving renovations is lower than the cost, the behavioral strategies of the three parties in the game are all uncooperative; (4) key factors affecting tripartite cooperation in the game are as follows: government subsidies and fines, the overall interests of society, government supervision costs, loss of corporate image, standardization of the skills and services provided by enterprises, and willingness of rural residents to participate in the transformation.

Keywords: evolutionary game analysis; energy-saving renovation; the existing rural residential buildings; stakeholders' perspective

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1. Introduction

1.1. The Energy Crisis Is Becoming Severe in China

With the rapid development of the social economy and the acceleration of urbanization, climate change, the energy crisis and biodiversity loss—caused by resource depletion and noticeable environmental pollution problems—are seriously threatening the sustainable development of the social economy and have become the biggest challenge for the progress of human society. China's economy has long maintained a good momentum of high-speed growth, which requires the support of sufficient energy resources. As a country with relatively scarce oil and gas resources, China requires a large amount of energy, such as coal and oil, to ensure its normal functioning and future development. Beyond that, it faces the requirement for an unyielding supply of energy due to the demand caused by extensive development, and the contradiction between economic development and resource shortages. According to the statistics released by the International Energy Agency (IEA), the total energy consumption of oil equivalent worldwide in 2018 was 9,937,702 kilotons, while the total energy consumption of oil equivalent in China was as high as 2,057,666 kilotons, accounting for 20.71% of the world's total, far higher than the 16.04% used by the United

States, thus making China the largest energy consumer in the world [1]. This low energy efficiency not only wastes energy, but also causes serious environmental pollution problems. According to the data from the BP World Energy Statistics Yearbook 2021, China's total carbon dioxide emissions in 2020 totaled 9.899 billion tons, accounting for 30.7% of the world's total emissions, compared with 20.9% in 2005 [2]. Therefore, considering the need for energy conservation and pollution control, it is urgent to "decouple" China's economic growth from energy consumption and carbon dioxide emissions.

1.2. The Construction Industry Is the Focus of Energy Conservation and Emission Reductions

Energy consumption and greenhouse gas emissions are often closely related to industrial production and development, to which the construction industry is a great contributor [3]. As one of the main driving forces to promote economic development, the construction industry plays a key role in economic and social development, but is one of major factors affecting the sharp increase in energy consumption and carbon emissions each year. In 2018, the total energy consumption of the global construction industry was as high as 2,109,205 kilotons of oil equivalent, and produced 2033 $MtCO_2$ [1]. In Britain, the total energy consumed by buildings accounted for about 40% of the total consumption and the carbon emissions caused by this account for 50% of the total emissions [4]. In the European Union, buildings consume about 50% of the total energy and produce about 50% of the carbon emissions during their life cycle [5,6]. In Malaysia, the construction industry consumed about 7750 GWh of energy and released about 5301 kilotons of carbon dioxide in 2008 [7,8]. In Canada, the total energy consumption of residential buildings and commercial buildings accounts for 30% of the national total, forming about 29% of carbon emissions [9]. For China, in terms of energy consumption, by 2018, the energy consumption of the national construction industry reached 2,109,205 kilotons of oil equivalent and produced 391$MtCO_2$ [10]. Moreover, the building construction sectors in countries all over the world, when combined, are responsible for over one-third of the global final energy consumption, and the carbon emissions share of the building sector will reach 50% by 2050, as estimated based on the current energy usage and emission intensity [11–13]. Buildings will, therefore, add substantial pressure to the primary energy supply if further policy actions are not taken at a global level to improve their efficiency [14,15].

1.3. Energy-Saving Renovation of Existing Rural Residential Buildings Is Key to the Sustainable Development of the Construction Industry in China

The urbanization rate in China grew from 42.99 percent in 2005 to 63.89 percent in 2020, and is expected to exceed 80 percent by 2050. With the increase in the urbanization rate, the rural population will gradually decrease, but the energy consumption of rural residential buildings still accounts for a very high proportion of the total energy consumption of buildings in China. In 2005, the energy use by rural residential buildings accounted for around 65% of total building energy use in China (including traditional biomass). Even with rapid urbanization, this is still expected to take up a quarter of China's building energy use in 2050 [16–19]. Due to serious lagging in the technical standards for rural residential building planning, design and construction, there are a great deal of problems in the construction of rural residential buildings, such as the over-simplified technical standards and the delay in the adoption of energy-saving evaluations. Compared with the 50% standard for building energy-efficiency in urban residential buildings, few strict energy-saving measures have been taken in the construction of most rural residential buildings in China. The low heating and cooling efficiency of residential buildings, and their poor thermal insulation performance, are also notable. At present, there are almost no accurate statistical data on the energy consumption of rural residential buildings in China. The evaluation of the energy consumption of rural residential buildings in China remains weak in all aspects. For instance, there is no effective evaluation system for the energy-saving performance and grading of rural residential buildings. In addition, the construction of rural residential buildings mainly utilizes the self-built and decentralized modes. Hence, the commercialization rate of residential buildings is extremely low, and the engineering quality, functional quality and environmental quality of residential buildings are poor. In terms of residential construction technology, traditional techniques and methods are frequently adopted, such as manual masonry, a brick–concrete structure, few prefabricated components, low modular and assembly components, low labor productivity and low application levels for new technology. Since energy saving techniques have not been integrated into the design, planning and initial construction [20], these buildings consume a large amount of energy and emit large amounts of greenhouse gases. Therefore, it is imperative to carry out energy-saving renovations of existing rural residential buildings. This is an important part of the new rural construction and urbanization process, and is widely accepted as the best solution for aging residential buildings. Moreover, this could have various benefits, such as saving energy, decreasing environmental pollution, and promoting inhabitants' health [21,22].

2. Literature Review and Methods

2.1. Literature Review

Compared with new buildings, energy-saving renovations of existing buildings have greater potential for reductions in carbon emissions. The existing building area exceeds 60 billion square meters in China, and more than 60 percent of buildings are without energy conservation due to low construction standards and delayed maintenance. The large-scale demolition and reconstruction of existing buildings will not only cause a great waste of resources, but also lead to environmental degradation. A previous study has shown that buildings are responsible for 40% of the primary energy consumption and lead to over 30% of global greenhouse gas emissions [23]. While new energy efficiency regulations are applied to new buildings, the existing building stock remains energetically inefficient. Therefore, energy-saving renovations to the existing buildings are considered the most scientific and effective solution to reduce total energy consumption and global greenhouse gas emissions. However, the implementation of energy-saving renovations to existing buildings in China is still relatively slow. There are so many stakeholders involved in the process of energy-saving renovations to existing buildings. As the main body regulating energy-saving renovations of existing buildings, the participation intentions of the government, energy saving service enterprises and village residents directly affect the promotion of energy-saving renovations of existing buildings. Only when the government, energy saving service enterprises and village residents have the subjective willingness to participate can energy-saving renovations of the existing buildings be effectively promoted. However, previous studies on energy-saving renovations to existing buildings mainly focused on evaluation methods [20,24–27], retrofitting influence factors [28,29], cost–benefit analysis of retrofitting [30–34], evaluations of the effectiveness of retrofitting [35,36], barriers to retrofitting [37], and technical or scheme retrofittings [38–42]. In addition, some scholars are committed to reducing existing building energy consumption through energy modernization of buildings. Richarz et al. emphasized that modernizing existing non-residential buildings can significantly contribute to declared emission reduction targets. And they presented a mixed-integer linear program that schedules measures for a building energy system including envelope and supply system [43]. Dorota presented a case study for theoretical and real effect of the school's thermal modernization and found that the real energy use reduction after the thermal modernization effect was 33% [44]. Moreover, research on buildings from other regions of Poland has shown similar possibilities of reducing energy demands by up to 64% [45–47]. Staniūnas et al. made an ecological–economical assessment of multi-dwelling houses modernization and revealed that a complete replacement of windows would help decline total emissions approximately by 30% and thus greatly fulfilled initial expectations [48]. Pozo et al. analyzed the tax incentives to modernize the energy efficiency of the housing in Spain and the analysis showed that tax benefits are insufficient to promote energy efficiency, especially in those of old construction [49]. Belany et al. dealt with the possibilities the lighting retrofit and the life cycle cost analysis economic analysis in the process of increasing the energy efficiency of buildings [50]. Furthermore, most prior studies focused on urban existing buildings, commercial buildings [27,31], historical buildings [32], educational buildings [39], and office buildings [41]. Only some of the literature discusses energy-saving renovations to existing rural residential buildings, such as the work of Hu et al. [51], Tahsidoost and Zomorodian [52], Liu et al. [53], Alev et al. [54], and Rocchi et al. [55]. However, they still focused on technical or scheme retrofitting, a cost–benefit analysis of retrofitting and evaluation methods, while ignoring the influence of stakeholders' willingness to participate in energy-saving renovations to existing rural residential buildings. In particular, energy-saving renovations of existing rural residential buildings do not have the complete policies and regulations that are implemented for urban buildings in China. Moreover, the intention of each stakeholder to participate in energy conservation transformation may only be to maximize their own interests, but it is worth investigating the best way in which to make decisions that can increase the intention of participation.

2.2. Evolutionary Game Theory

Evolutionary game theory is different from the assumption of the completely rational man in traditional game theory, which holds that man is a bounded rationality. The research object of game theory is multiple market participants, and it discusses the dynamic evolution of system groups. In evolutionary game theory, the participating groups have an active learning ability, can constantly choose and try to make mistakes through mutual imitation and learning, and can constantly change the basic behavior strategies of the game players, so as to maximize their own benefits. Smith proposed that the basis of constructing the evolutionary game model was mutation and choice [56]. Mutation refers to the solution to diversity stability in evolutionary games. Choice refers to the process of making choices by learning or imitating in groups and constantly optimizing one's own choices, that is, the process of generating higher payments [57]. According to the mutation and choice theory in evolutionary game theory, replication dynamic equation and evolutionary stability strategy constitute the core of the evolutionary game model. Copying the dynamic equation is actually a dynamic strategy adjustment mechanism. It is assumed that the game players (insiders) are all bounded, rational people, and the individuals in the group with a lower income than the average will change their strategies and learn from the surrounding group members whose income is higher than their own. Therefore, the probability of each strategy choice of the game players in the group will change accordingly. Evolutionary Stable Strategy (ESS), as another core concept in evolutionary game theory, reflects the stable state of the equilibrium solution of the system. Evolutionary stability strategy thinks that the optimal equilibrium of people's game is a function to be revised, so evolutionary stability strategy cannot be achieved at the beginning. It can only be achieved through trial and error and learning, and through the repetition of games by players to modify and improve individual strategies. Among the current research, Fan et al. developed an evolutionary game model to analyze the operation mechanism of local governments' different expenditure preferences regarding the production behavior of industrial polluting enterprises [58]; Liu et al. applied an evolutionary game model to analyze the necessity and effect of orderliness–synergy in the sustainable development of China's power generation industry during the transition period [59]; Su investigated the evolutionary decision-making process and stable strategies of three stakeholders involved in the construction waste recycling industry based on the evolutionary game model [60]. However, no scholar has thus far employed the evolutionary game model to analyze the behavioral strategies of stakeholders involved in energy-saving renovations of existing rural residential buildings. In this work, we construct a tripartite evolutionary game model to analyze the evolutionary rules and stable strategies of tripartite behaviors regarding energy-saving renovations of existing rural residential buildings, and analyze the influencing factors accordingly.

3. Dilemma Analysis of Energy-Saving Renovations of Existing Rural Residential Buildings

3.1. Positive Externality of Energy-Saving Renovation Market

Positive externality means that the marginal private cost is greater than the marginal social cost, that is, the marginal private benefit is less than the marginal social benefits, such as energy conservation, emission reductions, and low-carbon construction. At present, China has made some achievements in improving energy efficiency, but there is still a long way to go in terms of energy-saving renovations to existing buildings due to strong positive externalities and proneness to "market failure". In the energy-saving renovation of existing rural residential buildings, participants often only consider the benefits and costs related to their own interests, ignoring all other unrelated factors. For example, rural residents, as users of existing buildings, can not only improve their living standards, reduce building energy consumption, save use and maintenance costs, and benefit their physical and mental health, but also reduce the total energy consumption of the whole society, reduce environmental pollution, and improve the surrounding living environment. However, in the market mechanism, rural residents predominantly care about the maximization of their own interests, instead of the marginal benefits brought to society, since this "extra income" will not bring them extra rewards. In addition, the process of energy-saving renovations will inconvenience residents' daily life and will increase their economic burden. Rural residents' attention is drawn to the renovation costs, ignoring the "positive externalities" brought about by energy-saving renovations of existing rural residential buildings to the wider society. As a result, many of them choose to forego energy-saving renovations.

3.2. Market Information Asymmetry

Information asymmetry is a common phenomenon in many economic fields at present. Many participants are involved in energy-saving renovations of existing rural residential buildings, with different interests and unequal amounts of renovation information. For example, when choosing energy-saving renovation technology, rural residents often do not have the ability to distinguish between good and bad, and cannot obtain reliable quality information about whether an energy-saving technology is advanced, economical or feasible. On the other hand, energy-saving service enterprises hold a great deal of relevant information on energy-saving technology, meaning that there is serious information asymmetry regarding the knowledge of energy-saving transformation technology.

In addition, information asymmetry also exists between the government and rural residents, and between the government and energy-saving service enterprises. In this case, the information-superior party will make a self-interested market choice, taking advantage of its information superiority, while the information-inferior party will be unable to make a correct judgment on the energy-saving effect of the purchased products due to the lack of information. Therefore, the information-inferior party will assume that all construction products in the construction market are of low value, and tend to choose construction products with lower prices. To maximize their own profits, the information-superior party will cater to the purchasing behavior of the information-inferior party, and produce building materials of poor quality at a low price, forcing high-quality, energy-saving building materials to withdraw from the market because their manufacturers cannot find suitable trading partners. Ultimately, the result of this is that most of the products left on the market are low-value products, which exemplifies the phenomenon of "inferior products driving out good products" [61,62].

3.3. The Existing Rural Residential Buildings Have a Large Stock That Is Difficult to Transform

Although the majority of building regulations and standards in China are targeting new and future buildings, existing buildings still constitute the largest share of the buildings stock [38]. Energy-saving construction in existing rural residential buildings is the key to building energy-saving work, and has always been a neglected but urgent problem that remains to be solved. In recent years, Chinese people's living standards have been greatly improved, accompanied by the rapid increase in building energy consumption. As one of the most important aspects of the total energy consumption in China, more attention should be paid to rural residential building energy consumption [63]. According to the Statistical Bulletin of Urban and Rural Construction in 2016, by 2016, the rural residential building area in China was about 32.32 billion square meters, accounting for 84.4% of the total area of villages and towns in China [64]. With the increase in per capita income in rural areas, the living standards of farmers have gradually improved, and the construction of rural residential buildings has reached an unprecedentedly high level. In 2019, the per capita housing construction area of rural residential buildings in China reached 48.9 m^2/person, 9.1 m^2 more than that of urban residents. The total number of houses has shown a continuously growing trend. As with the improvement in living quality, rural residents have also changed their energy consumption. In rural areas, people used to mainly rely on traditional biomass energy resources, such as firewood and straw [63,65,66], but these are gradually being replaced by commercial energy resources including coal, electricity, liquefied petroleum gas (LPG) and refined oil products, due to the low thermal efficiency and combustion-generated pollution of these biomass resources [63,66,67]. Thus, with the increase in the total number of rural residential buildings, the buildings' energy consumption levels are bound to rise. As a result, this building category is one of the first places in which action should be taken to reduce energy consumption and pollutant emissions [68,69].

4. Subject Game Relationship

The energy-saving renovation of the existing rural residential buildings is a complex systematic project, which involves both collective and individual interests, national interests, enterprise interests and individual interests. Firstly, as the policy maker and supervisor of energy-saving renovations of existing rural residential buildings, the government represents the national interest, and has the highest degree of participation. Secondly, the energy-saving service enterprises, as participants in contracting the energy-saving renovations of existing rural residential buildings, possess the energy-saving renovation technology for the existing rural residential buildings, and are the main representatives of the interests of all enterprises. Thirdly, the rural residents, as the owners and users of the existing rural residential buildings, can benefit from the energy-saving renovations to the existing rural residential buildings, but, at the same time, face an increased cost of living, which affects their personal interests. All three parties are the main participants in the energy-saving renovations of existing rural residential buildings, and this study also focuses on their evolutionary game relationships. As for other auxiliary participants, such as banks, financial institutions, the environmentalists, etc., they have not directly participated in energy-saving renovation of existing rural residential buildings. Their suggestions or financial support can promote energy-saving renovation of existing rural residential buildings, but compared with the government and rural residents as funders and energy-saving service enterprises as designers and constructors, their impact is less. For example, suppose the environmentalists propose that energy-saving renovation of existing rural residential buildings is beneficial to protecting the ecological environment. However, if the government and rural residents do not realize or support it, their proposal will not be effectively solved. On the contrary, if the government and the rural residents are also aware of the importance of energy-saving renovation of existing rural residential buildings, and actively respond to the environmentalists' proposals, but the environmentalists are not involved in the related issues such as who will supervise, who will renovate, and who will bear the cost during the promotion process. These auxiliary participants will be a new field for our research team to further study in the future, but this study will focuses on the main participants.

4.1. The Government

In the process of energy-saving renovations of existing rural residential buildings, the government, as the policy maker, shoulders the task of supervision, management and publicity, and regulates the behaviors of other participants by implementing economic incentive policies and administrative supervision, which mainly focuses on the social and environmental benefits brought by energy-saving renovations of existing rural residential buildings. Therefore, as a special participant, the government will pursue the long-term social and environmental benefits of energy-saving renovation, as well as the improvement in people's living standards and social stability.

4.2. Energy-Saving Service Enterprises

At present, the energy-saving renovation market for the existing residential buildings in China takes contract energy management as its main operation mode. The energy-saving service enterprises provide a package of professional energy-saving technical services, including energy-saving condition diagnosis, energy-saving project design, financing, renovation (construction, equipment installation and commissioning) and operation management, etc., for the energy-saving renovation of existing residential buildings. These enterprises are the main suppliers of energy-saving service products and they act as an internal driving force for the development of the energy-saving renovation market of existing residential buildings in China. The energy-saving service enterprises, as practitioners of the energy-saving renovation of existing rural residential buildings, have advanced energy-saving renovation technologies and resources. By signing renovation contracts with the government or rural residents and adhering to the government's incentive policies, they can obtain corresponding benefits according to contract stipulations or by reducing energy-saving renovation costs. In addition, energy-saving service enterprises have relatively complete information on the energy-saving renovation market of existing rural residential buildings, which may lead to more speculation in the process of energy-saving renovation, thus undermining the benign cooperation among energy-saving service enterprises, the government and rural residents. Therefore, the main purpose of energy-saving service enterprises participating in energy-saving renovations of existing rural residential buildings is to standardize their own behaviors and maximize their own interests while weighing the advantages and disadvantages.

4.3. Rural Residents

As users and direct beneficiaries of energy-saving renovations of existing rural residential buildings, residents' willingness to renovate and awareness of energy conservation and environmental protection will affect the development of the energy-saving renovation market and the improvements in the social environment. However, on August 1, 2008, the State Council of the People's Republic of China issued Regulations on Energy Conservation of Civil Buildings, which clearly stipulated that the cost of energy conservation renovations to existing buildings shall be borne jointly by the government and the building owner, and suggested that residents pay from 15 to 20 percent of the renovation cost. Therefore, as individuals, rural residents need to bear part of the cost of energy-saving renovation and accept the impact of the energy-saving renovation process on their normal work and life. Accordingly, residents in existing rural residential buildings are more concerned with their own financial status and the utility brought about by energy-saving transformations than with the maximization of social utility.

5. Game Model Construction

5.1. Basic Assumptions of the Model

Assumption 1. *The government, energy-saving service enterprises and rural residents are all bounded and rational.*

Assumption 2. *All participants have two different selection strategies: government behavior strategy set S_1 = [regulatory incentives, laissez-faire]; service enterprise behavior strategy set S_2 = [providing energy-saving services, not providing energy-saving services]; rural residents' behavior strategy set S_3 = [fulfill energy-saving transform ation, refuse energy-saving transformation].*

Assumption 3. *Based on the assumption of bounded rationality, the probability that the government will supervise and encourage the energy-saving renovation of existing rural residential buildings is x, and the probability of laissez-faire is $1 - x$; the probability of the energy-saving service enterprises choosing to provide energy-saving services is y, and the probability of them choosing not to provide energy-saving services is $1 - y$; the probability of residents performing energy-saving renovations is z, and the probability of them refusing energy-saving renovations is $1 - z$, in which x, y and z ∈ [0,1].*

On the basis of on-the-spot investigation and the literature review, comprehensive analyses of the parameter settings of the cost, benefit and loss variables that affect the government, energy-saving service enterprises and rural residents' decisions are shown in Table 1.

Table 1. Symbols and meanings of parameters.

Participants	Parameters	Meanings
Government	S_1	Subsidies offered by the government to encourage the energy-saving service enterprises that provide standardized energy-saving services.
	S_2	Subsidies offered by the government to village and town residents who voluntarily perform energy-saving transformation
	F_1	Fines imposed by the government on the energy-saving service enterprises that do not provide standardized energy-saving services, where $F_1 > S_1$
	F_2	Fines imposed by the government on the residents of the existing rural residential buildings who refuse to perform energy-saving renovations, in which $F_2 > S_2$
	R_1	Under the supervision and encouragement of the government, the social and environmental benefits of the cooperative strategies adopted by the energy-saving service enterprises and the rural residents.
	R_2	Under the government's laissez-faire, the social and environmental benefits produced by the cooperative strategies from the energy-saving service enterprises and the rural residents.
	L_1	Loss of social and environmental benefits caused by speculative behavior or failure to provide energy-saving services by the energy-saving service enterprises.
	L_2	Loss of social and environmental benefits caused by residents' refusal to carry out energy-saving renovations in the existing rural residential buildings.
	C_1	The supervision costs paid by the government when implementing supervision incentives.
Energy saving service enterprise	E_1	The income of the energy-saving service enterprises when they choose to provide standardized energy-saving services and the rural residents perform energy-saving transformations.
	C_2	The costs paid by the energy-saving service enterprises when they choose to provide energy-saving services in a standardized way.
	C_3	Credit loss caused by the energy-saving service enterprises not providing energy-saving services or providing non-standard energy-saving services.
	C_4	Loss caused by residents' refusal to carry out energy-saving renovations in villages.
Rural resident	E_2	The rural residents choose to perform energy-saving transformation and the energy-saving service enterprises provide standardized energy-saving services.
	C_5	The costs paid by residents in the existing rural residential buildings when performing energy-saving renovations.
	C_6	Loss caused by the energy-saving service enterprises refusing to provide energy-saving services or providing non-standard energy-saving services.

5.2. Construction of Evolutionary Game Revenue Matrix

According to the above-mentioned capital construction conditions and profit and loss parameters, a tripartite game model of the government, energy-saving service enterprises and rural residents is constructed, and an evolutionary game income matrix is obtained, as shown in Table 2.

Table 2. Evolutionary game income matrix.

Participants				Rural Resident	
				Fulfill Energy-Saving Transformation (z)	**Refuse Energy-Saving Transformation ($1-z$)**
Government	Regulatory incentives (x)	Energy saving service enterprise	Providing energy-saving services (y)	$R_1 - S_1 - S_2 - C_1$, $E_1 + S_1 - C_2$, $E_2 + S_2 - C_5$	$F_2 - S_1 - L_2 - C_1$, $S_1 - C_4$, $-F_2$
			Not providing energy-saving services ($1-y$)	$F_1 - S_2 - L_1 - C_1$, $-F_1 - C_3$, $S_2 - C_6$	$F_1 + F_2 - L_1 - L_2 - C_1$, $-F_1$, $-F_2$
	Laissez-faire ($1-x$)	Energy saving service enterprise	Providing energy-saving services (y)	R_2, $E_1 - C_2$, $E_2 - C_5$	$-L_2$, $-C_4$, 0
			Not providing energy-saving services ($1-y$)	$-L_1$, $-C_3$, $-C_6$	$-L_1 - L_2$, 0, 0

6. Equilibrium Analysis of Tripartite Evolutionary Game

6.1. Expectation Function Construction

(1) The expected return of the government's choice of regulatory incentives:

$$\begin{aligned} P_{11} &= yz(R_1 - S_1 - S_2 - C_1) + y(1-z)(F_2 - S_1 - L_2 - C_1) + (1-y)z(F_1 - S_2 - L_1 - C_1) + \\ &(1-y)(1-z)(F_1 + F_2 - L_1 - L_2 - C_1) \\ &= yzR_1 + y(L_1 - S_1 - F_1) + z(L_2 - S_2 - F_2) + (F_1 + F_2 - L_1 - L_2 - C_1) \end{aligned} \tag{1}$$

The expected return of the government's laissez-faire:

$$P_{12} = yzR_2 = y(1-z)(-L_2) + (1-y)z(-L_1) + (1-y)(1-z)(-L_1 - L_2) = yzR_2 + yL_1 + zL_2 - L_1 - L_2 \tag{2}$$

Average expected revenue of government:

$$\begin{aligned} P_1 = xP_{11} + (1-x)P_{12} &= xyzR_1 - xyzR_2 - xyS_1 - xyF_1 - xzS_2 - xzF_2 + xF_1 + xF_2 \\ &-xC_1 + yzR_2 + zL_2 + yL_1 - L_1 - L_2 \end{aligned} \tag{3}$$

Replication dynamic equation of government's choice of regulatory incentives:

$$F(x) = \frac{dx}{dt} = x(P_{11} - P_1) = x(1-x)[y(zR_1 - zR_2 - S_1 - F_1) - z(S_2 + F_2) + F_1 + F_2 - C_1] \tag{4}$$

(2) The expected benefits of the energy-saving service enterprises choosing to provide energy-saving services:

$$\begin{aligned} P_{21} &= xz(E_1 + S_1 - C_2) + x(1-z)(S_1 - C_4) + (1-x)z(E_1 - C_2) + (1-x)(1-z)(-C_4) \\ &= xS_1 + zE_1 - zC_2 - C_4 + zC_4 \end{aligned} \tag{5}$$

Expected benefits of the energy-saving service enterprises choosing not to provide energy-saving services:

$$P_{22} = xz(-F_1 - C_3) + x(1-z)(-F_1) + (1-x)z(-C_3) + (1-x)(1-z) \times 0 = -xF_1 - zC_3 \tag{6}$$

Average expected income of the energy-saving service enterprises:

$$P_2 = yP_{21} + (1-y)P_{22} = xyS_1 + yzE_1 + yzC_4 - yzC_2 - yC_4 - xF_1 - zC_3 + xyF_1 + yzC_3 \quad (7)$$

Replication dynamic equation of the energy-saving service enterprises choosing to provide energy-saving services:

$$F(y) = \frac{dy}{dt} = y(P_{21} - P_2) = y(1-y)[z(E_1 + C_3 + C_4 - C_2) + x(S_1 + F_1) - C_4] \quad (8)$$

(3) The expected income of rural residents who choose to perform energy-saving transformations:

$$\begin{aligned} P_{31} &= xy(E_2 + S_2 - C_5) + x(1-y)(S_2 - C_6) + (1-x)y(E_2 - C_5) + (1-x)(1-y)(-C_6) \\ &= xS_2 + yE_2 + yC_6 - yC_5 - C_6 \end{aligned} \quad (9)$$

The expected benefits of rural residents choosing to refuse energy-saving renovations:

$$P_{32} = xy(-F_2) + x(1-y)(-F_2) + (1-x)y \times 0 + (1-x)(1-y) \times 0 = -xF_2 \quad (10)$$

Average expected income of rural residents:

$$P_3 = zP_{31} + (1-z)P_{32} = xz(S_2 + F_2) + zy(E_2 + C_6 - C_5) - xF_2 - zC_6 \quad (11)$$

Replication dynamic equation of rural residents choosing to perform energy-saving transformations:

$$F(z) = \frac{dz}{dt} = z(P_{31} - P_3) = z(1-z)[x(S_2 + F_2) + y(E_2 + C_6 - C_5) - C_6] \quad (12)$$

6.2. Asymptotic Stability Analysis of Evolutionary Game

In the process of energy-saving renovations of existing rural residential buildings, there is serious information asymmetry between the government, energy-saving service enterprises and rural residents in terms of energy-saving renovation information. The three parties in the game will choose the strategies that maximize their own interests in the process of trial and error. When all three parties reach a stable state, all the participants in the game achieve Nash equilibrium through the process of trial and error. According to the stability principle of differential equations, the duplicated dynamic equation of the tripartite subject strategy is simultaneously established. By setting $F(x) = F(y) = F(z) = 0$, we find that there are eight pure strategy equilibrium points in the equation, namely (0,0,0); (1,0,0); (0,1,0); (0,0,1); (1,1,0); (1,0,1); (0,1,1); (1,1,1).

In view of the asymptotic stability of the equilibrium points, this study uses the Lyapunov discriminant method (indirect method) to judge, list the Jacobian matrix (as in Formula (13)), and discuss the stability of the above equilibrium points. Firstly, the Jacobian matrix is calculated as in Formula (14):

$$\begin{bmatrix} \frac{dx/dt}{dx} & \frac{dx/dt}{dy} & \frac{dx/dt}{dz} \\ \frac{dy/dt}{dx} & \frac{dy/dt}{dy} & \frac{dy/dt}{dz} \\ \frac{dz/dt}{dx} & \frac{dz/dt}{dy} & \frac{dz/dt}{dz} \end{bmatrix} \quad (13)$$

$$\begin{bmatrix} \begin{array}{c}(1-2x)[y(zR_1 - zR_2 - S_1 - P_1) \\ -z(S_2 + P_2) + P_1 + P_2 - C_1]\end{array} & x(1-x)(zR_1 - zR_2 - S_1 - P_1) & x(1-x)(yR_1 - yR_2 - S_2 - P_2) \\ y(1-y)(S_1 + P_1) & \begin{array}{c}(1-2y)[z(E_1 + C_3 + C_4 - C_2) \\ +xS_1 + xP_1 - C_4]\end{array} & y(1-y)(E_1 + C_3 + C_4 - C_2) \\ z(1-z)(S_2 + P_2) & z(1-z)(E_3 + C_6 - C_5) & \begin{array}{c}(1-2z)[x(S_2 + P_2) + y(E_3 \\ +C_6 - C_5) - C_6]\end{array} \end{bmatrix} \quad (14)$$

According to Lyapunov's stability theorem, when the characteristic roots of the Jacobian matrix are all negative, the equilibrium point is a stable node. By substituting the equilibrium points into the Jacobian matrix, the eigenvalue corresponding to each equilibrium point can be obtained, as shown in Table 3.

Table 3. Eigenvalues corresponding to pure strategy equilibrium points.

Equilibrium Point	Eigenvalue	Positive and Negative	Stability	Asymptotically Stable Condition
H_1 (0,0,0)	$\lambda_1 = P_1 + P_2 - C_1$	−	Stable point	/
	$\lambda_2 = -C_4$	−		
	$\lambda_3 = -C_6$	−		
H_2 (0,0,1)	$\lambda_1 = P_1 - C_1 - S_2$	−	Unstable point	/
	$\lambda_2 = E_1 + C_3 - C_2$	+		
	$\lambda_3 = C_6$	+		
H_3 (0,1,0)	$\lambda_1 = -S_1 + P_2 - C_1$	−	Unstable point	/
	$\lambda_2 = C_4$	+		
	$\lambda_3 = E_3 - C_5$	+		
H_4 (0,1,1)	$\lambda_1 = R_1 - R_2 - S_1 - S_2 - C_1$	Uncertain	Uncertain point	$R_1 < R_2 + S_1 + S_2 + C_1$
	$\lambda_2 = -E_1 - C_3 + C_2$	−		
	$\lambda_3 = -E_3 + C_5$	−		
H_5 (1,0,0)	$\lambda_1 = -P_1 - P_2 + C_1$	+	Unstable point	/
	$\lambda_2 = S_1 + P_1 - C_4$	+		
	$\lambda_3 = S_2 + P_2 - C_6$	+		
H_6 (1,0,1)	$\lambda_1 = S_2 - P_1 + C_1$	+	Unstable point	/
	$\lambda_2 = E_1 + C_3 - C_2 + S_1 + P_1$	+		
	$\lambda_3 = -S_2 - P_2 + C_6$	−		
H_7 (1,1,0)	$\lambda_1 = S_1 - P_2 + C_1$	+	Unstable point	/
	$\lambda_2 = -S_1 - P_1 + C_4$	−		
	$\lambda_3 = S_2 + P_2 + E_3 - C_5$	+		
H_8 (1,1,1)	$\lambda_1 = -R_1 + R_2 + S_1 + S_2 + C_1$	Uncertain	Uncertain point	$R_1 > R_2 + S_1 + S_2 + C_1$
	$\lambda_2 = -E_1 - C_3 + C_2 - S_1 - P_1$	−		
	$\lambda_3 = -S_2 - P_2 - E_3 + C_5$	−		

It can be seen from Table 3 that there are three situations in which evolutionary stability can be achieved to meet the eigenvalue requirements of the Lyapunov discriminant method (indirect method).

Scenario 1: If the external conditions remain unchanged, only equilibrium point H_1 (0,0,0) can meet the requirements of Liapunov's discriminant method (indirect method) for the eigenvalue, and other equilibrium points cannot form evolutionary stability, that is, the equilibrium point H_1 (0,0,0) (laissez-faire, no energy-saving service, no energy-saving renovations) is an evolutionary stability strategy. The phase diagram is shown in Figure 1.

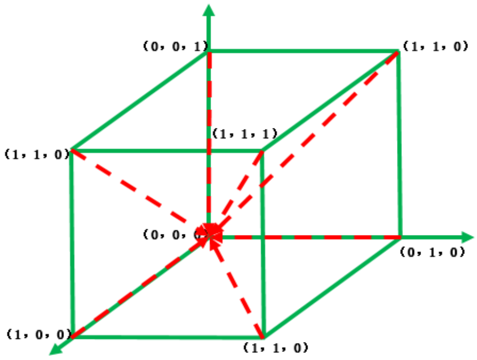


Figure 1. Phase diagram of equalization point H_1 (0,0,0).

Scenario 2: if the external conditions change, i.e., $R_1 < R_2 + S_1 + S_2 + C_1$, then equilibrium points H_1 (0,0,0) and H_4 (0,1,1) can achieve evolutionary stability, that is, H_1 (0,0,0) (laissez-faire, not providing energy-saving services, refusing energy-saving renovation) and H_4 (0,1,1) (laissez-faire, providing energy-saving services, fulfilling energy-saving renovations) are evolutionary stable strategies. The phase diagram is shown in Figure 2.

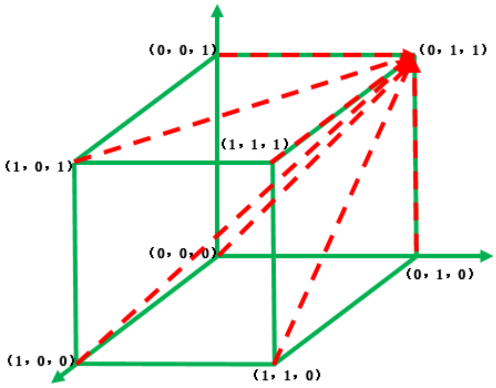


Figure 2. Phase diagram of equilibrium point H_4 (0,1,1) when $R_1 < R_2 + S_1 + S_2 + C_1$.

Scenario 3: if the external conditions change, i.e., $R_1 < R_2 + S_1 + S_2 + C_1$, then equilibrium points H_1 (0,0,0) and H_8 (1,1,1) can achieve evolutionary stability, that is, H_1 (0,0,0) (laissez-faire, not providing energy-saving services, refusing energy-saving renovations) and H_8 (1,1,1) (supervision and encouragement, providing energy-saving services, fulfilling energy-saving renovations) are evolutionary stable strategies. The phase diagram is shown in Figure 3.

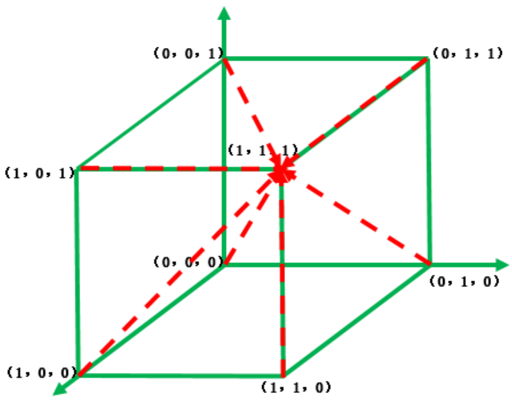


Figure 3. Phase diagram of equalization point H_8 (1,1,1) when $R_1 > R_2 + S_1 + S_2 + C_1$.

However, in the case of a laissez-faire approach by the government, the energy-saving service enterprises choose to provide energy-saving renovation services by themselves, and this provides an ideal state for rural residents to perform energy-saving renovations by themselves, without considering the renovation costs and the impact on their daily lives. According to the evolutionary game hypothesis, the government, energy-saving service enterprises and the rural residents are all bounded and rational. Therefore, under the premise of bounded rationality, all players in the three-party game hope to maximize their interests. Without the support of incentive policies and the guidance of relevant energy-saving renovation policies, low enthusiasm is displayed by energy-saving service enterprises and rural residents in the existing rural residential buildings to actively carry out energy-saving renovations, as is also confirmed in the actual investigation. Therefore, during the energy-saving renovations of existing rural residential buildings, the equilibrium points for realizing the tripartite evolutionary and stable strategy among the government, energy-saving service enterprises and rural residents are mainly H_1 (0,0,0) (laissez-faire, no energy-saving service, no energy-saving renovation] and H_8 (1,1,1) [supervision and encouragement, providing energy-saving service, fulfilling energy-saving renovations). This study also focuses on these two situations.

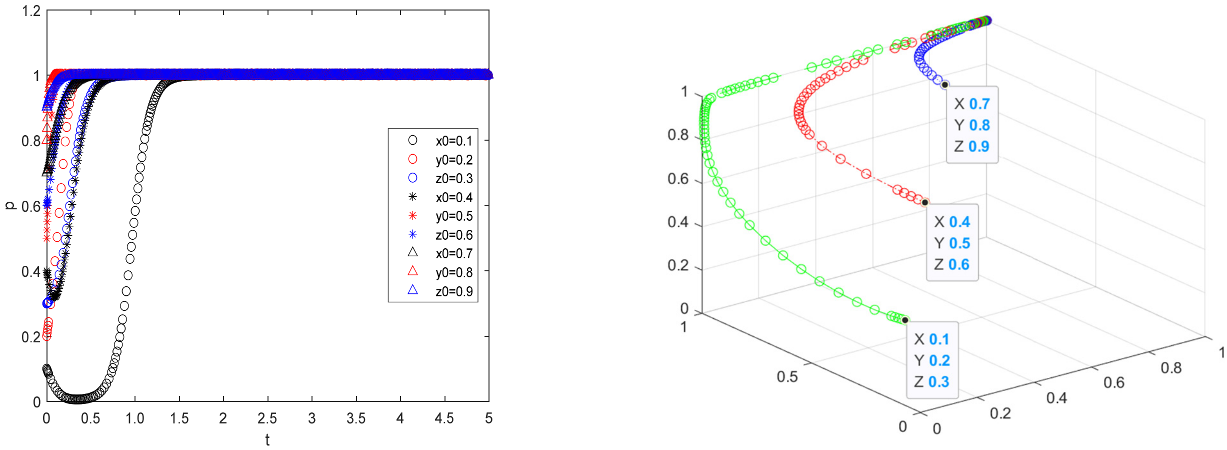
7. Numerical Simulation Analysis

To further verify the accuracy of the model and more intuitively show the results that the government, energy-saving service enterprises and rural residents in the existing rural residential buildings achieved, as well as the evolutionary stability under different constraints and strategies, this study uses MATLAB2020A to analyze the evolution of equilibrium points H_1 (0,0,0) and H_8 (1,1,1) from the perspective of cost and benefit, subsidies and penalties, combined with the replication of dynamic equations and assumptions.

7.1. When the Benefits of Energy-Saving Renovations Are Greater than the Cost, the Change in the Initial Proportion of the Three Parties in the Game Will Affect the Evolution Results

Suppose x0, y0 and z0 represent the initial proportions of the government's choice to implement supervision and incentive strategies, energy-saving service enterprises' choice to provide energy-saving service strategies and rural residents' choice to implement energy-saving transformation strategies, respectively. The initial test time is 0, the evolution end time is 5, and the initial states are (0.1, 0.2, 0.3), (0.4, 0.5, 0.6), (0.7, 0.8, 0.9). $F_1 = 40$, $F_2 = 10$, $S_1 = 30$, $S_2 = 5$, $R_1 = 300$, $R_2 = 180$, $E_1 = 120$, $E_2 = 50$, $C_1 = 60$, $C_2 = 40$, $C_3 = 15$, $C_4 = 8$, $C_5 = 25$, $C_6 = 5$. The stability of the equilibrium point and system evolution results are shown in Figure 4.

It can be found that when the profits of energy-saving renovations are greater than the cost of energy-saving renovations, no matter which initial state the three parties chose, the three parties choose the cooperative strategy H_8 (1,1,1) (supervision and encouragement, providing energy-saving services and performing energy-saving renovations), but the time taken to reach a stable and balanced state differs. Figure 4 shows that when the government, the energy-saving service enterprises and the rural residents choose supervision and encouragement, providing energy-saving services and performing energy-saving transformations with a strategy ratio of 0.1, 0.2 and 0.3, the system reaches an evolutionary stable equilibrium state at around t = 3.5. When the initial ratio increases by 0.3 or 0.6, that is, 0.4, 0.5, 0.6 or 0.7, 0.8, 0.9, the system reaches an evolutionary stable equilibrium state at about t = 2.5 or t = 1.8. This shows that, when the government chooses to implement supervision and incentive strategies for energy-saving renovations of existing rural residential buildings, energy-saving service enterprises choose to provide energy-saving service strategies, and rural residents choose to improve the proportion of energy-saving renovation, this helps to shorten the system evolution and achieve a stable and balanced state, which also helps to stimulate participants' enthusiasm for energy-saving renovations of existing rural residential buildings, and promote the development of energy-saving renovations of existing rural residential buildings.



(**a**) (**b**)

Figure 4. System evolution results under different initial intentions when the benefits of energy-saving renovations outweigh the costs. (**a**) The time at which the system evolves to a stable state. (**b**) Evolution rate.

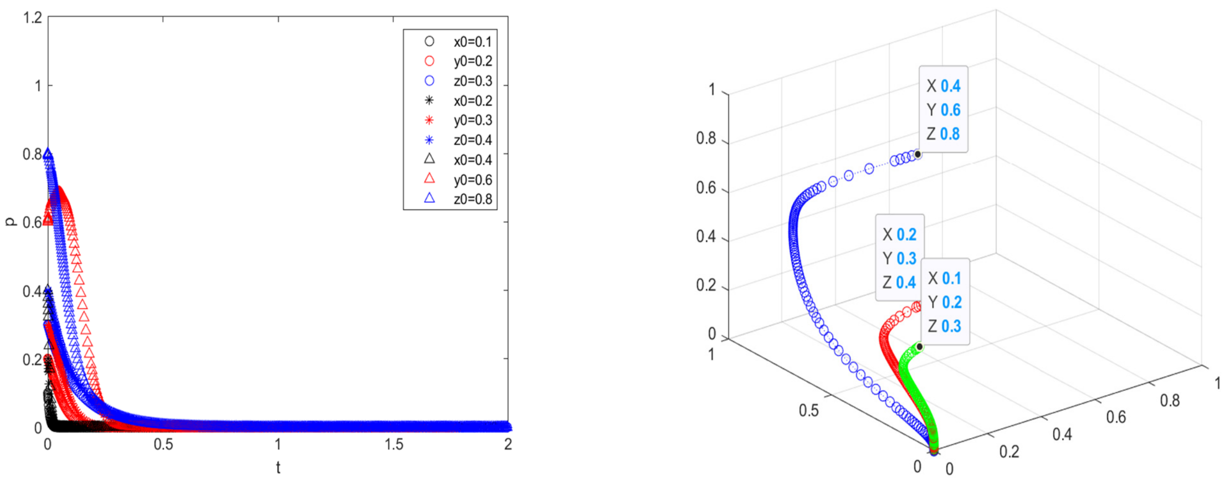
7.2. When the Cost of Energy Savings Is Greater than the Income, the Change in the Initial Proportion of the Three Parties in the Game Will Affect the Evolution Result

It is assumed that the initial test time is 0, the evolution end time is 5, the initial states are (0.1, 0.2, 0.3), (0.2, 0.3, 0.4), (0.4, 0.6, 0.8), and the parameters are $F_1 = 20$, $F_2 = 10$, $S_1 = 15$, $S_2 = 5$, $R_1 = 100$, $R_2 = 60$, $E_1 = 80$, $E_2 = 30$, $C_1 = 160$, $C_2 = 100$, $C_3 = 40$, $C_4 = 10$, $C_5 = 30$, $C_6 = 8$. The stability of the equilibrium point and system evolution results is shown in Figure 5. Through the simulation results, it can be found that when the cost of energy-saving renovation is greater than the profits, the choice strategies of the tripartite government, energy-saving service enterprises and rural residents will not change due to the change in the initial state ratio; they all choose the behavior strategy H_1 (0,0,0), in which energy-saving service enterprises do not provide energy-saving renovation services, and rural residents do not perform energy-saving renovations. The reason for this is that, as the number of rational people is limited, the ultimate goal of the energy-saving service enterprises and the rural residents participating in the energy-saving renovations of existing rural residential buildings is to obtain relevant benefits. Therefore, when the cost of energy-saving renovation is greater than the profits, because the renovations are unprofitable, energy-saving service enterprises and rural residents naturally choose to revoke their participation, and the ultimate behavior strategy of the three parties in the game is uncooperative.

7.3. Influence of Changes in Government Subsidies and Fines on Evolution Results When Energy-Saving Benefits Outweigh Costs

(1) When the benefits of energy-saving renovations are greater than the cost, the government subsidies increase. As shown in Figure 6, assuming that the initial state remains unchanged, the subsidies obtained by energy-saving service enterprises and rural residents voluntarily participating in the energy-saving renovations of existing rural residential buildings under the government's regulatory incentive policy are increased from $S_1 = 30$, $S_2 = 5$ to $S_1 = 35$, $S_2 = 8$. The ultimate behavior strategy of the three parties in the game is still H_8 (1,1,1) (regulatory incentive, providing energy-saving services and performing energy-saving renovation). However, when comparing Figure 4 with Figure 6, due to the improvement in government subsidies, the energy-saving service enterprises and the rural residents can be fully mobilized to participate in energy-saving renovations of existing rural houses, and the benefits of both can be increased. Therefore, the rate at which an evolutionary stable equilibrium state is reached accelerates with the increase in the initial ratio. However, increasing government subsidies will increase the cost of supervision and the incentives for the government to participate in energy-saving renovations of existing

rural residential buildings. Therefore, by comparing Figures 4a and 6a, it can be found that no matter which initial state is chosen, the ultimate behavior strategy of the government is to implement supervision and incentive policies. However, in the same initial state, increasing subsidies will obviously slow down the process and bias the government's behavior strategy towards the implementation of supervision and incentive policies. The time needed for the system to evolve to an equilibrium and stable state is, therefore, also prolonged. By comparing Figure 4b with Figure 6b, it can be found that, in the same initial state, the curvatures of the three curves in Figure 4b are larger than the corresponding three curves in Figure 6b, and the trend rate of (1,1,1) is obviously larger. This conclusion can be verified again in conjunction with Figure 7. When the initial state is the same as (0.4, 0.5, 0.6), and when the government subsidy increases from S_1 = 30, S_2 = 5 to S_1 = 35, S_2 = 8, although the increase in the subsidy is moderate for energy-saving service enterprises and rural residents, their behavior strategies with regard to providing energy-saving services and performing energy-saving renovations are consistent, and the rate of the curve-biased cooperative strategy is also accelerated. However, raising subsidies has a significant impact on the government, which leads the three parties in the game taking more time to reach an evolutionary stable equilibrium state. The reason for this lies in the increase in subsidies, which increases the cost of government supervision.

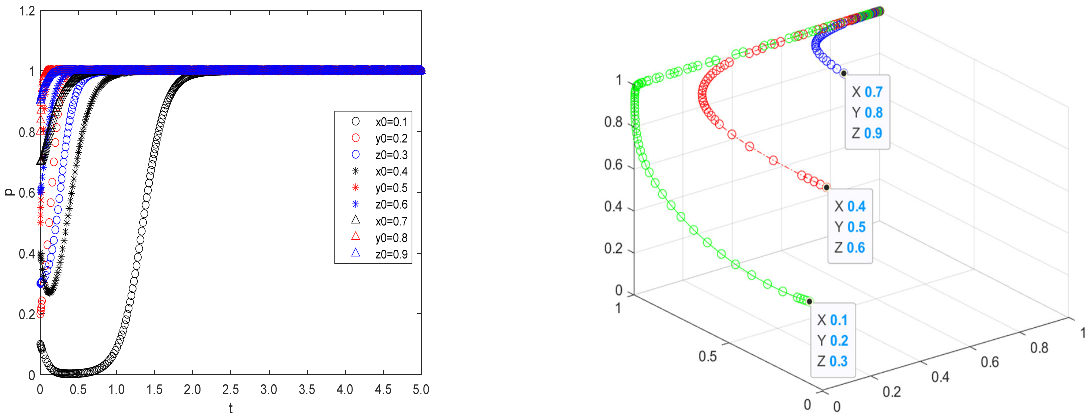


(**a**) (**b**)

Figure 5. System evolution results under different initial intentions when the cost of energy-saving renovations is greater than the benefit. (**a**) The time at which the system evolves to a stable state. (**b**) Evolution rate.

(2) When the income of energy-saving renovations is greater than the renovation costs, the government increases its fines. As shown in Figure 8a, when other conditions are unchanged, and the initial state is (0.4, 0.5, 0.6), government fines will increase from F_1 = 40 and F_2 = 10 to F_1 = 60 and F_2 = 15. The ultimate behavioral strategy of the three parties in the game is still H_8 (1,1,1) (supervision and encouragement, providing energy-saving services and performing energy-saving transformations). However, it can also be seen from Figure 8 that when government fines increase, the time needed for the three parties in the game to reach an evolutionary stable equilibrium state is shortened on the premise that the income from energy-saving renovation is still greater than the renovation costs. At the same time, combined with Figure 8b, it can be seen that, when F_1 = 60, F_2 = 15, and the initial state increases from (0.2, 0.3, 0.4) to (0.5, 0.6, 0.7), the time needed for the three parties to reach an evolutionary stable equilibrium state is also shortened. When ensuring that the income created by energy-saving renovations is greater than the renovation costs, a moderate increase in government punishment will serve as a warning to energy-saving service enterprises providing standardized energy-saving services and rural residents

who refuse to perform energy-saving renovations. On the premise of the rational person, the energy-saving service enterprises and rural residents will choose to participate in the energy-saving renovations of existing rural residential buildings to ensure the maximization of their own interests after weighing the benefits and costs.



(**a**) (**b**)

Figure 6. System evolution results under different initial intentions when subsidies are increased. (**a**) The time at which the system evolves to a stable state. (**b**) Evolution rate.

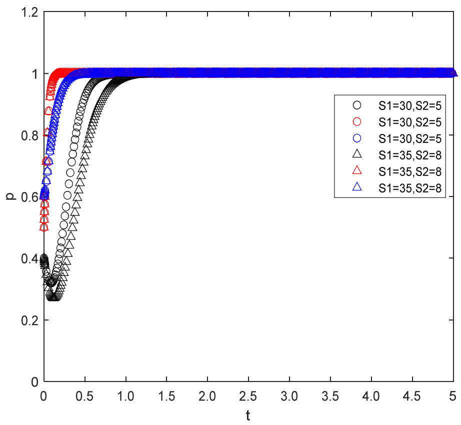
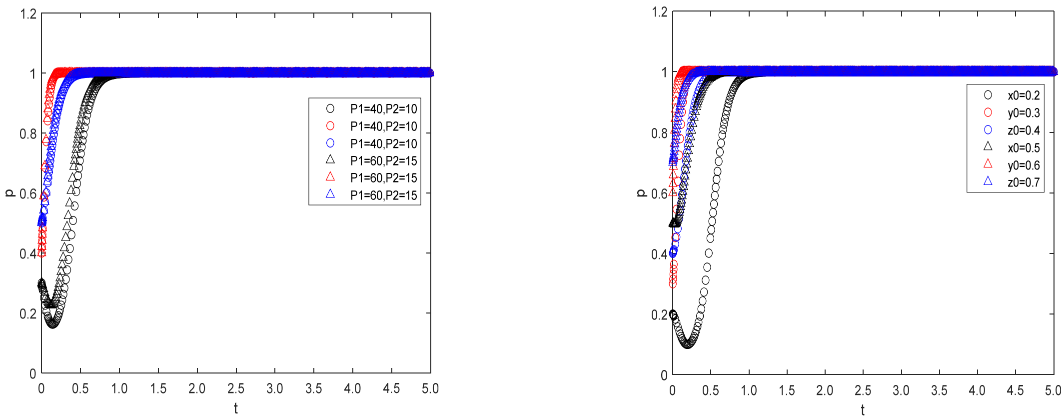


Figure 7. Evolution results of subsidy enhancement system under the same initial state.



(**a**) (**b**)

Figure 8. System evolution results under different initial intentions when punishment is increased. (**a**) The time at which the system evolves to a stable state. (**b**) Evolution rate.

8. Conclusions

Energy-saving renovations of existing rural residential buildings is an important part of national energy-saving and emission-reduction work, which is of great significance for saving energy, improving the indoor thermal environment, reducing greenhouse gas emissions, and promoting the transformation of development mode in the field of housing, urban–rural construction, and sustainable economic and social development. In this paper, the evolutionary game theory of bounded rationality is used to analyze the evolution law of the behavior strategies of the main bodies involved in energy-saving renovations of existing rural residential buildings, and an evolutionary game model and dynamic decision equations of the three-party behavior bodies of the government, energy-saving service enterprises and rural residents are constructed. By solving the stability points of these dynamic equations, the stability strategies and influencing factors of tripartite actors in different situations are analyzed.

(1) In energy-saving renovations of existing rural residential buildings, as the decision-maker and supervisor, the government's behavior strategies are mainly influenced by supervision cost and incentive policies. When the government does not supervise energy-saving service enterprises and rural residents, they have relatively low willingness to participate in existing rural buildings on the premise of limited rationality, and choose uncooperative behavioral strategies, that is, H_1 (0,0,0) (laissez-faire, providing no energy-saving services, rejecting energy-saving renovations). However, in order to promote energy-saving renovations of existing rural residential buildings, and achieve energy conservation and emission reductions, the government tends to supervise the choice of behavior strategies. Therefore, in the process of supervision, the appropriate fines and subsidies provided by the government to energy-saving service enterprises and rural residents will help to mobilize their enthusiasm to participate in energy-saving transformations, and the behavior strategies of the three parties will tend towards H_8 (1,1,1) (supervision incentives, providing energy-saving services and performing energy-saving transformations).

(2) The energy-saving service enterprises are the information-superior party, and they have complete information on energy-saving technologies. When participating in energy-saving renovations of existing rural residential buildings, their behavior strategies are mainly affected by the benefits and costs of providing standardized energy-saving services, and the loss caused by providing unstandardized energy-saving services. Therefore, when the benefits of participating in energy-saving transformation outweigh the costs, the behavior strategy of the energy-saving service enterprises is to provide standardized energy-saving services, regardless of whether the government subsidies or penalties are increased.

(3) As the inferior-information party, rural residents participate in energy-saving renovations of existing rural residential buildings in the hope of not only improving their living conditions, but also of obtaining certain government subsidies. The main influencing factors are the government subsidies, the loss caused by the unqualified energy-saving services provided by the energy-saving service enterprises and the extra economic expenses incurred during the energy-saving renovations. Hence, when the subsidies provided by the government are greater than the loss caused by unqualified energy-saving services provided by energy-saving service enterprises and the extra economic expenditure generated during the energy-saving transformation, the behavior strategy of rural residents is to carry out energy-saving transformations.

(4) The limitation of the research. The main limitation in this study is the research on the behavior strategy of market participants in energy-saving renovation of existing rural residential buildings only starts with three core participants, and the related auxiliary participants in energy-saving renovation of existing rural residential buildings have not been analyzed. That is because in the process of energy-saving renovation of existing rural residential buildings, the behaviors and strategies of the government, energy-saving service enterprises and rural residents have a relatively large mutual restriction and influence, while other related auxiliary participants may have an influence on a certain participant, but not all of them. For example, the bank's behavior strategy may have a greater impact

on the government and energy-saving service enterprises, but it has a less impact on rural residents. Therefore, the impact on the research results is not great, but it can be a direction for further research in the future.

Therefore, in the process of energy-saving renovations of existing rural residential buildings, the government, energy-saving service enterprises and rural residents, as the three main participants, will choose the most favorable behavior strategies, weighing the government subsidies and fines and the cost of their own participation to maximize their own interests under limited rationality. Therefore, in order to realize the energy-saving renovations of existing rural residential buildings, participants' cooperation is needed. In future research, we will further discuss the impact of increased stakeholder participation in energy-saving renovations of existing rural residential buildings, and analyze their development path, as influenced by various factors.

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References

1. International Energy Agency (IEA). Data and Statistics. Available online: https://www.iea.org/data-and-statistics/?country=WORLD&fuel=Energy+consumption (accessed on 10 August 2021).
2. BP. World Energy Statistics Yearbook. 2021. Available online: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html (accessed on 10 August 2021).
3. Huang, M.Q.; Wang, B. Evaluating green performance of building products based on gray relational analysis and analytic hierarchy process. *Environ. Prog. Sustain. Energy.* **2014**, *33*, 1389–1395. [CrossRef]
4. Pan, W.; Garmston, H. Compliance with building energy regulations for new-build dwellings. *Energy* **2012**, *48*, 11–22. [CrossRef]
5. Pataki, D.; Emmi, P.; Forster, C.; Mills, J.; Pardyjak, E.; Peterson, T.; Thompson, J.; Dudley-Murphy, E. An integrated approach to improving fossil fuel emissions scenarios with urban ecosystem studies. *Ecologi. Complex.* **2009**, *6*, 1–14. [CrossRef]
6. Li, D.Z.; Chen, H.X.; Hui, E.C.M.; Zhang, J.B.; Li, Q.M. A methodology for estimating the life-cycle carbon efficiency of a residential building. *Build. Environ.* **2013**, *59*, 448–455. [CrossRef]
7. GEF. Malaysia: Buildings Sector Efficiency Project. 2008. Available online: http://www.thegef.org/gef/sites/thegef.org/files/repository/11-30-09%20ID3598%20-%20Council%20letter.pdf (accessed on 10 August 2021).
8. Yau, Y.H.; Hasbi, S. A review of climate change impacts on commercial buildings and their technical services in the tropics. *Renew. Sustain. Energy Rev.* **2013**, *18*, 430–441. [CrossRef]
9. Wang, W.M.; Zmeureanu, R.; Rivard, H. Applying multi-objective genetic algorithms in green building design optimization. *Build. Environ.* **2005**, *40*, 1512–1525. [CrossRef]
10. International Energy Agency (IEA). Data and Statistics. Available online: https://www.iea.org/data-and-statistics/data-browser/?country=CHINA&fuel=CO2%20emissions&indicator=CO2BySource (accessed on 10 August 2021).
11. International Energy Agency (IEA). Buildings-A source of enormous untapped efficiency potential. Available online: https://www.iea.org/topics/buildings (accessed on 10 August 2021).
12. Rhodes, C. The 2015 Paris climate change conference: COP21. *Sci. Prog.* **2016**, *99*, 97–104. [CrossRef] [PubMed]
13. Liu, Z.J.; Zhou, Q.X.; Tian, Z.Y.; He, B.-J.; Jin, G. A comprehensive analysis on definitions, development, and policies of nearly zero energy buildings in China. *Renew. Sustain. Energy Rev.* **2019**, *114*, 109314. [CrossRef]

14. International Energy Agency. Modernising Building Energy Codes to Secure Our Global Energy Future, Policy Pathway Publications, OECD/IEA and United Nations Development Programme (UNDP). 2013. Available online: https://www.iea.org/publications/freepublications/publication/PolicyPathwaysModernisingBuildingEnergyCodes.pdf (accessed on 10 August 2021).
15. Sesana, M.M.; Salvalai, G. A review on Building Renovation Passport: Potentialities and barriers on current initiatives. *Energy Build.* **2018**, *173*, 195–205. [CrossRef]
16. Evans, M.; Yu, S.; Song, B.; Deng, Q.; Liu, J.; Delgado, A. Building energy efficiency in rural China. *Energy Policy* **2014**, *64*, 243–251. [CrossRef]
17. National Bureau of Statistics of China. *China Energy Statistical Yearbook*; China National Bureau of Statistics: Beijing, China, 2006.
18. IEA. *Energy Balances of Non-OECD Countries*, 2007th ed.; IEA: Paris, France, 2007.
19. Yu, S.; Eom, J.; Evans, M.; Clarke, L. A long-term, integrated impact assessment of alternativebuilding energy code scenarios in China. *Energy Policy* **2014**, *67*, 626–639. [CrossRef]
20. Ouyang, J.L.; Wang, C.Y.; Li, H.F.; Hokao, K. A methodology for energy-efficient renovation of existing residential buildings in China and case study. *Energy Build.* **2011**, *43*, 2203–2210. [CrossRef]
21. Papadopoulos, A.; Theodosiou, T.; Karatzas, K. Feasibility of energy saving renovation measures in urban buildings: The impact of energy prices and the acceptable pay back time criterion. *Energy Build.* **2002**, *34*, 455–466. [CrossRef]
22. Jakob, M. Marginal cost and co-benefits of energy efficiency investments: The case of the Swiss residential sector. *Energy Policy* **2006**, *34*, 172–187. [CrossRef]
23. Li, J.; Ng, S.T.; Skitmore, M. Review of low-carbon refurbishment solutions for residential buildings with particular reference to multi-story buildings in Hong Kong. *Renew. Sustain. Energy Rev.* **2017**, *73*, 393–407. [CrossRef]
24. Zheng, D.L.; Yu, L.J.; Wang, L.; Tao, J. Integrating willingness analysis into investment prediction model for large scale building energy saving retrofit: Using fuzzy multiple attribute decision making method with Monte Carlo simulation. *Sustain. Citie Soc.* **2019**, *44*, 291–309. [CrossRef]
25. Fan, Y.L.; Xia, X.H. Energy-efficiency building retrofit planning for green building compliance. *Energy Build.* **2018**, *136*, 312–321. [CrossRef]
26. Zhao, J.; Wu, Y.; Zhu, N. Check and evaluation system on heat metering and energy efficiency retrofit of existing residential buildings in northern heating areas of China based on multi-index comprehensive evaluation method. *Energy Policy* **2009**, *37*, 2124–2130. [CrossRef]
27. Ho, M.Y.; Lai, J.H.K.; Hou, H.Y.; Zhang, D. Key Performance Indicators for Evaluation of Commercial Building Retrofits: Shortlisting via an Industry Survey. *Energies* **2021**, *14*, 7327. [CrossRef]
28. Dolšak, J.; Hrovatin, N.; Zorić, J. Factors impacting energy-efficient retrofits in the residential sector: The effectiveness of the slovenian subsidy program. *Energy Build.* **2020**, *229*, 110501. [CrossRef]
29. Morelli, M.; Harrestrup, M.; Svendsen, S. Method for a component-based economic optimisation in design of whole building renovation versus demolishing and rebuilding. *Energy Policy* **2014**, *65*, 305–314. [CrossRef]
30. Oberegger, U.F.; Pernetti, R.; Lollini, R. Bottom-up building stock retrofit based on levelized cost of saved energy. *Energy Build.* **2020**, *210*, 109757. [CrossRef]
31. Zheng, L.Z.; Lai, J. Environmental and economic evaluations of building energy retrofits: Case study of a commercial building. *Build. Environ.* **2018**, *145*, 14–23. [CrossRef]
32. Ciulla, G.; Galatioto, A.; Ricciu, R. Energy and economic analysis and feasibility of retrofit actions in Italian residential historical buildings. *Energy Build.* **2016**, *128*, 649–659. [CrossRef]
33. Ouyang, J.L.; Ge, J.; Hokao, K. Economic analysis of energy-saving renovation measures for urban existing residential buildings in China based on thermal simulation and site investigation. *Energy Policy* **2009**, *37*, 140–149. [CrossRef]
34. Wang, X.T.; Lu, M.J.; Mao, W.; Ouyang, J.; Zhou, B.; Yang, Y. Improving benefit-cost analysis to overcome financing difficulties in promoting energy-efficient renovation of existing residential buildings in China. *Appl. Energy* **2015**, *141*, 119–130. [CrossRef]
35. Piccardo, C.; Dodoo, A.; Gustavsson, L. Retrofitting a building to passive house level: A life cycle carbon balance. *Energy Build.* **2020**, *223*, 110135. [CrossRef]
36. Rakhshan, K.; Friess, W.A. Effectiveness and viability of residential building energy retrofits in Dubai. *Build. Engrg.* **2017**, *13*, 116–126. [CrossRef]
37. Yau, Y.; Hou, H.Y.; Yip, K.C.; Qian, Q.K. Transaction Cost and Agency Perspectives on Eco-Certification of Existing Buildings: A Study of Hong Kong. *Energies* **2021**, *14*, 6375. [CrossRef]
38. Liu, X.; Wang, C.C.; Liang, C.Z.; Feng, G.H.; Yin, Z.K.; Li, Z.H. Effect of the energy-saving retrofit on the existing residential buildings in the typical city in northern China. *Energy Build.* **2018**, *177*, 154–172.
39. Pohoryles, D.A.; Maduta, C.; Bournas, D.A.; Kouris, L.A. Energy performance of existing residential buildings in Europe: A novel approach combining energy with seismic retrofitting. *Energy Build.* **2020**, *233*, 110024. [CrossRef]
40. Javid, A.S.; Aramoun, F.; Bararzadeh, M.; Avami, A. Multi objective planning for sustainable retrofit of educational buildings. *Build. Engrg.* **2019**, *24*, 100759. [CrossRef]
41. Charles, A.; Mahid, W.; Ouellet-Plamondon, C.M. Case study of the upgrade of an existing office building for low energy consumption and low carbon emissions. *Energy Build.* **2019**, *183*, 151–160. [CrossRef]
42. Salvalai, G.; Sesana, M.M.; Lannaccone, G. Deep renovation of multi-storey multi-owner existing residential buildings-A pilot case study in Italy. *Energy Build.* **2017**, *148*, 23–36. [CrossRef]

43. Richarz, J.; Henn, S.; Osterhage, T.; Müller, D. Optimal scheduling of modernization measures for typical non-residential buildings. *Energy* **2022**, *238*, 121871. [CrossRef]
44. Dorota, A.K. Theoretical and real effect of the school's thermal modernization—A case study. *Energy Build.* **2014**, *81*, 30–37.
45. Sadowska, B.; Woroniak, J.P.; Woroniak, G.; Sarosiek, W. Energy and Economic Efficiency of the Thermomodernization of an Educational Building and Reduction of Pollutant Emissions—A Case Study. *Energies* **2022**, *15*, 2886. [CrossRef]
46. Michalak, P.; Szczotka, K.; Szymiczek, J. Energy Effectiveness or Economic Profitability? A Case Study of Thermal Modernization of a School Building. *Energies* **2021**, *14*, 1973. [CrossRef]
47. Siuta-Olcha, A.; Cholewa, T. Energy demand for space heating of residential buildings in Poland. In *Environmental Engineering III*; CRC Press: Boca Raton, FL, USA, 2010.
48. Staniūnas, M.; Medineckienė, M.; Zavadskas, E.K.; Kalibatas, D. To modernize or not: Ecological–economical assessment of multi-dwelling houses modernization. *Arch. Civ. Mech. Eng.* **2013**, *13*, 88–98. [CrossRef]
49. Pozo, M.V.; Bustos, J.P.G. Tax incentives to modernize the energy efficiency of the housing in Spain. *Energy Policy* **2019**, *128*, 530–538. [CrossRef]
50. Belany, P.; Hrabovsky, P.; Kolkova, Z. Combination of lighting retrofit and life cycle cost analysis for energy efficiency improvement in buildings. *Energy Rep.* **2021**, *7*, 2470–2483. [CrossRef]
51. Hu, X.Y.; Xiang, Y.M.; Zhang, H.; Lin, Q.; Wang, W.; Wang, H. Active–passive combined energy-efficient retrofit of rural residence with non-benchmarked construction: A case study in Shandong province, China. *Energy Rep.* **2021**, *7*, 1360–1373. [CrossRef]
52. Tahsildoost, M.; Zomorodian, Z. Energy, carbon, and cost analysis of rural housing retrofit in different climates. *Build. Engrg.* **2020**, *30*, 101277. [CrossRef]
53. Liu, Z.J.; Wu, D.; He, B.J.; Wang, Q.; Yu, H.; Ma, W.; Jin, G. Evaluating potentials of passive solar heating renovation for the energy poverty alleviation of plateau areas in developing countries: A case study in rural Qinghai-Tibet Plateau, China. *Sol. Energy* **2019**, *187*, 95–107. [CrossRef]
54. Aleva, Ü.; Eskolab, L.; Arumägic, E.; Jokisalo, J.; Donarelli, A.; Siren, K.; Broström, T.; Kalamees, T. Renovation alternatives to improve energy performance of historic rural houses in the Baltic Sea region. *Energy Build.* **2014**, *77*, 58–66. [CrossRef]
55. Rocchi, L.; Kadziński, M.; Menconi, M.E.; Grohmann, D.; Miebs, G.; Paolotti, L.; Boggia, A. Sustainability evaluation of retrofitting solutions for rural buildings through life cycle approach and multi-criteria analysis. *Energy Build.* **2018**, *173*, 281–290. [CrossRef]
56. Smith, J.M. The theory of games and the evolution of animal conflicts. *Theor. Biol.* **1974**, *47*, 209–211. [CrossRef]
57. Yamamoto, H.; Ishida, K.; Ohta, T. Modeling Reputation Management System on Online C2C Market. *Comput. Mathe. Organi. Theory* **2004**, *10*, 165–178. [CrossRef]
58. Fan, W.; Wang, S.; Gu, X.; Zhou, Z.; Zhao, Y.; Huo, W. Evolutionary game analysis on industrial pollution control of local government in China. *Environ. Manag.* **2021**, *298*, 113499. [CrossRef]
59. Liu, P.K.; Peng, H.; Wang, Z.W. Orderly-synergistic development of power generation industry: A China's case study based on evolutionary game model. *Energy* **2020**, *211*, 118632.
60. Su, Y.B. Multi-agent evolutionary game in the recycling utilization of construction waste. *Sci. Total Environ.* **2020**, *738*, 139826. [CrossRef] [PubMed]
61. Huang, M.Q.; Cui, S.H.; Li, X.F. Analysis on the Influence Factors of Energy-saving Building Product Promotion and Application by Structural Equation Model. *J. Huaqiao Univ.* **2016**, *4*, 447–450. (In Chinese)
62. MHuang, Q.; Lin, R.J. Analysis on the difficulties and countermeasures of energy saving reconstruction of existing rural residential buildings. In Proceedings of the 2020 3rd International Workshop on Environment and Geoscience, Chengdu, China, 20–22 July 2020.
63. He, B.J.; Yang, L.; Ye, M.; Mou, B.; Zhou, Y. Overview of rural building energy efficiency in China. *Energy Policy* **2014**, *69*, 385–396. [CrossRef]
64. Statistical Bulletin of Urban and Rural Construction in 2016. Available online: https://www.mohurd.gov.cn/gongkai/fdzdgknr/sjfb/tjxx/tjgb/201708/20170822_232983.html (accessed on 10 August 2021).
65. Wang, X.H.; Feng, Z.M. Rural household energy consumption with the economic development in China: Stages and characteristic indices. *Energy Policy* **2001**, *29*, 1391–1397.
66. Zeng, X.; Ma, Y.; Ma, L. Utilization of straw in biomass energy in China. Renew. Sustain. *Energy Rev.* **2007**, *11*, 976–987.
67. Chang, J.; Leung, D.Y.; Wu, C.Z.; Yuan, Z. A review on the energy production, consumption, and prospect of renewable energy in China. Renew. Sustain. *Energy Rev.* **2003**, *7*, 453–468.
68. Ferrante, A. Energy retrofit to nearly zero and socio-oriented urban environments in the Mediterranean climate. *Sustain. Cities Soc.* **2014**, *13*, 237–253. [CrossRef]
69. Fotopoulou, A.; Semprini, G.; Cattani, E.; Schihin, Y.; Weyer, J.; Gulli, R.; Ferrante, A. Deep renovation in existing residential buildings through façade additions- A case study in a typical residential building of the 70s. *Energy Build.* **2018**, *166*, 258–270. [CrossRef]