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RESEARCH ARTICLE

A Principal-Agent Approach for the Effective Design of a Renewable Energy Incentive for a Heavily Subsidized Residential Sector: The Case of Qatar

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ABSTRACT Qatar's per capita electricity consumption is one of the highest in the world, mainly due to the availability of heavily subsidized electricity. The residential sector alone accounts for 60% of produced electricity. The effectiveness of imposing regulatory measures that aim to reduce consumption, such as carbon pricing and rebates, depends on the design of the introduced policy, region dynamics, and population characteristics. Using principal-agent theory, this study addresses the agency problem between the government and households by proposing a policy that aims to incentivize households to shift towards renewable energy sources and reduce their overall energy demand. The study quantifies the potential impact of the policy over a period of five years and estimates that 495 GWh of electricity could be saved, resulting in a significant reduction of 203,710 Tons of CO2e emissions. The cost of implementing the policy is estimated to be 0.838 billion Qatari riyals. The effect of varying model parameters on incentive design is investigated, and a detailed financial analysis is conducted based on the redirection of saved energy resources from domestic consumption to international exports of gas and electricity.

INDEX TERMS Renewable energy, carbon price, carbon rebate, principal-agent problem, renewable energy incentives, solar PV, residential PV adoption.

NOMENCLATURE

INDICES

h	Households' agent.
g	Government agent.
a	Action dependent variable.
t	Time-dependent variable.

Parameters

N	No of the households in the study.
ρ	Households risk preference.
θ	Threshold of RE benefit for households.
d	Discount rate.

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ACRONYMS

CAC	Command and Control.
CGE	Computable general equilibrium.
DCF	Discounted cash flow.
EER	Energy efficiency retrofit.
ETS	Emissions trading scheme.
FIT	Feed-in Tariff.
GHG	Greenhouse gases.
HVAC	Heating, Ventilation, and Air Conditioning.
IRR	Internal Rate of Return.
MBA	Market-based approaches.
MMBTU	Metric million British thermal unit.
NPV	Net present value.
O&M	Operation and Maintenance.

QAR	Qatari riyal.
RE	Renewable energy.

VARIABLES

$U^h_{a,t}$	Households' utility.
f^h_a	Effort of households.
$B^h_{a,t}$	Household's economic benefit from RE.
$c^h_{a,t}$	Cost of RE For 1kw system.
μ^h_t	Cost coefficient of RE system.
$\lambda^h_{a,t}$	Environmental benefit share to households.
$e^b_{a,t}$	Energy usage before the incentive.
$e^a_{a,t}$	Energy usage after the incentive.
$i^g_{a,t}$	Incentive to the household.
$\gamma^h_{a,t}$	Subsidy for the RE equipment purchase.
CR^h_a	Carbon rebate.
$U^g_{a,t}$	Government's incentive utility.
CP^h_a	Carbon price.
x_t	Random variable representing uncertainty (risk) of investing in RE.
r^{ec}_t	Coefficient of economic benefit from re, $r^{ec}_t \geq 0$.
r^{en}_t	Coefficient of environmental benefit from re, $r^{en}_t \geq 0$.
τ^{ec}_t	Economic benefit of RE.
τ^{en}_t	Environmental benefit of RE.
φ^h	Initial investment by households for re system.
	$*$ a, t represents the dependence of variable on action and/or time.

I. INTRODUCTION

To mitigate the effects of climate change and keep temperature rise below 2°C as specified in the Paris Agreement [1], a massive shift in energy usage is required in all sectors. Currently, the household sector consumes, on average, 27% of world energy resources, contributing to 17% of the total Greenhouse Gas (GHG) emissions [2]. Energy consumption in households has increased with the growing population and urbanization [3]. Households' energy usage is higher than the global average in high-income and energy-exporting countries such as Qatar, Saudi Arabia, Kuwait, the United States (US), Canada and the United Arab Emirates (UAE) [4]. Therefore, the global energy conservation attention has been shifted from the industrial to the household sector [2]. Energy conservation is influenced by the regulatory measures introduced by the government and the source of the supplied energy for the households [5].

Several regulatory approaches have been proposed to urge households to reduce consumption from the grid and adopt clean energy resources [6], [7] and the literature comprises a wide variety of policies and regulatory instruments with a particular focus on carbon pricing (see [6], [7], [8]). Regulatory instruments are generally classified into two main categories, i.e., Command and Control (CAC) and Market-Based Approaches (MBA) [9]. CAC is a regulatory measure to control industries via enforcing strict regulations. In comparison, the MBA involves a behavioural change of market participants, i.e., households. MBAs are divided into two types, namely (i) cap and trade system, also known as an Emission Trading Scheme (ETS), and (ii) carbon pricing or carbon taxation [10].

Many countries around the world have introduced carbon pricing and ETS to help reduce emissions and promote the use of Renewable Energy (RE) in different sectors [11]. Finland was the first to implement a carbon price in 1990 on the carbon content of fossil fuels. As a result, with subsequent reforms in 1997, 2008, 2011, and 2013, Finland has reduced 23% of its total emissions in 2020 compared to 1990 [12]. Being an early adopter of the carbon tax, Finland has pledged to be carbon neutral by 2035 [13]. Similarly, in 1991 Sweden became the second country to impose a tax on carbon emissions and has successfully decreased its emissions by 27% between 1990 and 2018 [14].

Australia, on the other hand, first implemented a carbon price in 2011, which reduced GHG emissions by 7% until 2014. More recently, in 2021, the German government introduced a combination of ETS and a carbon pricing program for the residential and transport sector. The government expects a revenue generation of 40 billion EUR with the program and an emission reduction of 12.4 million tons CO_2e by 2035 [15]. The USA and China have also started implementing carbon pricing policies, highlighting a significant shift in their approach towards GHG emissions. Figure 1 reveals the impact of carbon pricing for the abovementioned countries where a lower trajectory of emissions states the effectiveness of the policy.

Regulatory measures such as carbon price have been used in various countries; however, due to the energy abundance in the GCC region, regulatory measures are not introduced; hence, households currently have no economic incentive to switch to RE or reduce consumption [16]. Figure 2 shows the percentage increase in the total emissions for the GCC region from 2000 to 2020, with Qatar showing a rise of 131% in its total emissions.

In Qatar, 93% of electricity is produced from natural gas (NG) [17], [18] and the household sector consumes around 60% of produced electricity [19]. Nationals and residents enjoy the benefits of free or heavily subsidized electricity, leading to high per capita consumption and, thus, a high carbon footprint. To counter emissions increase, it is essential to transform the energy sector by utilizing clean energy technologies such as Solar and Wind. Qatar is rich in its potential capability of generating RE via solar. The average range of global solar radiation, shown in Figure 3, is between 7.34 kWh/m^2/day to 5.18 kWh/m^2/day, one of the world's highest in the world, signifies the claim of solar energy utilization [20].

Qatar's commitment to sustainable development, as stated in Qatar's National Vision 2030 [21], has led to the development of three large-scale RE (Solar) projects. The first of which is the Al-Kharsaah solar PV project of 800 MW, launched in 2020, is expected to be fully operational by the

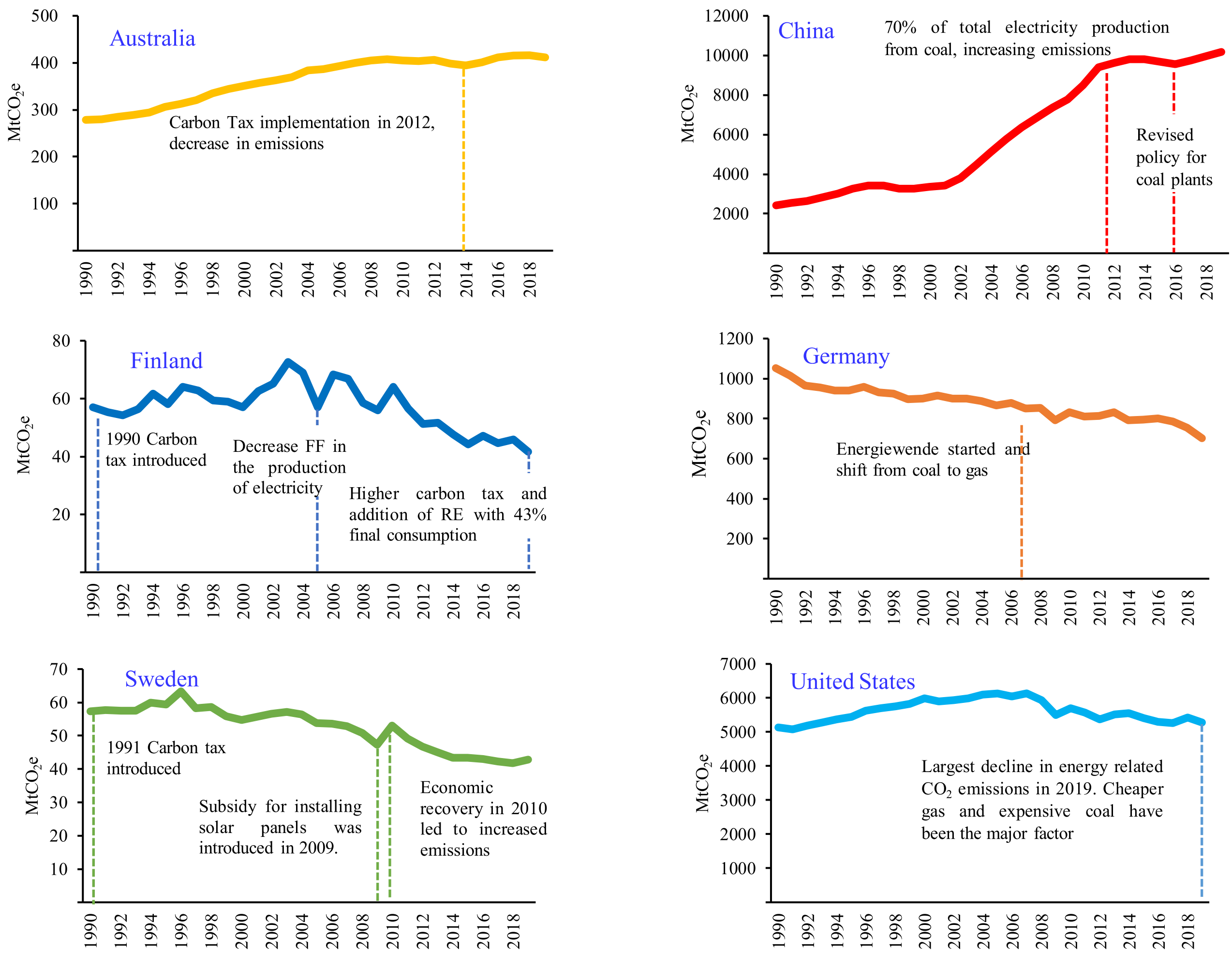

FIGURE 1. The total yearly CO$_2$ emissions from all sectors in six early adopting, repealing and largest emitter countries, showing the impact of Carbon Tax and ETS policies.

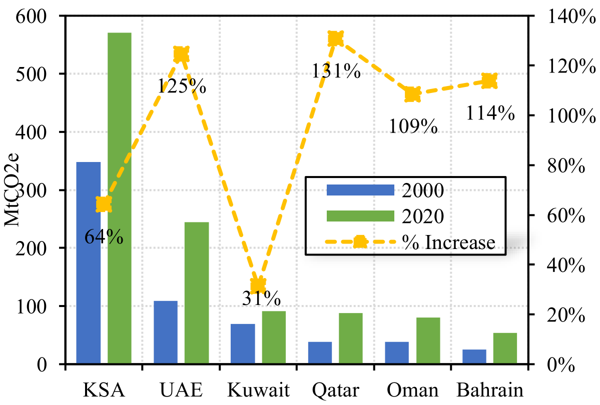

FIGURE 2. Comparison of total emissions in 2000 and 2020 for GCC countries [26].

end of 2022 [22]. Additionally, the Mesaieed Industrial City solar project with a production capacity of 417 MW and the Ras Laffan Industrial City solar project with a production capacity of 458 MW [23]. Although such large-scale projects will help meet overall electricity demand from the grid, the usage of clean energy in the household sector remains almost negligible, despite the country's huge potential for RE [18], [20].

Qatar has a relatively small population, and its primary source of revenue is from natural gas exports. Natural gas is also used for domestic electricity production [24]. Thus, gas revenue from exports can be increased if domestic consumption is reduced. Furthermore, electricity saved from reduced domestic consumption can be directly exported via Gulf Cooperation Council Interconnection Authority (GCCIA) grid.

By implementing incentive-based policies, a significant reduction in emissions through cautious energy usage and adoption of RE could be observed. Hence, it is necessary to develop an incentive design framework that includes the behaviour of the households and depicts the potential financial gains received by the households. Principal-agent theory can be used to study the interaction between a principal

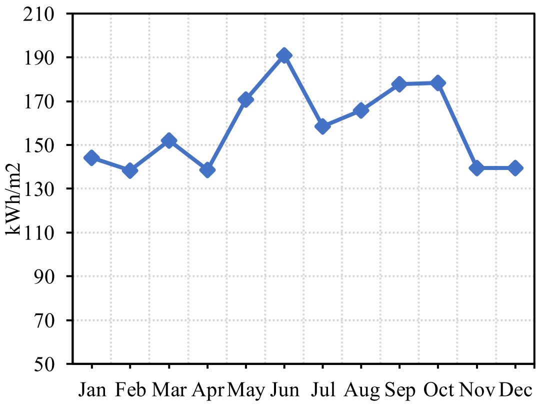

FIGURE 3. Monthly average direct normal irradiation (DNI) for Qatar in 2022 suggests the high feasibility of solar PV [27].

(such as a government) and an agent who has been assigned decision-making authority by the principal. Decisions taken by the agents are not always aligned with the principal's objective since the agent is trying to maximise their utility, while the principal is trying to maximise the utility of the organisation, namely the government. Principal-agent theory was developed to address this issue in the presence of asymmetric information, i.e. when agents have more information than the principal and can utilise this to pursue their interests [25].

In this study, we utilize principal-agent theory to propose a comprehensive framework for a carbon price and rebate incentive to promote the use of RE in the residential sector, in the the presence of highly subsidised electricity. The novelty of the proposed framework in this study lies in the integration of principal-agent theory (typically used in economics), into a carbon pricing and rebate incentive system for promoting renewable energy (RE) use, while considering the unique characteristics of the Qatar's residential sector. These have been understudied in relation to carbon pricing and rebate incentives, particularly with respect to the specific challenges posed by highly subsidized electricity. The framework proposed in this study provides a novel and tailored solution for promoting RE adoption in this context.

Various scenarios based on different levels of risk aversion of the agents, namely the households, are developed to investigate the feasibility of the proposed incentive. An economic analysis is also conducted to calculate the profitability of the incentive for the households. Furthermore, policy evaluation is carried out for the government considering saved energy resources that are redirected to, e.g., gas and electricity exports.

The rest of the paper is organized as follows: Section II provides an overview of the literature from three perspectives, namely the impact of carbon pricing policies, policies involving carbon price coupled with rebate and an analysis of the various RE incentive policies previously used; Section III provides a detailed description of the proposed framework and the implementation of the proposed framework for Qatar; Section IV includes the results and discussion, and the paper concludes in Section V and highlights future research directions.

II. LITERATURE REVIEW

Carbon pricing is classified as the most economical and effective tool to curb emissions [28] and has been widely discussed in the environmental tax literature. Garaffa et al. use a multi-regional computable general equilibrium (CGE) model to assess the impact of the carbon price on households in the Brazilian context. The authors concluded that further carbon-intensive infrastructure investments could be prevented using carbon pricing [29]. On the other hand, a study on Malaysia has shown that carbon price effects are negligible on the country's economic activities. Also, with the carbon price, households will be cautious about unnecessary energy expenditure [30]. Khastar et al. also used a CGE model to analyse the effects of carbon taxation in Finland, given that carbon taxation has existed there for the last three decades. The authors found that the carbon taxation policy has had a positive effect on emissions reduction but has had some negative impacts on social welfare. The authors argue that an optimal value of carbon taxation should be determined and coupled with some revenue recycling so that it will not affect the social welfare of the population [31].

A comparative study of carbon pricing in Sweden, France and Canada shows that carbon pricing is a convenient way to reduce emissions, but the implementation phase is relatively complicated. They discovered that public confidence in government revenue management plays a crucial role in policy acceptance in all three countries discussed [6]. Al-Sarihi emphasized the need for carbon pricing for the Gulf Cooperation Council (GCC) to cut emissions and avoid the adverse effect of climate change in the region [32]. A detailed overview of carbon pricing policies is given by Bashir et al. [33]. However, the advantages of a carbon price can be overshadowed if a significant proportion of the public is against it [34], [35]. Researchers have identified several barriers to limited public acceptance, namely that (i) the public perception that carbon price will not reduce emissions [36], [37], [38], (ii) it will decelerate economic progress [39], [40], and (iii) it will be a financial burden on low-income households [31], [41].

In response to the public opposition to carbon pricing, revenue recycling has been proposed in two ways: through tax cuts or lump-sum rebates to households, with the former being more effective [34]. Carbon pricing policies are popular if the revenues collected are utilized directly for the welfare of the citizens [30], [42], [43]. Moz-Christofoletti and Pereda recommend that the compensation mechanism in terms of monetary benefits coupled with carbon pricing is essential for implementing incentives [44]. Klenert et al. suggest that if the public is aware of the benefits of carbon rebates, the acceptability of the carbon price will be improved due to the visible rebate they would receive [45]. In total, 3623 Economists, including 28 Nobel laureate economists, have endorsed the idea of the carbon price and rebate, which signifies the viability of the carbon price and rebate to reduce emissions [46]. A plethora of hypothetical studies exist in the literature that show that public acceptance of carbon price could rise when coupled with a carbon rebate, based on studies from the United States [40], [41], Canada [47], Switzerland [48], Australia [42], United Kingdom [42], [49], Germany [41] and France [35]. In terms of the practical application of carbon price and rebate, only two countries have thus far implemented such a policy, i.e., Canada and Switzerland [34].

To design an incentive for RE usage and adoption, earlier studies have used various approaches to assess psychological behaviour with multiple theories such as Social Cognitive Theory [50]; Social Norms Theory [51]; Theory of Reasoned Action [52]; and the Theory of Planned Behaviour [53]. The household's willingness is essential to the success of an incentive designed to increase the adoption of RE [53]. However, exclusively studying the households' psychological behaviour will not guarantee an incentive's success. Examining the financial benefits linked with an incentive for households is crucial [54]. Sarzynski et al. studied the influence of financial benefits for households and found that cash incentives for RE adoption proved more robust for RE deployment than incentives that do not involve cash. The authors used econometric techniques to show that cash incentive is better than others but lacks in providing an optimal value for the amount of cash incentive [55]. Sheikhhoseini et al. employed a Feed-in Tariff (FIT) incentive policy to evaluate its effect on RE adoption. Their results reveal that the impact of a FIT policy is relatively weak in a highly subsidized energy market [56]. Gaviria et al. utilized system dynamics model approach to evaluate the impact of various incentives on the adoption of RE in Colombia. The authors developed a system dynamics model to capture the complex interactions between various factors that influence RE adoption, such as technological advancements, economic factors, and policy frameworks. Their findings indicate that relying solely on legislation for RE integration in policy design is inadequate, and direct monetary incentives must be incorporated to promote the widespread deployment of RE. It is therefore imperative that policymakers take into account the importance of monetary incentives in developing policies that encourage RE adoption [57]. Mostafaeipour et al. conducted a study to investigate the impact of incentive design on the cost and carbon emissions of electricity generation from RE sources. They found that with an efficient incentive design, the cost of electricity from RES can be reduced, while the carbon emissions can be minimized [58]. Cost and revenue generated with the installation of RE are critical to an incentive's success [59]. Similarly, the environmental awareness of the occupants of the households [60], [61] and the effect of the neighbourhood [62], [63] are also factors that may influence the adaptability of incentives. While all of these studies have highlighted the essential factors needed for the successful implementation of an incentive, they lack in providing a comprehensive framework for designing such an incentive [64].

Principal-agent theory is considered an effective tool for the design of an incentive, with both behavioural and financial components, and can be implemented by a government as the principal, with their choice of agents [65]. The approach can be used to provide a direct financial motivation to the agent to achieve specific performance targets, which can be observed and measured. This approach ensures that the interests of the principal and the agent are aligned, and the agent has a clear understanding of the rewards they will receive for achieving the targets set by the principal. Such an approach can be adapted to different situations and provides flexibility in designing incentives that are tailored to the specific needs of the principal and the agent. It has been widely used by businesses, governments, and non-profit organizations (see for example [66], [67], [68], [69], [70]).

Chen and Hong used the principal-agent theory to motivate developers to invest more in green buildings [66]. Zhao and Chen applied a principal-agent model to incentivize consumers to use green (eco-friendly) products [67]. Zhang et al. investigated the government reward-penalty mechanism between two competing producers and a recycler in a loop-locked supply chain with asymmetric knowledge [68]. Wang and Liu developed a government optimal incentive model by merging fairness preference theory with a principal-agent model to ensure that investors get the due share for their risk. They show that with excess revenue sharing, there is a high probability of the project's success [69]. Altenburg and Engelmeier applied principal-agent theory involving solar investors and the government and concluded that the correct design of government subsidies and their implementation are significant for promoting solar investment [70]. Chen and Song used principal-agent theory to find an optimal subsidy for the PV investors. The authors established that to achieve larger-scale deployment of photovoltaic (PV) and reduce subsidy costs, environmental policy makers must focus on improving investor preferences and reduce the impact of asymmetric information. In other words, creating a favorable investment climate and increasing transparency in information about PV projects will be key to achieving these goals [71]. Yu et al. used the principal-agent theory to find an optimal value of subsidy between the government and microgrid users for the energy storage. They concluded that an optimal strategy for the government is to provide tailored incentive to the microgrid users for energy storage [72]. Liang et al. use the principal-agent theory for the building sector energy efficiency retrofit (EER) and explain the agency problem that exists between the government and the building owners. The authors show that building owners will only invest in EER if there is a financial incentive for them to invest. Since all building owners have various characteristics, a customized policy for each building owner is presented [73], [74].

Thus, from surveying the literature, it can be seen that the principal-agent model has been applied in previous studies on several areas, such as project management, supply chain and green buildings. However, to the best of the authors' knowledge, no study has used principal-agent theory to analyse the decision-making behaviour of households in receipt of a high electricity subsidy or where there is no electricity charge for certain segments of society, such as the case of Qatar.

This manuscript overcomes the limitations of the studies in [31], [59], [73], and [74], by introducing both a carbon rebate and price incentive to the case of multi-storey households (i.e. villas). Table 1 presents the differences between this study and related studies.

The contributions of this study can be summarised as follows:

1) By making use of principal-agent theory, this study proposes a comprehensive framework to develop a renewable energy incentive for households to help reduce their electricity consumption from the national grid. This is implemented in Qatar's residential sector, where electricity is highly subsidized.
2) The proposed incentive combines both carbon price and carbon rebate components and uses different characteristics of a residential unit, such as area, number of occupants and annual electricity consumption, to develop an optimized and individualised incentive for each unit.
3) To determine the viability of the incentive, different scenarios are formulated based on (i) the level of risk averseness of the household and (ii) a varying level of electricity bill subsidization. An environmental and economic analysis is conducted for different residential units under various scenarios to demonstrate the effectiveness of the proposed incentive.
4) A financial analysis is conducted based on the 'surplus' natural gas made available through reduced domestic electricity consumption, that can either be exported directly in raw form or in the form of electricity based on the profitability of the two options.

III. METHODOLOGY

In this section, the proposed incentive framework is described and the model characteristics i.e., model agents, relationship between agents and variables are defined in the subsequent subsection. The optimization problem of the proposed incentive is defined in the last subsection. Our approach is partially motivated by the work in [73] and [74], where principal-agent theory was applied to the building sector energy efficiency retrofit. We extend their approach by proposing a framework for the residential sector comprising multi-storey households (villas) in Qatar, introducing new variables, i.e., carbon price and rebate incentive and solving the optimization problem using an extensive search (brute-force) algorithm. We also conduct an environmental and economic analysis specific to the context of Qatar (c.f. Table 1 highlighting the contributions of this work). This is followed by the methodology for the financial analysis, demonstrating the profitability of the incentive for the government. The data used is presented in the last subsection.

TABLE 1. Comparison of the model with similar studies.

Model Details	[31]	[57]	[58]	[59]	[71]	[73]	[74]	Proposed
Carbon price	✓	×	✓	×	×	×	×	✓
Carbon rebate	×	×	×	×	×	×	×	✓
Financial analysis for the households	×	✓	×	✓	×	×	×	✓
Energy saving analysis	✓	×	✓	✓	✓	×	×	✓
Emissions saving with policy implementation	✓	×	✓	×	×	×	×	✓
Environmental benefit share	×	×	×	×	✓	✓	✓	✓
Sensitivity analysis	✓	✓	×	×	✓	✓	✓	✓
Electricity bill (Highly Subsidized)	×	×	×	×	×	×	×	✓

A. PROPOSED INCENTIVE FRAMEWORK

The study proposes a framework for an efficient contract between the government and the households in the form of a renewable energy incentive; and uses a principal-agent theory approach to address the agency problem between the government, as the principal, and individual households, as the agents. The problem can be defined as what amount of incentive should be given by the government to maximize the household's efforts for RE? The optimal balance between emissions reduction and the corresponding benefits for the households should be identified to achieve this objective.

The principal (government) wishes to maximize the utility of the incentive by increasing the adoption of RE and associated environmental benefits, while the household's objective is to maximize their utility by maximizing their monetary benefit, making the objectives (and benefits) for the government and households conflicting. In addition, the government does not have information about the effort and decisions of the households, creating information asymmetry. This makes principal-agent theory suited to our problem. The principal-agent approach has two constraints: i) individual rationality, i.e., households should get benefits greater than their individual threshold, and ii) incentive compatibility, which states that the incentive provided to the households must persuade them to act in the principal's interest [25].

The proposed framework is divided into three sections: process, data and functions, as highlighted in different colours in Figure 4. The framework can be described as follows: the government, as the principal, proposes an incentive policy to the households by first offering the environmental benefit share to the households based on their efforts to reduce their energy consumption. Second, a carbon rebate is offered to households based on their energy reductions. Third, the government provides partial support for the installation costs of RE equipment; this will help counter the uncertainties felt by the households associated with RE. The households can adopt

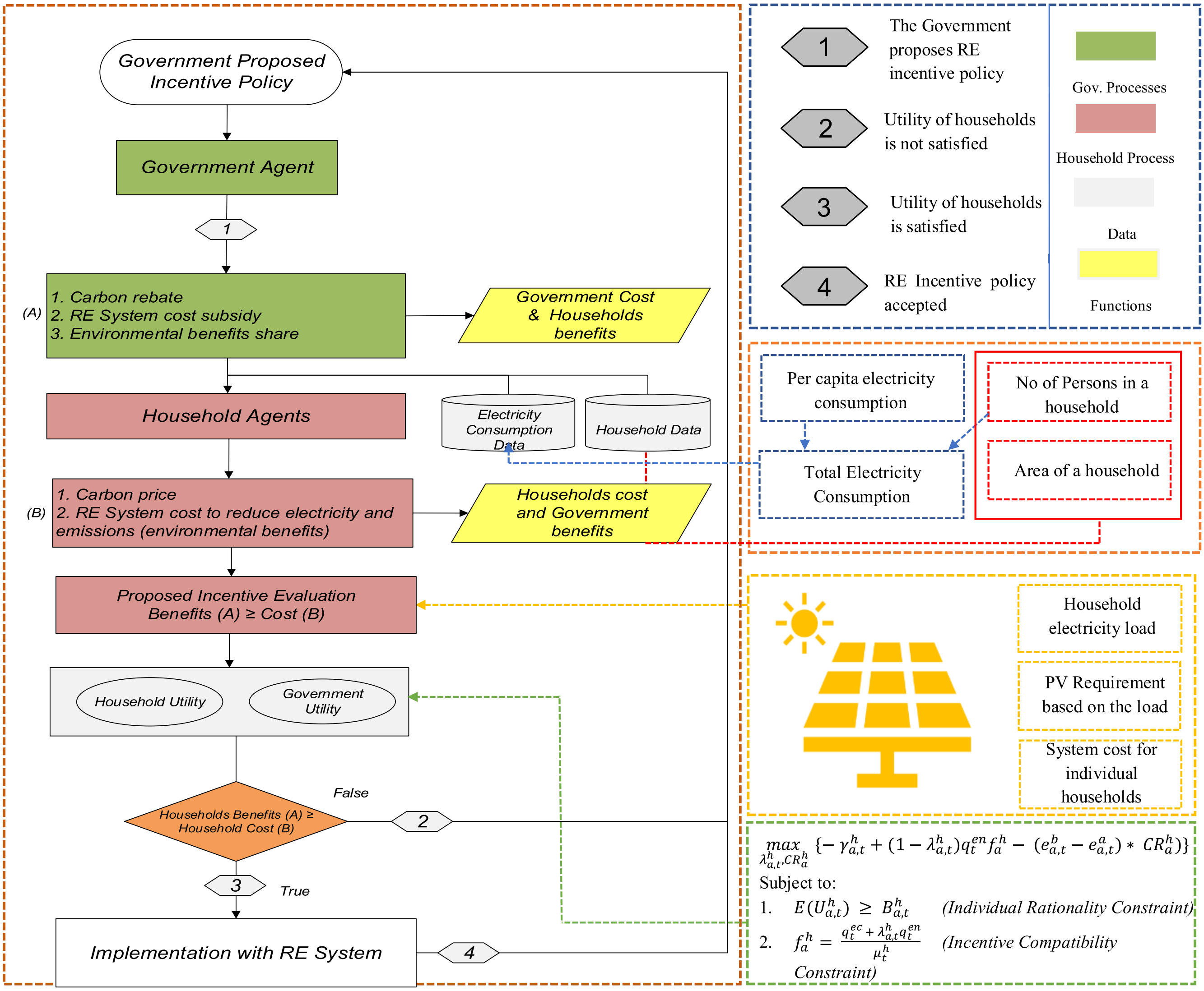

FIGURE 4. **The proposed framework for the incentive as a principal-agent problem between the government and the households where the government proposes an incentive for promoting the use of RE, and the households evaluate their cost and benefit before choosing to accept or reject the proposed incentive.**

or reject the policy based on the cost and benefits associated with it. The aim of providing an incentive is to increase the households' benefit so the agency problem's effect is minimized. If the total benefit for the households exceeds the costs, the policy will be accepted; else, the household will reject the policy. Policy benefits for the household are the financial incentive they receive from the government (and is thus a cost for the government). The cost for the households includes the installation of the RE system and the carbon price, which are both correlated to their overall electricity consumption.

B. MODEL DESCRIPTION

In order to determine the optimal value of the incentive, it is essential that the characteristics of the households are known. Considering each household as one single agent, the energy requirements for each unit will be different. Therefore, in the following subsections, first, the electricity load of the household is determined that will be utilized to calculate the size of the PV most suited to it. The size of the PV system has a direct link with the cost of the system as it will impact each household's economic benefit. In the subsequent subsection, a detailed description of model variables is stated.

1) LOAD AND PV GENERATION

The aim of the government in this study is to promote the use of RE (in this case, PV) and provide incentives to households based on the grid energy saved due to RE usage. It is necessary to estimate the size of the PV system required by individual households. For PV system sizing, the electricity load of each household L_P, [75], solar hours S_H [76], environmental factor E_P [77] and offset percentage B_o are needed. First, the

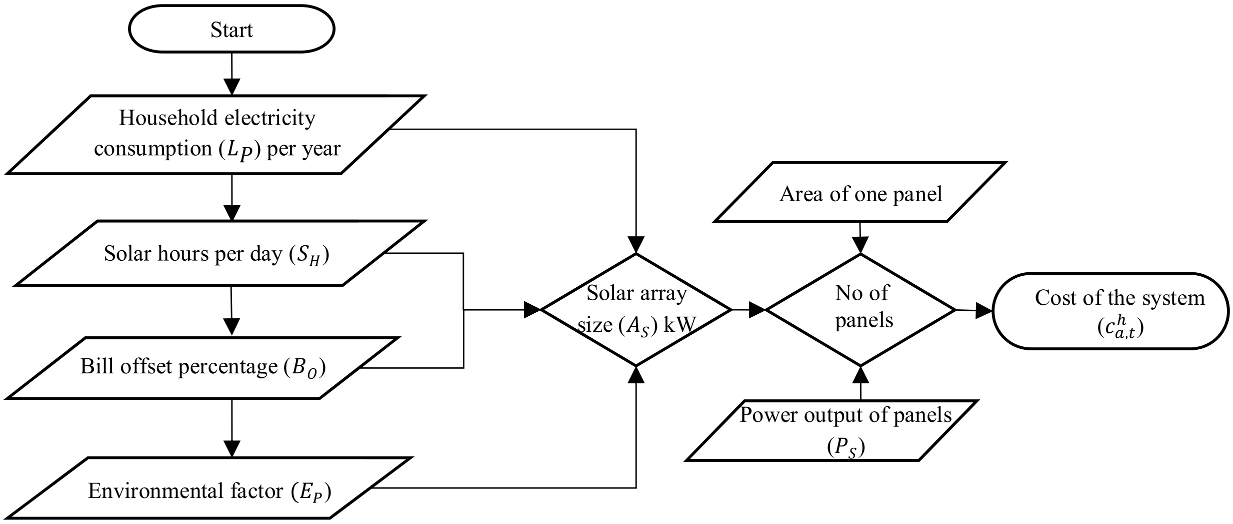

FIGURE 5. Optimal methodology for selecting the size of the RE system (Solar PV) based on the household's electricity requirements, which will be utilized to calculate the cost of the RE system (Solar PV).

solar array size A_S is calculated using Eq. (1), then the Power output of the solar array P_s is determined using Eq. (2) [77].

$$A_S = \frac{L_P}{365 * S_H} \tag{1}$$

$$P_S = A_S * \frac{B_o}{E_P} \tag{2}$$

Since each household has a different requirement based on its electricity consumption, an optimal system size that fulfils the need to offset 20% of the energy for every house is determined [78]. Figure 5 shows the steps of the adopted methodology to calculate the PV Power and, subsequently, the cost of the RE system.

2) CONSIDERED VARIABLES

The model has primary variables relating to households, government, and environment, as well as secondary variables introduced to aid in calculations. The first two relate to the characteristics of the agent and the principal, whereas the environmental variables depend on the external situation and cannot be changed by the agents.

The household variables are further divided into five categories: namely, economic benefit, utility, risk, threshold and cost variables. Households benefit, $B^h_{a,t}$ represents the economic benefit from RE adoption minus the cost of installing RE. The utility of the households is calculated using the economic benefit $B^h_{a,t}$ minus the risk premium. It represents the overall satisfaction the household experiences by investing in RE [79]. In the principal-agent problem, the risk preference ρ of the households is a critical variable. It represents the amount of risk each household is willing to take [80]. For this study, the government is assumed to be risk neutral while the household is risk-averse. The individual rationality constraint of the principal-agent problem is related to the threshold θ. In this study, we assume that the threshold of the household is zero ($\theta = 0$), indicating the point where the benefits and costs are equal. The cost of the RE system $c^h_{a,t}$, is the cost of solar PV considered in this study. This is derived using the total size of the system required. The cost of the RE system is also linked with the effort of the household. The more effort for RE system installation, the more cost they have to pay [81], [82]. The amount of effort a household makes to install RE is represented by f^h_a. It is an indirect cost for households. The effort is determined by the time, resources, and knowledge gained to understand the actual requirements of the household. The range for this variable is $0 - 1$, where zero represents no effort, while 1 represents 100% effort. The value of effort f^h_a will affect the cost of the RE system $c^h_{a,t}$ and subsequently, the economic benefit $B^h_{a,t}$.

There are two variables for the government in the proposed framework, i.e., the government utility $U^g_{a,t}$ and incentive $i^g_{a,t}$ provided by the government. These two variables are the most critical variable of the model as the objective of the model is to maximize government utility and provide the maximum incentive to the households. When a household reduces its energy consumption and adopts the incentive policy, government economic and social benefits will increase, thereby increasing government utility. To motivate the household to invest in renewable energy, the government has to offer an incentive represented by $i^g_{a,t}$.

The environmental variables in the model are the random variable x_t representing related (external) sources of uncertainty, the carbon price CP^h_a and the carbon rebate CR^h_a. The latter two both depend on the external factors; although the government sets carbon prices and rebates, the external factors influences the government's decision. In the proposed model, an optimal value for CR^h_a is needed to satisfy the constraints of the problem. x_t, represents the uncertainty, i.e., the risks associated with the adoption of the incentive. Several sources of uncertainty have been identified by the previous studies, such as energy price fluctuation, climate change effect, technological risk and uncertain income

[83], [84], [85]. Thus, x_t is assumed to follow a Gaussian distribution with mean 0 and variance σ. In our proposed framework, we also make the assumption that there is no charge for electricity consumption on a selected group of households. This is in line with the local laws in Qatar where certain households are exempt from paying electricity bills [24]. A carbon price CP^h_a is introduced in the model to control the unrestricted usage of electricity to motivate households to reduce electricity consumption. The government charges an amount based on per kWh usage of electricity. Similarly, an optimal carbon rebate CR^h_a amount is provided to each household based on the difference in electricity consumption in two succeeding years.

Some secondary variables are introduced in the model to link the government, household, and environmental variables. With energy savings by the household, the government will have environmental and social benefits such as pollution reduction [86], lower health budget [87] and lower energy infrastructure investment. $\lambda^h_{a,t}$ represents the share of environmental benefits distributed by the government to the households; μ^h_t is coefficient of the RE system cost $c^h_{a,t}$.

It is a conversion coefficient from households' effort to households' cost. Since the marginal cost increases typically, it is defined as a quadratic function, $c^h_{a,t} = \frac{1}{2}\mu^h_t f^{h2}_a$. The use of RE brings economic benefits for households and environmental benefits for the government. Economic benefit τ^{ec}_t represents the household's benefit ($B^h_{a,t} = \tau^{ec}_t + i^g_{a,t} + c^h_{a,t}$). The environmental benefit τ^{en}_t is a connecting variable for the government's utility $U^g_{a,t}.q^{ec}_t$ is a connecting variable for τ^{ec}_t & q^{en}_t is an intermediate variable for τ^{en}_t, where q^{ec}_t &q^{en}_t depend on technology development and household condition such as Heating, ventilation, and air conditioning (HVAC) systems, lighting systems and windows.

3) THE OPTIMIZATION PROBLEM

The formulation of an optimal model for maximizing the government's utility is done through three steps. The first follows the derivation approach in [73] and [74] to obtain an optimal equation for the incentive policy. This is used to calculate the households' utility from the incentive, and finally, the input from the households' incentive and utility equation is used to find the optimal government utility. The goal of the government is to maximize its own utility by designing an incentive policy that induces households to take actions that benefit the government. The objective function of the principal-agent problem is given in Eq. (3). It has two decision variables: $\lambda^h_{a,t}$, which represents the weight of the household's utility in the government's objective function, and CR^h_a, which represents the incentive payment to the household. The superscript h denotes that the variable is specific to household h, and the subscript a, t denotes that the variable is specific to action a at time t. The expected government utility $E(U^g_{a,t})$ consists of the subsidy for solar PV $\gamma^h_{a,t}$, environmental benefit share, $(1 - \lambda^h_{a,t})$, effort, f^h_a and q^{en}_t which represents the environmental benefit. CR^h_a is the carbon rebate received, which is dependent on the difference of electricity of usage: $e^b_{a,t} - e^a_{a,t}$.The detailed derivation can be found in Appendix A.

TABLE 2. Pseudo code for the brute force algorithm.

```
Initialize
Input:
No of households, Per capita electricity consumption, Number of
household members, Economic benefit, Environmental benefit
Risk preference of households, Cost of the RE system, Government
subsidy, Variance of uncertainty, Area of the house, Threshold of the
households

Output:
Optimal environmental benefit share ($\lambda^h_{a,t}$) and carbon rebate ($CR^h_a$)

//Determine optimal environmental benefit share and carbon rebate
coefficient for all households
//Given the constraints

for $\lambda^h_{a,t}$ and $CR^h_a$:
$f^h_a = \frac{q^{ec}_t + \lambda^h_{a,t} q^{en}_t}{b^h_t}$
 if:
  $U^g_{a,t}$ (Government utility) $= max\ (U^g_{a,t})$ and
  $U^h_{a,t}$ (Household utility) $\geq B^h_{a,t}$
 else:
   update $\lambda^h_{a,t}$ and $CR^h_a$
return $\lambda^h_{a,t}$ and $CR^h_a$
```

$$max_{\lambda^h_{a,t},CR^h_a} E(U^g_{a,t}) = max_{\lambda^h_{a,t},CR^h_a}\{-\gamma^h_{a,t} + (1 - \lambda^h_{a,t})q^{en}_t f^h_a - (e^b_{a,t} - e^a_{a,t}) * CR^h_a)\} \tag{3}$$

Subject to;

$$E(U^h_{a,t}) \geq B^h_{a,t} \tag{4}$$

$$f^h_a = \frac{q^{ec}_t + \lambda^h_{a,t} q^{en}_t}{\mu^h_t} \tag{5}$$

where Eq. (4) ensures individual rationality by requiring that all participating agents receive non-negative utility. This means that the households will only agree to participate if the scheme provides them with some benefit. By ensuring individual rationality, the government can design an incentive that is attractive to the households and induces them to participate. Eq. (5) ensures incentive compatibility by requiring that participating households act according to the government's desire. This means that the household's actions are aligned with the government's interests, which reduces the risk of the household engaging in behavior that is harmful to the government's objectives. By ensuring incentive compatibility, the government can design an incentive that induces the household to act in a way that maximizes the government's utility [74]. The optimization problem Eq. (3) can be solved using an extensive search (brute-force) algorithm, as shown in Table 2. The algorithm is used to determine the optimal value of the environmental benefit share to households $\lambda^h_{a,t}$ and Carbon rebate CR^h_a, given the constraints above. Although extensive

TABLE 3. Factors considered for the financial analysis of the proposed incentive.

Cost of the PV panel [78]	2 kW	20,000 QAR	O&M cost [78]	30 QAR/kW/year
	5 kW	50,000 QAR	Discount rate [88]	4.50%
	8 kW	80,000 QAR	Inflation rate [89]	5%
	12 kW	120,000 QAR	Module degradation [90]	0.5%/Year
	15 kW	150,000 QAR		

search algorithms are usually computationally expensive, the number of parameters in our study is limited, making its application feasible and computationally efficient in our context.

4) ECONOMIC APPRAISAL OF THE INCENTIVE FOR HOUSEHOLDS

Household adoption of the policy is primarily driven by its monetary benefits. Hence, to encourage households to invest in RE energy, it is essential to demonstrate the financial analysis of the proposed incentive for each household based on the optimal size of the system chosen. For this, several factors are considered, as shown in Table 3. Five different sizes of RE systems (Solar PV) are considered, and the feasibility of the RE investment is conducted for each system, with various economic indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), and Payback for the households. To assess the value of an investment, two main indicators are normally calculated. The Net Present Value (NPV) and the Internal Rate Return (IRR). Households will only invest if the NPV is positive. To account for the time value of money, investors also typically assess the Discounted Cash Flows (DCF), which estimates an investment's value using its expected future cash flows. Moreover, households expect an early return on their investment, thus, to determine the time period taken by the investment to generate positive cash-flows, the payback period is calculated. The payback period is classified into two types: Simple and discounted. A simple payback period shows the number of years an investment takes to reach the breakeven point without including the discount rate, while for the discounted payback period, the future worth of the cash flow is estimated using the discount rate, and then the payback period is calculated. The formulae for the NPV and IRR are given by Eq. (6) and III-B5.

$$\mathrm{NPV} = \sum_{i=1}^{T} \frac{(CR_a^h + \lambda_{a,t}^h q_t^{en} f_a^h - CP_a^h)_i}{(1-d)^i} + \gamma_{a,t}^h - \varphi^h \quad (6)$$

$$0 = \sum_{i=1}^{T} \frac{(CR_a^h + \lambda_{a,t}^h q_t^{en} f_a^h - CP_a^h)_i}{(1-IRR)^i} + \gamma_{a,t}^h - \varphi^h \quad (7)$$

5) FINANCIAL VALUATION OF SURPLUS ENERGY EXPORTS

Electricity production in Qatar is roughly 93% from natural gas; saving natural gas or electricity using the proposed policy will be useful in generating additional revenue from exports (or can be left unused to prolong the lifetime of the reserves [91]). There is currently a shortage of energy globally, specifically in Europe. Since Qatar is the biggest NG exporter, it has an opportunity to replace the current gap in the market [92]. Moreover, the availability of the GCC grid interconnectivity via GCCIA provides an additional option to directly export the surplus (saved) electricity to neighbouring GCC countries [93].

The profitability of exporting surplus gas or electricity arising from implementing the proposed incentive policy can be calculated as follows. Gas Saved is computed by taking the product of total energy saved and gas to electricity conversion factor represented by Eq. (8). A MMBTU of gas can produce 97.65 kWh of electricity considering the combined cycle plant efficiency of 33% or 0.010240 MMBTU of gas is needed to produce 1 kWh [75], [94]. The analysis considers varying gas prices (current price = 27.92 QAR/MMBTU) [95] to examine the effect of gas prices on financial savings. Financial Savings from gas export is calculated using Eq. (9) and Eq. (10) is used to calculate the financial savings from electricity exports. To calculate the financial savings from electricity, the average price for electricity selling in the GCC region is taken from the United Nations (UN) Comtrade database, which is found to be \$0.059/kWh (QAR 0.21476/kWh) [96].

$$\sum_{i=1}^{5} GS_i = \sum_{i=1}^{5} TES_i * GkWh \quad (8)$$

$$\sum_{i=1}^{5} FS_i^{gx} = \sum_{i=1}^{5} GS_i * GP \quad (9)$$

$$\sum_{i=1}^{5} FS_i^{ex} = \sum_{i=1}^{5} TES_i * EP \quad (10)$$

where, GS is Gas saved, TES is Total electricity saved, $GKwh$ is Gas used to produce 1kWh, GP and EP is Gas selling price/MMBTU and Electricity selling price/kWh, FS_i^{gx} is Financial savings from gas export, FS_i^{ex} is Financial savings from electricity exports.

The net gain/loss for the government is calculated using Eq. (11). where PC^g is the net government incentive policy cost, FS^{gx} is financial savings from selling surplus gas, and NGL^{gx} is net government gain/loss. The superscript gs represents the gas exports. Eq. (12) shows net government gain/loss in the case of electricity export where FS^{ex} is financial savings from selling additional electricity, and NGL^{ex} is net government gain/loss. The superscript ex represents the

TABLE 4. Data configuration.

Symbol	Unit	Initial value	Reference
N	NA	45,545	[99]
ec^h	kWh	11,840	[75]
m^h	NA	2 - 14	[99]
τ_t^{ec}	NA	0 - 420	[74]
τ_t^{en}	NA	0 - 111	[74]
$c_{a,t}^h$	QAR	20,000- 150,000	[78]
$\gamma_{a,t}^h$	QAR	2,000 – 15,000	-
ρ	NA	3, 6, 9	[100]
σ	NA	3	[74]
A^h	m^2	220 - 420	[78], [101], [102]
θ	%	0	-

TABLE 5. Optimal parameters for the base case.

Parameter	Value
No of households	45545
Optimal environmental benefit share	0.65
Total households' energy usage before the policy	4253 GWh
Total households' energy usage after the policy	3757 GWh
Total energy Save	495 GWh
Energy reduction %	11.65%
Emissions reduction	0.203 $MTCO_2e$
Carbon price revenue	0.121 B QAR
Net policy cost	(0.838) B QAR

electricity exports.

$$\sum_{i=1}^{5} NGL_i^{gx} = \sum_{i=1}^{5} PC_i - \sum_{i=1}^{5} FS_i^{gx} \tag{11}$$

$$\sum_{i=1}^{5} NGL_i^{ex} = \sum_{i=1}^{5} PC_i - \sum_{i=1}^{5} FS_i^{ex} \tag{12}$$

6) DATA AND EXPERIMENTAL SETUP

In this section, the proposed framework in Section a is applied to the household sector in Qatar. This study has considered only multi-storey houses (villas) in Qatar since these usually cover a larger area and have more occupants, hence have higher energy consumption [97], [98]. For the model input data, the distribution data of the total number of villas and household members m^h is taken from the 2020 census [99]. Per capita electricity consumption (ec^h) in Qatar is taken from Qatar's sole utility provider, Kahramaa's annual report 2020 [75]. The environmental benefit is subjective but can be quantified through different approaches. We use Liang et al. methodology to approximate the value of the five different RE systems used in our study [74]. The cost of the RE system is also an essential parameter for model input, the cost of the various RE systems is taken from [78]. Government subsidy, $\gamma_{a,t}^h$ is set to be the 10% cost of the RE system provided by the government. Risk averseness of the households for the current study is taken as 3,6, and 9 for the low, moderate and high risk aversion cases, respectively [100]. We assume that the variance σ for the Normally distributed uncertainty is equal to 3 [74]. Several sources of data are used to estimate the number of households [78], [101], [102]. The area of the households is also a critical parameter for the model as it links with the economic benefit for each household.

TABLE 6. Scenarios based on the risk aversion of the households.

Simulation results	Scenario 1 Low-risk aversion	Scenario 2 Moderate-risk aversion	Scenario 3 High-risk aversion
Environmental benefits			
Emissions reduction in 5 years (Tons of CO_2)	203,710	213,359	219,646
Emissions percentage reduction (%)	6.014 %	6.299 %	6.485 %
Total energy saved (GWh)	495	519	534
Energy percentage reduction (%)	11.65%	12.20%	12.56%
Financial benefits			
Total government incentive (B QAR)	(0.96)	(1.02)	(1.05)
Carbon price revenue (B QAR)	0.122	0.121	0.120
Policy cost (B QAR)	(0.838)	(0.898)	(0.928)

Simulation results	Scenario 4 Low-risk aversion 25% bill charged	Scenario 5 Low-risk aversion 50% bill charged	Scenario 6 Low-risk aversion 75% bill charged	Scenario 7 Low-risk aversion 100% bill charged
Environmental benefits				
Emissions reduction in 5 years	203,710 Tons of CO_2			
Emissions percentage reduction	6.014 %			
Total energy saved	495 GWh			
Energy percentage reduction	11.65%			
Financial benefits				
Total government incentive (B QAR)	(0.96)			
Carbon price revenue (B QAR)	0.465	0.808	1.152	1.495
Policy cost (B QAR)	(0.495)	(0.152)	0.192	0.535

The end user of the designed incentive framework is the government, who evaluates the cost and benefit linked with the RE incentive implementation and can generate suggestions based on the different characteristics of the households.

The variables and model parameters used in this study are given in Table 4. This study is simulated for five years (2022 -2027) to estimate the potential energy reduction; subsequently, the drop in electricity consumption from the grid and emissions from the household sector are reported. The proposed framework is implemented using Python 3.7 using a workstation with a Windows 10 64-bit operation system, Intel Core i5-10210U, 8GB RAM and 500 GB hard disk.

IV. RESULTS AND DISCUSSION

In this section, we address the question of what the environmental benefit would be from implementing the proposed

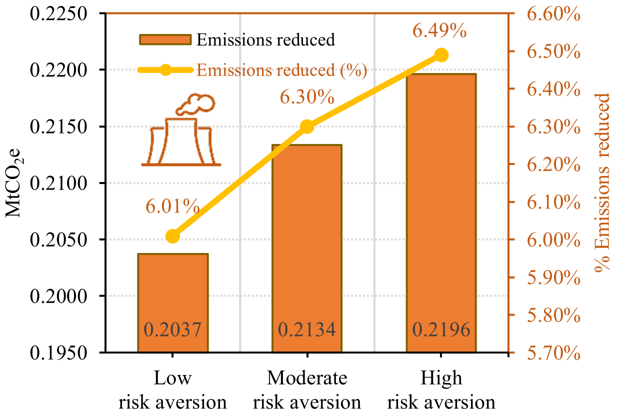

FIGURE 6. Total emissions reduced with the implementation of the proposed incentive given different degrees of household risk aversion. The respective percentage of emissions reduced is presented in relation to the total emissions in the year before implementing the program. A higher risk aversion results in higher emissions reduction since the incentive design accounts for risk aversion by offering higher rebates.

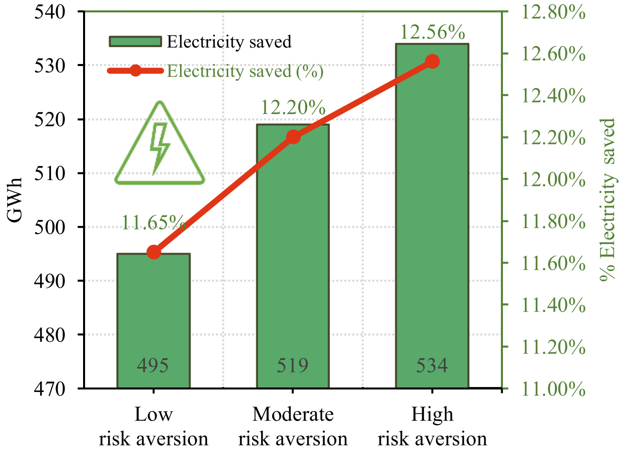

FIGURE 7. Total electricity saved in GWh given different degrees of household risk aversion and the corresponding percentage of electricity saved relative to the year before implementing the program. A higher risk aversion results in higher electricity reduction.

TABLE 7. Payback period for the various re system sizes.

PV panel size	2 kW	5 kW	8 kW	12 kW	15 kW
Payback period (years)	3.6	3.7	3.8	3.8	3.9
Discounted payback period (years)	4.0	4.1	4.3	4.3	4.4

incentive and then present the financial benefits for the households from adopting the proposed framework. We follow this with an analysis of the profitability of exports of gas or electricity arising from the 'surplus' energy resources obtained from reduced domestic consumption. We draw comparisons based on market prices of gas and electricity.

1) ENVIRONMENTAL BENEFIT FOR THE GOVERNMENT

Risk aversion of the households is considered an important factor in their decision-making. Here, a baseline case is created with a lower level of household risk aversion to examine the proposed incentive policy results. Given the inputs, we obtain an optimal value of 65% for the environmental benefit share ($\lambda_{a,t}^{h}$) over the five-year simulation period for the baseline case and an optimal carbon rebate (CR_a^h) of 2 QAR/ kWh. These two values ensure maximum government utility while satisfying positive utility for all households. Results shown in Table 5 show that with the proposed policy, 495 GWh of energy usage, equivalent to 11.65% from the grid, will be reduced over five years. It will also offset 0.203 MTCO$_2$e of emissions. The total amount of carbon price revenue generated is 0.121 billion Qatari riyals. The net policy implementation cost for the government is 0.839 billion QAR, including the initial support provided to the households for RE system installation and the carbon rebate provided based on the consumption reduction. A summary of the base case results is shown in Table 5.

In addition to the base case where the household's risk aversion is low, a comparative analysis is conducted for varying degrees of risk aversion. The environmental benefit share shows the risk sharing between the government and households. If the households' risk aversion is extremely higher ($\rho \rightarrow \infty$), then the best environmental benefit share is zero ($\lambda_{a,t}^{h} = 0$). It indicates that households are unwilling to take the incentives and will not make efforts for RE installation. Hence, different scenarios are developed with varying risk aversion to analyse the five years' results in Table 6.

With increasing risk aversion, households expect higher incentives from the government as they are unwilling to adopt the proposed policy. In such a case, the households' confidence will increase with higher incentives, and more effort would be put into energy reduction due to higher returns. Since electricity in scenarios 1, 2, and 3 is still heavily subsidized, we extend our scenarios by reducing the subsidy for the high-energy consumers in scenarios 4, 5, 6 and 7. Those consumers are charged an electricity price of 0.26 QAR/kWh if their per capita consumption after the policy has not changed [103]. Households having per capita consumption higher than a defined threshold is penalized. Total consumption over the five years is determined for such households, and 25%,50%, 75% and 100% electricity bills are charged, represented by scenarios 4, 5, 6 and 7, respectively.

Table 6 demonstrates the results of the comparative analysis for lower (base case), moderate and higher risk aversion. Furthermore, with electricity bills charged to higher electricity consumers, the government can expect positive cash flows with 75% and 100% bill charging, and government costs for the policy will become zero. Emissions reductions and energy saving over the five years with different degrees of risk are shown in Figure 6 and Figure 7, respectively.

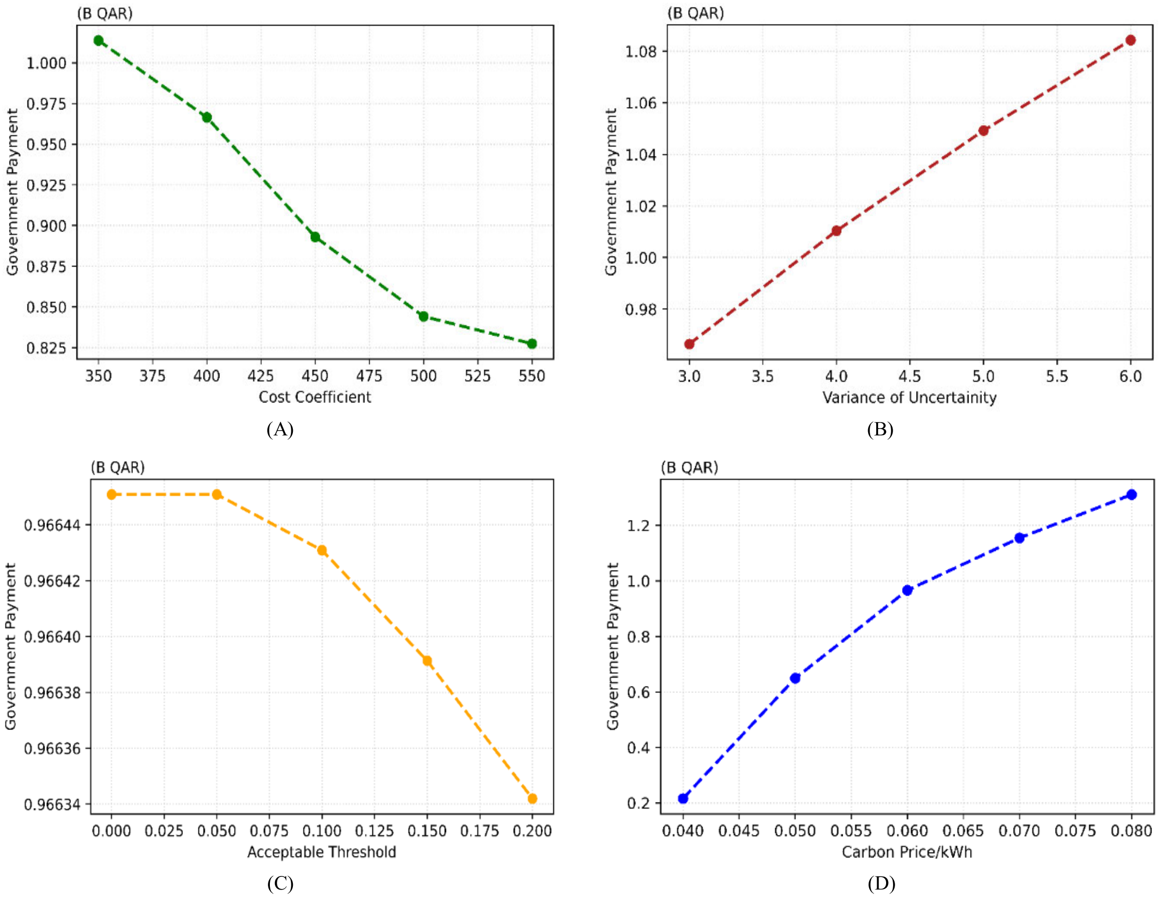

FIGURE 8. **(A) Effect of cost coefficient on government incentive, (B) Effect of variance of uncertainty on government incentive, (C) Effect of households' threshold on government incentive and (D) Effect of the carbon price on government incentive.**

TABLE 8. **Electricity and Natural gas saved with the proposed model and revenue generated with saved gas and electricity export.**

TES (kWh)	GS (MMBTU)	GP = 24 QAR/MMBTU	GP = 27.92 QAR/MMBTU	GP = 32 QAR/MMBTU	GP = 36 QAR/MMBTU	EP = 0.258 QAR/kWh
			FS^{gx} (B QAR)			FS^{ex}(B QAR)
495,000,000	5,075,527	0.121	0.141	0.162	0.182	0.126
519,000,000	5,315,935	0.127	0.148	0.170	0.191	0.132
534,000,000	5,472,592	0.131	0.152	0.175	0.197	0.136

2) SENSITIVITY ANALYSIS

In this section, a sensitivity analysis is performed on the main model parameters to see the effect of varying these parameters on the incentive. This will help identify the critical parameters for the incentive design, from the cost coefficient of RE, energy price, level of uncertainty, and threshold of households. The cost coefficient is linked with the effort of the households. When the cost coefficient is higher, household efforts will decrease as the cost of adopting the policy is higher, and hence the government incentive will decrease because there will be lesser participation, leading to less energy reduction. Therefore, the government's spending will reduce, as shown in Figure 8(A). To control the cost coefficient, the government should try to reduce the cost of the RE system by providing subsidies. This will help in reducing the sensitivity of the cost factor. On the other hand, the government incentive increases when the level of randomness is higher as the possibility of a successful RE adoption policy decreases, as shown in Figure 8(B). Higher randomness can be associated with changing environmental conditions, adopted technology and other unforeseen circumstances. More incentives should be provided to mitigate the effects of the higher randomness in the RE adoption policy. Higher randomness leads to higher payments to households which will increase the cost of the policy implementation. To control this factor, government policies should be clear and certain so that no additional incentives are required to motivate the households.

When the household's income expectation is higher than their investment, the effort of the household will decrease.

TABLE 9. Net expense for incentive implementation after additional gas or electricity export.

Scenario	TES (kWh)	GP = 24 QAR/MMBTU	GP = 27.92 QAR/MMBTU	GP = 32 QAR/MMBTU	GP = 36 QAR/MMBTU	EP = 0.258 QAR/kWh
		NGL^{gx} (B QAR)				NGL^{ex} (B QR)
Scenario 1	495,000,000	(0.717)	(0.697)	(0.676)	(0.656)	(0.732)
Scenario 2	519,000,000	(0.771)	(0.750)	(0.728)	(0.707)	(0.787)
Scenario 3	534,000,000	(0.797)	(0.776)	(0.753)	(0.731)	(0.813)
Scenario 4 (25% charge)	495,000,000	(0.374)	(0.354)	(0.333)	(0.313)	(0.389)
Scenario 5 (50% charge)		(0.031)	(0.011)	0.010	0.030	(0.046)
Scenario 6 (75% charge)		0.313	0.333	0.354	0.374	0.298
Scenario 7 (100% charge)		0.656	0.676	0.697	0.717	0.641

* Values in parentheses () represent negative values

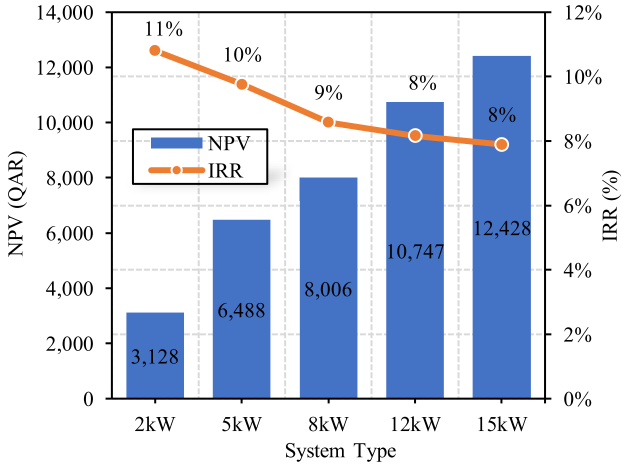

FIGURE 9. NPV and IRR for households with various PV system sizes.

Some households will prefer not to participate in the incentive since their expectation from the policy is higher, and they continue using energy in the same way. Hence as shown in Figure 8(C), a higher threshold leads to less energy reduction, and thus, the incentive provided by the government will be lower. Threshold values depend on the income of the households. Households with lower incomes prefer to benefit more from the incentive policy and expect an additional payment. Similarly, if a household's total income is comparatively higher, additional benefit from the policy will not affect their participation. On the other hand, the government incentives will increase when the carbon price increases in the proposed approach, as shown in Figure 8(D). q_t^{ec} the coefficient of the economic benefit of households is directly proportional to the area of the household and the carbon price. The saving potential will be higher with a larger house area and higher energy prices. Therefore, more households are willing to participate in the policy to reduce their electricity and are likely to put additional effort into the RE system when the carbon cost is higher.

3) FINANCIAL BENEFITS FOR THE HOUSEHOLDS

The financial viability of the five types of renewable energy systems used in the model was evaluated using net present value (NPV) and internal rate of return (IRR). As shown in Figure 9, the results indicate that all five systems generate a positive NPV and good IRR. This is an encouraging finding as it suggests that investing in renewable energy is a financially sound decision for households.

Additionally, according to an earlier study, the average payback period of a residential solar installation globally is around 11.5 years, subject to incentives provided [104]. However, our proposed model's average payback period is only four years. This indicates that the carbon price and rebate policy implementation proposed for five years will be sufficient, as households will recoup their investment in a relatively short period and will be incentivized to reduce their consumption.

Moreover, it is essential to note that solar PV systems typically have an operational life of 25 years on average [105], which means that households will continue to benefit from the installation for many years.

Table 7 provides a summary of the economic analysis conducted for the five types of renewable energy systems, and it is evident that all of the proposed systems generate a positive NPV and an average IRR of 9%, as shown in Figure 9. This is considerably higher than the average IRR for household solar projects reported in a previous study [90]. The high returns resulting from the carbon rebate provide a strong motivator for households to adopt renewable energy systems.

Overall, the economic analysis demonstrates that investing in renewable energy systems is a financially feasible and sustainable option for households, and the proposed carbon price and rebate policy can play a crucial role in incentivizing their adoption.

4) POLICY INFLUENCE ON QATAR'S ENERGY EXPORTS

Since the government is providing incentives using its resources, estimating the expense for the policy implementation is necessary. The methodology for calculating the gas and electricity savings described in Section 0 is used to calculate the financial savings as given in Table 8. The net expense for incentive implementation is shown in Table 9 with different scenarios, considering varying gas and electricity prices. With the implementation of the policy there are two advantages. A significant amount of emissions can be reduced, and thus gas export can also increase. The presence of the GCCIA is also an advantage for all GCC countries to fulfil the demand in high peak periods in their neighbouring countries. Electricity saved due to the incentives, can be directly exported to the GCCIA grid-connected countries. An electricity buyer can be chosen where the profitability of this transaction is maximised [93]. Although net monetary benefit for the government might not be positive in all the scenarios, emissions reduction in all scenarios will bring environmental benefit for the government and the country in general.

Based on the various scenarios shown in Table 9 in scenarios 1,2,3, and 4, with gas and electricity selling, the government has to provide the incentive amount from their budget. In scenario 5, where 50% of electricity billed is charged, and when the gas price is 32 QR/MMBTU or 36 QR/MMBTU, there is a net positive monetary benefit for the government in addition to environmental benefits. The incentive provided by the government is totally recovered by charging 50% of the electricity bill and selling additional energy saved. Similarly, for scenarios 6 and 7, where 75% and 100% billed are charged, respectively, there is no incentive policy cost for the government to implement.

The government's objective in this study is to maximize the utility of the incentive and not to make a profit from the policy, it is desirable to provide maximum benefit to the households considering the amount of liquidity the government is willing to pour into the incentive. Financially weak governments cannot provide a generous monetary benefit to their nationals, in which case a viable policy for them would be to put a maximum charge on the consumers having higher energy usage. However, in the case of Qatar, where the government is financially strong, the decision to select the amount of spending for the incentive policy is relatively not difficult. The higher the spending from the government, the higher the benefits a household will receive that aid in reducing the grid electricity consumption and increase the reliance on renewable energy.

V. CONCLUSION AND POLICY IMPLICATIONS

The residential sector in Qatar heavily relies on subsidised electricity, leading to high consumption of fossil fuel generated electricity. This study proposed a general and flexible framework for incentivising the reduction of grid electricity from Qatar's residential sector. Using principal-agent theory, the proposed framework aimed to maximise the utility of the incentive by providing monetary benefits to households based on their characteristics. Scenarios were created based on different levels of risk aversion and electricity bill subsidization. A sensitivity analysis was performed to examine the effect of varying model parameters on the performance of the policy. The baseline results revealed that with an efficient incentive design, a household's overall electricity consumption is reduced by 495 GWh, decreasing emissions by 203,710 tons of CO_2e over a period of five years. The cost of the policy for the government is 0.838 billion Qatari riyals, with an average payback period and IRR for the households of four years and 9.2%, respectively. Results demonstrate that uncertainty in the proposed policy significantly impacts the incentive offered to the households.

Since a reduction in domestic electricity consumption would result in surplus energy that can either be exported as natural gas or as electricity (via, e.g. Gulf Cooperation Council Interconnection Authority (GCCIA) grid), we evaluated the net cost of the government incentive policy by exporting the saved gas and electricity. Naturally, a greater amount of energy saved leads to earnings from these exports.

The results of this study can be used to inform policymakers in the State of Qatar to implement a targeted incentive policy for Qatar's residential sector. Indeed, a significant amount of capital currently used to provide heavily subsidised electricity for the residential sector could be transferred to renewable energy incentive programs. The household agents in this study were considered to behave rationally towards the policy, i.e., a household will take part in reducing their energy consumption if they have guaranteed benefit from the incentive. However, some households may choose not to participate due to cognitive bias. A future study can integrate such irrational behaviour into the framework to improve its feasibility and practical implementation. This would need to include data collection through surveys, interviews and focus groups to measure the willingness of household occupants to participate in such incentive programs and better understand the reasons driving irrational behaviour in this context. A more realistic evaluation of the proposed incentive policy can be performed with access to more detailed data on the occupants of individual households. This will also allow the extension of the framework to include factors such as the ages of occupants, their employment status and education level. A pilot study would need to be conducted on a group of households (could be opt-in) to detect issues and risks that can only be identified through real-world implementation.

APPENDIX A

A. OPTIMAL DECISION FOR INCENTIVE POLICY

In a household, electricity consumption depends on the number of household members (m^h) and electricity consumed by a household's members in a year (ec^h); hence total energy consumed (TE) by all members of a household is calculated using Eq. (13):

$$TE = ec^h * m^h \tag{13}$$

The value of the economic benefit π_t^{ec} is derived using the effort of the households $q_t^{ec} f_a^h$ and the uncertainty γ_t. k_t^{ec} is directly proportional to the household's area and the energy carbon price. Eq. (14) represents the value of π_t^{ec}:

$$\tau_t^{ec} = q_t^{ec} f_a^h + \gamma_t \tag{14}$$

Environmental benefit for the government is also dependent on the effort $q_t^{en} f_a^h$ and a random variable representing the external sources of uncertainty θ_t. Eq. (15) represents the value π^{en}_t:

$$\tau^{en}_t = q^{en}_t f^h_a + \gamma_t \tag{15}$$

The households will only make an effort f^h_a if there is a financial benefit for them in adopting renewable energy. The government provides partial support for the investment cost of the PV Panels ($\gamma^h_{a,t}$). Additionally, the government share the τ^{en}_t with the households, which is represented by the $\lambda^h_{a,t}$. One of the distinctive factors of this study is the CR^h_a provided to households based on the amount of electricity they reduced. Eq. V-B gives the value of the incentive, where $e^b_{a,t} - e^a_{a,t}$ is the difference between consumption in two consecutive years.

$$i^g_{a,t} = \gamma^h_{a,t} + \lambda^h_{a,t}\tau^{en}_t + (e^b_{a,t} - e^a_{a,t}) * CR^h_a \tag{16}$$

B. OPTIMAL DECISION FOR THE HOUSEHOLDS

The household net benefit $B^h_{a,t}$ is defined as the economic benefit τ^{ec}_t, an incentive that they receive from the government $i^g_{a,t}$ minus the cost of the PV Panels installation on their premises $c^h_{a,t}$ and the carbon price that they pay CP^h_a. If a household completely shifts their electricity usage to RE ($e^a_{a,t} = 0$), there will be no carbon price. Thus, a household has an opportunity to maximize their benefit by reducing the electricity usage from the grid. The net benefit $B^h_{a,t}$ for the households is given by Eq. (17).

$$B^h_{a,t} = \tau^{en}_t + i^g_{a,t} - c^h_{a,t} - (e^a_{a,t} * CP^h_a) \tag{17}$$

where $c^h_{a,t}$ is the cost for the RE system defined by Eq. (18):

$$c^h_{a,t} = \frac{1}{2}\mu^h_t f^{h2}_a \tag{18}$$

As discussed in the earlier section, it is assumed that households considered for this study are risk-averse. The utility function of the households is given by Eq. (19)

$$U^h_{a,t} = -e^{\rho B^h_{a,t}}, \rho = -\frac{U^{h\,\prime\prime}_{a,t}}{U^{h\prime}_{a,t}} \tag{19}$$

where ρ is the coefficient of absolute risk aversion. Risk aversion is critical in understanding the behaviour of the households for RE adoption [106]. RE investments are considered risky; this perception acts as a barrier to investments and reduces the number of individuals willing to participate [80]. Risk aversion of households is based on several factors, such as electricity price risk, technical risk and financial risk [107]. The higher value of ρ, the higher the risk-averse household, i.e., less willing to take part in the scheme/invest in RE. The certainty equivalent of the households is the expectation of income minus the risk premium, $\frac{1}{2}\rho\lambda^{h2}_{a,t}\sigma^2$ [108]. The expected utility of the households is given by Eq. (20)

$$\begin{aligned} E(U^h_{a,t}) &= E(B^h_{a,t}) - \frac{1}{2}\rho\lambda^{h2}_{a,t}\sigma^2 \\ E(U^h_{a,t}) &= q^{ec}_t f^h_a + \gamma^h_{a,t} + \lambda^h_{a,t} q^{en}_t f^h_a + (e^b_{a,t} - e^a_{a,t}) * CR^h_a \\ &\quad - \frac{1}{2}\mu^h_t f^{h2}_a - (e^a_{a,t} * CP^h_a) - \frac{1}{2}\rho\lambda^{h2}_{a,t}\sigma^2 \end{aligned} \tag{20}$$

The objective of the households is to maximize their utility after implementing the RE system, $\frac{\partial \mathrm{E}(U^h_{a,t})}{\partial f^h_a} = 0$.

$$f^h_a = \frac{q^{ec}_t + \lambda^h_{a,t} q^{en}_t}{\mu^h_t} \tag{21}$$

C. OPTIMAL DECISION FOR THE GOVERNMENT

The government agent is assumed to be risk neutral; the utility function of the government is the difference between environmental benefit and the incentive offered to the households. The utility Eq. (22) of the government can be written as:

$$U^g_{a,t} = \tau^{en}_t - i^g_{a,t} \tag{22}$$

Government certainty equivalent is given by Eq.(23)

$$E(U^g_{a,t}) = E(\tau^{en}_t - i^g_{a,t}) \tag{23}$$

Substituting Eq.(15) and (16) into Eq. (23) and taking the maximum over environmental benefit share to households $\lambda^h_{a,t}$ and Carbon rebate CR^h_a, we obtain the objective function of the principal-agent problem as shown in Eq. (3) in Section III.

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