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Data-Driven Analysis of Renewable Energy Policy Impact on Bahrain's Energy Market

A Thesis Submitted in Partial Fulfilment of the Requirements for the Doctor of Philosophy Degree in Business Analytics

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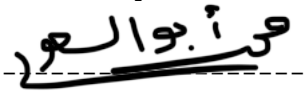
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ABSTRACT

Residential solar photovoltaic (PV) adoption is crucial for sustainable energy transitions but faces significant barriers in subsidized energy markets such as Bahrain. This doctoral research investigates policy pathways to optimize residential solar PV uptake by evaluating (1) financial incentives (VAT reduction, innovative loans) within the current subsidy system and (2) electricity subsidy reform coupled with compensatory cash transfer (CT) mechanisms (universal, targeted, and a novel tiered design). This study addresses the fundamental challenge of stimulating solar PV adoption in heavily subsidized electricity markets.

An empirically grounded Agent-Based Model (ABM) simulated heterogeneous Bahraini household adoption decisions (2025-2050), integrating economic rationality, behavioral factors (Diffusion of Innovation, Behavioral Economics), and social network influences (Social Capital Theory). The model assessed the policy impacts on solar PV diffusion, household economics, distributional equity, fiscal balance, and environmental benefits.

Key findings reveal that while combined financial incentives significantly boost solar PV adoption (to ~45.6%) over the baseline (~24%), an adoption ceiling persists due to existing subsidies. Subsidy reform paired with CTs proved more potent for higher adoption (71-73%) and improved solar PV financial viability (payback periods of 1.58-1.81 years). However, subsidy removal alone can lead to inequitable adoption. The novel Tiered CT design, achieving 70.99% adoption, delivered the most equitable adoption distribution across income quintiles by utilizing a rational "coupled" design that allocates compensation in proportion to household subsidy loss.

This study contributes by applying ABM to policy design in a subsidized GCC context, comparing distinct policy paradigms, and evaluating innovative CT. This underscores the necessity of pairing subsidy reforms with robust equitable compensation. Tiered CT has emerged as a promising policy for Bahrain to balance adoption, equity, and fiscal responsibility. This study offers evidence-based insights for Bahrain and other similar nations, aiming to accelerate sustainable energy transitions.

DEDICATION

This thesis is dedicated to my heartfelt gratitude to my parents' enduring memories. Their unwavering support and profound beliefs in the transformative power of education were constant sources of inspiration throughout my academic journey. The values they instilled and their encouragement shaped my perseverance and commitment to achieving this goal.

My sincere appreciation also extends to my beloved wife, children, siblings, and close friends. Your patience, understanding, and steadfast faith in my abilities provided invaluable motivation and strength during this challenging endeavor.

May this work serve as a lasting tribute to my parents' cherished legacy and the steadfast support of all those who accompanied me on this path.

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Chapter 1: Introduction

1.1. Background: The Energy Transition & Residential Solar PV

The global energy transition marks a critical shift from reliance on conventional fossil fuels towards more sustainable energy paradigms, largely propelled by increasing concerns about climate change and the objective of bolstering energy security (Alharbi & Csala, 2020; Griffiths, 2017; Mohandes et al., 2019). Central to this transformation are renewable energy sources, with solar photovoltaic (PV) and wind energy at the forefront, witnessing substantial global expansion driven by continuous technological improvements, decreasing generation costs, and supportive government policies (Farahat et al., 2024; Fauzi et al., 2023; Kapsalis et al., 2024).

Globally, residential solar PV is experiencing accelerated adoption, empowering households to become active participants in energy generation and fostering decentralized energy systems, which is anticipated to contribute to 80% of the total growth in renewable power by 2030 (IEA, 2024).

In the Gulf Cooperation Council (GCC) region, countries are harnessing their significant solar potential to integrate renewable energy, including residential PV, into their national energy frameworks, aiming to diversify their economies and advance sustainability, with nations such as the UAE and Saudi Arabia leading project development (Almasri & Narayan, 2021; Elrahmani et al., 2021; Farahat et al., 2024). Specifically, residential solar PV in Bahrain is recognized within national strategic plans, such as initiatives to install solar PV systems in government-constructed homes (Alsabbagh, 2019; Farahat et

al., 2024). Despite Bahrain's abundant solar radiation (Farahat et al., 2024), the adoption of residential solar PV systems faces hurdles, including considerable upfront investment costs, limited public awareness regarding the technology, and concerns about ongoing maintenance, underscoring the need for effective policy interventions to stimulate growth (Almasri and Narayan, 2021; Alsabbagh, 2019).

1.2. The Bahraini Context: Challenges and Opportunities

Similar to other nations within the GCC, Bahrain faces a unique set of energy challenges and opportunities, which are central to this study. The country's energy sector is predominantly reliant on natural gas, which constitutes nearly the entirety of its electricity generation capacity (EWA, 2020; IEA, 2022). This dependency is coupled with high per capita electricity consumption that significantly exceeds the global average (World Bank, 2022), driven by economic growth, urbanization, and historically subsidized energy costs (Al-Badi & AlMubarak, 2019; EzzEldin et al., 2022). The demand, largely met by limited domestic natural gas reserves that may face future shortages (SEU, 2017), places considerable pressure on energy infrastructure. The building sector, particularly residential properties, accounts for a substantial portion of this consumption, often representing more than 70-80% (EzzEldin et al., 2022), underscoring its importance as a focal point for energy policy initiatives.

A defining characteristic of Bahrain's residential energy market is the presence of substantial electricity subsidies provided by the government to maintain low consumer prices (IMF, 2021; World Bank, 2023). A tiered pricing model

is employed for Bahraini nationals, with tariffs ranging from $0.008/kWh to $0.042/kWh, depending on consumption bands (EWA, 2021). These rates remain significantly lower than the actual production cost, estimated at $0.077/kWh (EWA, 2021; SEA, 2021). While ensuring affordability, these artificially low prices distort market signals and fundamentally undermine the financial attractiveness of investing in self-generation technologies, such as solar PV (Alsabbagh, 2019). Consequently, the resulting long payback periods serve as major deterrents (Alnaser et al., 2023; Alsabbagh, 2019; EzzEldin et al., 2022). Despite this challenge, although tariff reforms were initiated in 2015, they largely excluded Bahraini nationals (UNDP, 2018), indicating that the core market distortion affecting solar PV adoption persists. Nevertheless, reforming these subsidies is recognized as a key policy direction within national plans, such as the National Energy Efficiency Action Plan (NEEAP) (SEU, 2017), to encourage conservation and improve the market conditions for renewables, yet doing so raises significant concerns about household welfare impacts.

Recognizing the need to diversify its energy mix and leverage its natural advantages, Bahrain has embraced renewable energy as a strategic priority, enshrined in national strategies such as Economic Vision 2030 and the National Renewable Energy Action Plan (NREAP) (SEU, 2017). The NREAP, launched in 2017, set ambitious targets, aiming for renewable energy to contribute 5% of electricity generation by 2025 and 20% by 2035 (GIF, 2023; NREAP, 2017; PMS, 2021), along with a long-term goal of achieving net-zero carbon emissions by 2060 (Alsabbagh & Alnaser, 2023a). Meeting these NREAP targets is a critical milestone on the path to this 2060 commitment, and this thesis provides an essential roadmap for the residential sector's

contribution to that ultimate national objective. A central policy instrument introduced to facilitate this and form a foundational component of all scenarios modeled in this thesis is the net metering program, which allows households with grid-connected solar PV systems to receive credits for surplus energy exported to the grid (EWA, 2017). By the end of 2023, more than 57.7 MW of renewable capacity had been integrated, with further growth projected (EWA, 2023). However, the effectiveness of current policies, such as net metering, is constrained by the prevailing low subsidized tariffs, which diminish the value of bill savings, as well as administrative hurdles related to approvals and grid connections. Furthermore, the prevailing single-buyer model in the electricity sector, where the state utility Electricity and Water Authority (EWA) is the sole purchaser and distributor of electricity (EWA, 2021), presents additional structural considerations that can limit opportunities for households to engage directly with the energy market and affect the terms for distributed generation from residential solar PV systems.

Despite the establishment of policy objectives, several distinct challenges have hindered the widespread adoption of residential solar PV systems. The most significant obstacle is the substantial initial investment required for the solar PV systems (Alnaser, 2023b; Alsabbagh, 2019; EzzEldin et al., 2022; Fauzi et al., 2023). Survey findings indicate that cost is the primary deterrent, with the public demonstrating limited willingness to invest without substantial financial incentives (Alsabbagh, 2019). Compounding the cost issue is the limited public understanding of the benefits and economic aspects of solar technology (Alnaser, 2023b; Alrashoud and Tokimatsu, 2020; Mohandes et al. 2018), as well as the reliability, maintenance, and long-term performance of the system. These concerns are particularly pertinent in harsh local

environments, where factors such as significant dust accumulation and high ambient temperatures can negatively impact the solar PV efficiency (Alnaser et al., 2018).

Nevertheless, Bahrain possesses exceptional solar energy potential, benefiting from some of the richest solar resources globally, with an average global horizontal irradiance (GHI) of approximately 6 kWh/m²/day (approximately 2,160 kWh/m²/year) (Alnaser et al., 2014; Alnaser & Alnaser, 2011; EzzEldin et al., 2022). This potential represents a significant opportunity for energy diversification. Given Bahrain's limited land availability (approximately 780 km²), utilizing existing rooftop spaces through distributed residential solar PV installations is considered a particularly viable and essential strategy (Alnaser, 2023a; EzzEldin et al., 2022). Pilot projects have confirmed the technical feasibility and potential for significant CO2 emission reduction through rooftop solar PV deployment (Alnaser, 2023a; EzzEldin et al., 2022). Effectively harnessing this potential necessitates overcoming the aforementioned financial, behavioral, and policy-related barriers.

1.3. Research Problem Statement

Despite Bahrain's significant solar potential and well-defined national renewable energy objectives, the adoption and dissemination of residential solar PV systems remains minimal, significantly lagging behind the pace required to meet the stated targets. Uptake in this subsidy-distorted market is sluggish, underscoring a complex underlying challenge rooted in the intricate decision-making environment faced by households. The decision to implement solar PV technology is multifaceted, involving economic considerations, such as substantial initial costs and the evaluation of payback periods influenced by subsidized tariffs. It also encompasses perceptions of

policy tools and their reliability, individual and household actions, and social factors, such as peer pressure and community standards. This complexity is particularly pronounced in energy markets with substantial subsidies, such as Bahrain, where current pricing signals actively discourage investment in self-generation. This scenario presents a unique policy challenge for the Bahraini officials. There is a recognized need to encourage solar PV adoption through financial incentives to overcome cost barriers. On the other hand, addressing fundamental market distortion necessitates reforming electricity subsidies, a step that, while potentially fostering a more supportive environment for renewables, inevitably increases electricity costs for consumers and threatens household welfare, particularly for lower- and middle-income groups. Effectively balancing these conflicting needs—promoting renewable energy investment while managing the social and political sensitivities of subsidy reforms —constitutes a central policy issue. Compounding this dilemma is a significant gap in the current understanding, particularly concerning the integrated effects of different policy combinations in Bahrain's specific context. While studies have examined the determinants of solar PV adoption or the impacts of subsidy reform internationally, there is a lack of research that holistically analyzes the combined and comparative effects of specific financial incentives versus comprehensive subsidy reform coupled with various compensatory mechanisms (such as cash transfers) using advanced modeling techniques. Specifically, no published models simultaneously track how different cash transfer designs might interact with subsidy removal to influence solar PV adoption trajectories, while also considering the crucial dimensions of distributional equity and overall fiscal sustainability within the Bahraini context.

1.4. Research Aim and Objectives

Based on the identified research problems and gaps in the existing literature, the primary aim of this thesis is as follows.

Aim: To evaluate and compare the effectiveness of different policy strategies (financial incentives and subsidy reform with cash transfers) in accelerating residential solar PV adoption in Bahrain and assessing their economic, social equity, and fiscal implications.

To achieve this aim, the following research objectives were established:

1. Develop an empirically grounded agent-based model (ABM) simulating household solar PV adoption decisions within the specific socio-economic and policy context of Bahrain.
2. Analyze the impact of specific financial incentives (VAT reduction and innovative loan schemes) on solar PV diffusion patterns and household financial viability within the existing electricity subsidy structure.
3. Evaluate the effects of removing residential electricity subsidies when coupled with different compensatory cash transfer mechanisms (universal, income-targeted, and household-size tiered), on solar PV diffusion, household economics, and distributional equity.
4. Compare the relative effectiveness, equity implications, and fiscal viability of the different policy scenarios simulated (incentives vs. reform/compensation).
5. Provide evidence-based, actionable policy recommendations relevant to accelerating sustainable energy transition in Bahrain and other similar subsidized markets.

1.5. Research Questions

Flowing directly from the research problem, aim, and objectives outlined above, this thesis seeks to answer the following specific research questions (RQs):

- RQ1: How effective are specific financial incentives (VAT reduction and innovative loans) for stimulating residential solar PV adoption in Bahrain's subsidized electricity market?
- RQ2: What are the effects of removing residential electricity subsidies on the solar PV adoption rates and household welfare in Bahrain?
- RQ3: How do different compensatory cash transfer designs (universal, targeted, and tiered) influence the speed, level, and equity of solar PV adoption following subsidy removal?
- RQ4: What are the comparative fiscal implications and environmental co-benefits of these different policy pathways (incentives versus reform/compensation)?

Addressing these questions through the simulation modeling approach described in subsequent chapters will provide a comprehensive evaluation of policy options for Bahrain's residential solar energy transition.

1.6. Research Significance

This research presents substantial implications across the academic, policy, and business domains by addressing critical gaps in understanding energy transitions within subsidized markets. The significance of this study is rooted in its innovative approach to a complex problem, its potential to inform critical policy decisions, and its contributions to both theoretical understanding and practical application in the renewable energy sector.

1.6.1 Methodological Rationale and Original Contribution

To effectively evaluate these policy interactions, this study employs ABM as its core analytical methodology. The choice of ABM was driven by its distinct advantage in capturing the micro-level behaviors of heterogeneous households and their emergent, system-level consequences—dynamics that traditional modeling approaches often fail to represent. This bottom-up approach enables the exploration of "what-if" scenarios, providing a virtual laboratory to assess the potential impacts of different financial incentives and subsidy reform packages before real-world implementation.

This doctoral research makes several original contributions by building upon and extending the existing literature on energy policy modeling in the GCC region. While prior agent-based studies have provided valuable insights, such as the work by Mohandes et al. (2018, 2019) on subsidy impacts for solar adoption in Qatar, a gap remains in the integrated and comparative analysis of competing policy paradigms. This thesis directly addresses this gap. Its originality lies not in being the first to apply ABM in the GCC, but in developing a more comprehensive framework to evaluate a wider range of interconnected policies and their equity impacts. The primary academic and methodological contributions are:

- Methodological and Contextual Innovation: This study delivers an empirically-grounded ABM of residential solar PV adoption tailored specifically to Bahrain's unique market conditions. It provides not only crucial, context-specific insights but also a transferable methodology for analyzing energy transitions in other subsidy-dependent nations.
- Integrated Policy Analysis Framework: The research moves beyond analyzing policies in isolation by developing a comparative framework

that simulates the dynamic and intersecting impacts of both market-based incentives and fundamental subsidy reform on adoption, equity, and fiscal outcomes.

- Novel Policy Design and Theoretical Integration: It contributes directly to energy policy literature by developing and evaluating a novel Tiered Cash Transfer (S3) mechanism, demonstrating a more rational and equitable approach to compensation. Furthermore, it enriches the ABM literature by explicitly operationalizing concepts from Diffusion of Innovation theory, Behavioral Economics, and Social Capital Theory to create a more holistic and behaviorally realistic model of socio-technical energy transitions.

1.6.2 Significance for Policy and Business

The contributions outlined above have direct and significant implications for key stakeholders:

- For Policymakers: This thesis provides quantitative, evidence-based insights that are directly pertinent to achieving national renewable energy objectives. By simulating and comparing various policy pathways, this study elucidates their potential effectiveness, distributional consequences, and fiscal viability. The evaluation of the novel Tiered CT, in particular, offers a practical blueprint for designing more effective and equitable compensation policies to support subsidy reform. Given the widespread presence of energy subsidies across the GCC, the findings are highly applicable to policymakers confronting similar challenges beyond Bahrain.
- For Business and Industry: This study offers valuable insights into the market drivers for residential solar PV. The analysis of financial

viability across different scenarios provides essential information for solar installers, financiers, and developers aiming to tailor their offerings and business models. Furthermore, by understanding how consumer behavior responds to specific policy interventions, firms can inform their marketing strategies and better anticipate market demand within the expanding renewable energy sector.

The findings and contributions stemming from this research were consolidated into two academic papers that are currently under peer review, further underscoring the study's scholarly contribution. The first paper, titled "Optimizing Residential Building Solar PV Adoption in Subsidized Energy Markets: An Agent-Based Modeling Approach," which focuses on the comparative efficacy of financial incentives and is under review at The Solar Energy Journal. The second paper, “Cash Transfers and Electricity Subsidy Reform: Unlocking Rooftop Solar Adoption in Subsidized Energy Markets," addresses the broader dynamics of electricity subsidy reform and policy implications for sustainable energy transitions in subsidized markets and is under review at The Energy Policy Journal.

1.7. Study Setting and Scope

1.7.1 Setting

This research is geographically focused on the Kingdom of Bahrain, a GCC member state characterized by high solar potential, high energy consumption, and heavily subsidized electricity tariffs. The specific population under investigation comprised households occupied by residential owners. The ABM developed for this study utilizes an empirically grounded dataset

representing 158 such households drawn from various governorates across Bahrain, capturing a spectrum of socioeconomic and dwelling characteristics.

1.7.2 Scope

The scope of this study is centered on understanding the adoption dynamics of grid-connected residential rooftop solar PV systems, all of which are assumed to operate under Bahrain's approved net metering policy framework (EWA, 2017). It specifically models and compares the impact of distinct policy interventions: first, financial incentives (VAT reduction and innovative loan schemes) applied within the existing subsidy framework; and second, electricity subsidy reform coupled with different compensatory CT mechanisms (universal, income-targeted, and household-size-tiered). The analysis utilizes ABM as the core methodology, leveraging empirical household data to simulate adoption decisions and their aggregate consequences over a defined period from 2025 to 2050. The assessment encompasses adoption rates, household economic impacts, distributional equity, governmental fiscal balance, and the associated environmental co-benefits.

1.8. Definition of Key Terms

For clarity and consistency throughout this thesis, the following key terms are defined:

Agent-Based Modeling (ABM): A computational simulation methodology is used to study complex systems by Modeling the actions and interactions of autonomous, heterogeneous entities called agents (in this case, households) and observing the emergent system-level patterns (e.g., technology adoption rates) that arise from these micro-level behaviors.

Cash Transfers (CTs): Direct payments made by the government to households, specifically explored in this research as mechanisms to compensate for the increased cost of living resulting from the electricity subsidy reform. This study examined the following three types:

Universal CT: Transfers are distributed broadly across the population, with adjustments based only on simple demographic factors such as household size.

Targeted CT: Transfers directed specifically towards predetermined groups, typically lower-income households identified through means testing or proxy indicators, often phasing out for higher earners.

Tiered CT: A specific, novel design proposed and modeled in this research, where transfer amounts are calculated based on estimated individual household subsidy loss and then adjusted according to factors such as income tiers and household size.

Compensation-to-subsidy ratio (CR): This metric represents the ratio of the cash transfer amount received by a household to the estimated value of the electricity subsidy that households lost due to reform. This indicates the degree to which the transfer compensates for the removal of subsidy benefit.

Gini index: A statistical measure used in this research to quantify the inequality in the distribution of cash transfer values among the simulated households. The Gini coefficient ranged from 0 (perfect equality) to 1 (perfect inequality).

Transfer-to-income ratio (T2I): A metric calculated to represent the cash transfer amount received by a household as a proportion of that household's

annual income. This helps gauge the relative financial significance of transfers to the household budget.

Diffusion of Innovation: The theoretical framework describing the process by which a new idea, practice, or technology spreads through a social system over time. It involves concepts such as different adopter categories (e.g., innovators and early adopters) based on their timing of adoption and the characteristic S-shaped curve of cumulative adoption (Rogers, 2003).

Net Metering: An electricity billing arrangement allows households with grid-connected renewable energy systems (such as rooftop PV) to receive credits on their electricity bills for surplus electricity exported back to the utility grid, typically offsetting their grid consumption.

Payback Period (PBP): A financial metric representing the time required for the cumulative financial savings generated by an investment (e.g., reduced electricity bills from a solar PV system) to equal the initial capital cost of that investment. This serves as a key indicator of the investment attractiveness of households.

Rate of Return (RoR): A financial performance measure, expressed as a percentage, indicates the profitability of an investment, such as a solar PV system, relative to its cost. This reflects the annualized net earnings expected from investments.

Rooftop Solar Photovoltaic (PV): Electricity generation systems utilizing solar PV panels installed directly on the roofs of residential buildings to convert sunlight into electrical energy for household use and potential export to the grid.

Social Capital: The resources embedded within social networks, including trust, norms, and interpersonal connections, can facilitate collective action, information sharing, and influence individual behaviors, such as the adoption of solar PV technology (Coleman, 1988).

Subsidy Reform: The policy process of modifying, reducing, or eliminating existing electricity subsidies often results in consumer tariffs approaching cost-reflective levels.

1.9. Thesis Structure

This thesis is organized into five chapters following a structure conducive to presenting empirical simulation research within the University of Bahrain framework.

Chapter 1 (this chapter) introduces the research by establishing the context of the global energy transition and Bahrain's specific situation concerning residential solar PV adoption, subsidies, and policy goals. It defines the research problem; outlines the study's aim, objectives, and guiding research questions; discusses the significance of the work; specifies the scope; defines key terminology; and presents this structural roadmap. To effectively address these research questions and understand the existing knowledge landscape surrounding residential solar PV adoption in subsidized markets such as Bahrain, a comprehensive review of relevant theoretical frameworks, empirical studies, and policy precedents is essential. Chapter 2 undertakes this critical review to identify existing knowledge, pinpoint research gaps, and establish the theoretical underpinnings for this study.

Chapter 2 presents theoretical and conceptual foundations. It reviews relevant theories (e.g., Diffusion of Innovation, Behavioral Economics, and Social

Capital), synthesizes the existing literature on the multifaceted determinants of residential solar PV adoption, examines the complexities of energy subsidy reform and compensatory mechanisms, such as cash transfers, discusses the application of ABM in energy policy, and presents an integrated conceptual framework guiding the simulation design.

Chapter 3 details the research methodology centered on the ABM. It describes the ABM approach, the specific model development process using NetLogo, the empirical data sources used to characterize Bahraini households, the design of distinct policy scenarios testing financial incentives and subsidy reform/cash transfer combinations, the rigorous procedures employed for model calibration and validation, and sensitivity analysis.

Chapter 4 presents the core empirical findings and discussions of ABM simulations. It analyzes the resulting solar PV adoption trajectories, household economic impacts (payback periods, savings), distributional equity outcomes, government fiscal implications, and environmental benefits across various policy scenarios. This chapter compares the effectiveness of different incentive and reform strategies and discusses the emergent dynamics observed in the simulations in light of the research questions and the existing literature.

Finally, Chapter 5 concludes this thesis. It provides a concise summary of the main research outcomes, reiterates the study's contributions, presents specific evidence-based policy recommendations for Bahrain, acknowledges the limitations inherent in the modeling approach, and suggests promising directions for future research on this topic.

Chapter 2: Literature Review and Theoretical Framework

Building upon the research problem and objectives outlined in Chapter 1, this chapter examines the current body of literature to establish a robust theoretical and empirical foundation for investigating residential solar photovoltaic (PV) adoption in Bahrain. Complex socio-technical and economic dynamics characterize the residential transition to solar PV systems, particularly in the context of established energy subsidies. Traditional policy approaches often fail to fully capture the intricate interplay between technology adoption, human behavior, and market structures. This complexity becomes particularly pronounced in Bahrain's distinctive energy landscape, where longstanding electricity subsidies have shaped consumption patterns and investment decisions (Alsabbagh, 2019). Understanding these dynamics requires a nuanced theoretical foundation that acknowledges both the universal adoption principles and context-specific factors.

This chapter develops a comprehensive conceptual framework to understand residential solar PV adoption in Bahrain's unique context. The discussion progresses from theoretical foundations through empirical evidence to modeling approaches, systematically building a robust framework for analyzing the complexities of solar PV adoption in subsidized energy markets.

2.1. Theoretical Foundations

To effectively model the complex dynamics of residential solar PV adoption in Bahrain, this study draws on several established theoretical foundations. This section reviews key theories that illuminate the multifaceted decision-making processes of individual households and the broader social diffusion of

innovations, such as solar PV. Specifically, insights from the Diffusion of Innovation (DOI) theory (Section 2.1.1), Behavioral Economics Section 2.1.2), and Social Capital Theory (Section 2.1.3) will be explored. These theories offer complementary perspectives that are essential for understanding why and how individuals and communities adopt new technologies. The principles and constructs discussed herein are not merely descriptive; they form the essential building blocks of the integrated conceptual framework developed for this study, which is presented in detail in Section 2.5 (see Figure 2.1). This framework guides the design and parameterization of the Agent-Based Model (ABM) used to simulate solar PV adoption dynamics.

2.1.1 Diffusion of Innovation (DOI) Theory (Rogers)

Everett Rogers' diffusion of innovation (DOI) theory (Rogers, 1962, 2003) remains a cornerstone in understanding how new ideas, practices, or technologies spread through a social system over time (Ahmed et al., 2022; Juliusson, 2024; Outcault et al., 2022). The theory posits that adoption follows an S-shaped curve, characterized by a slow initial uptake, followed by rapid acceleration as more individuals adopt, and finally, a plateau as market saturation approaches (Rogers, 2003). Central to DOI are the characteristics of adopters and the perceived attributes of the innovation.

2.1.1.1 Adopter Categories

Rogers (2003) categorizes individuals within a social system based on their innovativeness, or the degree to which they adopt new ideas relatively earlier than other members of their system. These categories are instrumental for understanding the diffusion process.

The first type is innovators. These individuals are characterized as venturesome and are eager to try new ideas, often with greater financial resources and higher risk tolerance (Rogers, 2003). Innovators play a critical role in launching the diffusion process of new technologies or ideas.

Following innovators, the next category is Early Adopters. This group consists of respected opinion leaders within their social system who are more integrated than innovators. Early Adopters serve as crucial role models for others, and their adoption of an innovation helps legitimize it in the eyes of the wider community (Rogers, 2003).

The Early Majority comprises deliberate individuals who tend to adopt new ideas just before the average member of a social system. They are pivotal for achieving widespread diffusion, as they effectively bridge the gap between earlier adopters and later, more skeptical segments of the population (Rogers, 2003).

Next, Late Majority includes skeptical individuals who adopt new ideas only after the average member of the system has already done so. Their adoption is often driven by economic necessity or increasing social pressure rather than a proactive desire for innovation itself.

Finally, Laggards are traditional individuals who are the last to adopt innovation. They are often suspicious of new technologies and tend to be more oriented towards past practices and beliefs.

Studies on solar PV adoption have frequently used these categories to understand adoption patterns. For instance, research often focuses on distinguishing the motivations and characteristics of early adopters from those of later adopters or non-adopters to tailor policies and marketing (Palm, 2020;

Ruokamo et al., 2023). Early adopters of solar PV are often motivated by environmental concerns and technophilia, while later adopters may prioritize economic motives (Palm, 2017; Sigrin et al., 2015). However, some of Rogers' original predictions about innovator characteristics have been challenged in recent empirical work. For example, a study on solar PV adoption in Finland found that, contrary to the theory, higher education levels were negatively associated with being an early adopter, and that adopters were more likely to be in rural rather than urban locations (Ruokamo et al., 2023). This suggests that adopter characteristics can be highly context-dependent.

2.1.1.2 Perceived Attributes of Innovation

Beyond adopter characteristics, DOI theory identifies five perceived attributes of an innovation that significantly influence its adoption rate (Rogers, 2003). These attributes shape how potential adopters view and assess a new technology such as solar PV.

The first attribute is Relative Advantage, which refers to the degree to which an innovation is perceived as better than the idea or product it supersedes. For solar PV systems, this relative advantage often manifests in economic benefits, such as reduced electricity bills and a return on investment, along with environmental benefits and increased energy independence (Ahmed et al., 2022; Qureshi et al., 2017). While empirically found to be a significant predictor of adoption for innovations like electric vehicles (Xia et al., 2022), this attribute has been criticized in the energy literature for being a "garbage pail characteristic" that is too broadly defined, encompassing a wide range of factors from economic profitability to convenience (Outcault et al., 2022).

Second is Compatibility, defined as the degree to which an innovation is perceived as consistent with the existing values, past experiences, and needs of potential adopters (Ahmed et al., 2022; Karahanna et al., 2006). In the context of solar PV, compatibility includes alignment with an individual's lifestyle, suitability of their housing, and existing energy infrastructure. Recent research continues to confirm that perceived compatibility is a strong positive predictor of adoption intention (Xia et al., 2022). However, like relative advantage, it has also been criticized for being subjective and interpreted in divergent ways across studies, making comparisons difficult (Outcault et al., 2022). An effective policy should consider how to enhance an innovation's compatibility with diverse household needs and financial conditions.

Third, Complexity denotes the degree to which an innovation is perceived to be difficult to understand and use. High complexity can act as a significant barrier to the adoption of solar PV, particularly concerning the understanding of the technology itself, installation process, and various incentive schemes available. Perceived ease-of-use, a key concept in the Technology Acceptance Model (TAM), is often considered synonymous with the inverse of complexity and is recognized as a strong influencing factor for perceived usefulness (Ahmed et al., 2022; Davis, 1993). Recent empirical studies confirm that higher perceived complexity is significantly and negatively related to consumer adoption of new energy technologies (Xia et al., 2022). Financial incentives can improve the perceived attributes of solar PV systems by reducing their perceived financial complexities.

Fourth, Trialability is the degree to which an innovation may be experimented with on a limited basis before full commitment is required. For solar PV

technology, true trialability is often challenging owing to the substantial upfront costs and permanent nature of installation (Ahmed et al., 2022; Juliusson, 2024). Consequently, some studies on solar adoption have excluded trialability from their models, recognizing that solar PV systems are typically not offered on a trial basis by suppliers (Ahmed et al., 2022; Faiers & Neame, 2006). This is reflected in the broader literature, where trialability is one of the least frequently studied of Rogers' five attributes in the energy sector (Outcault et al., 2022).

Finally, Observability (also referred to as visibility) is the degree to which an innovation's results or outcomes are visible to others. The visibility of solar PV installations, such as panels on neighbors' rooftops, can act as a powerful peer effect, signaling pro-environmental behavior and increasing awareness within a community (Mundaca & Samahita, 2020; Parsad et al., 2020). However, some studies have also noted that visibility alone may not always be a significant driver of adoption, or that its impact can be highly context-specific (Mundaca & Samahita, 2020). Like trialability, observability is often excluded from recent models, in some cases because it is considered an objective fact rather than a subjective perception in the context of highly visible products (Outcault et al., 2022; Xia et al., 2022). Leveraging positive social dynamics in order to improve observability is an effective strategy.

The DOI framework, particularly its emphasis on technological characteristics, has been extended and adapted for Distributed Energy Resources (DERs), including solar PV (Outcault et al., 2022). Studies frequently integrate DOI with other models, such as TAM, to explore the determinants of solar PV adoption (Ahmed et al., 2022; Fauzi et al., 2023). For example, Ahmed et al. (2022) found perceived usefulness, perceived ease

of use, compatibility, and observability to be significant predictors of attitudes towards solar PV adoption in developing countries.

Knowledge dissemination about solar PV technology and related programs also serves as a catalyst for adoption, aligning with DOI's emphasis on communication channels (Rogers, 2003), a factor explicitly considered in the social interaction components of this study's conceptual framework (Section 2.5). While many studies applying DOI utilize quantitative surveys analyzed with statistical models, such as multinomial logit, to examine adopter categories (Ruokamo et al., 2023), a notable limitation of such cross-sectional approaches is their inability to fully capture the inherently temporal nature of the diffusion process. Recognizing this, the current study employs an Agent-Based Modeling (ABM) approach (detailed in Chapter 3). This methodology is specifically chosen for its strength in simulating dynamic processes over time, allowing for an exploration of how individual adoption decisions, influenced by DOI principles, such as perceived innovation attributes and social interactions, accumulate to shape the overall diffusion curve. The conceptual framework (Section 2.5) operationalizes these dynamic aspects.

The DOI theory provides a robust lens for comprehending the macro-level diffusion patterns of solar PV. Nevertheless, a deeper exploration of micro-level decision making, especially the cognitive and psychological underpinnings of an individual's adoption choice, requires additional theoretical perspectives. Behavioral Economics offers such crucial insights, augmenting DOI by clarifying why individuals may diverge from strict economic rationality in complex choices, such as solar PV investment. Understanding these deviations is essential for calibrating the agent behavior in the ABM, the conceptual basis of which is outlined in Section 2.5.

2.1.2 Behavioral Economics & Decision Making

Traditional economic models often posit that rational actors maximize utility. Behavioral Economics, however, incorporates psychological insights to explain deviations from idealized rationality, particularly in complex decisions, such as technology adoption (Kahneman & Tversky, 1979). In the context of this thesis, understanding such psychological factors is not merely supplementary but vital. In Bahrain's heavily subsidized energy market, where standard economic signals for solar PV adoption are muted, these non-rational behavioral elements likely play an amplified role in shaping how households perceive and ultimately decide to adopt solar technology. Indeed, behavioral lenses are crucial in subsidized contexts, as the muted price signals mean that decisions are not based on simple cost-benefit logic, making subsidy reform a behavioral intervention as much as a fiscal one (Zaidan et al., 2025). Therefore, this study leverages Behavioral Economics to explore these often-overlooked drivers and barriers.

A foundational Behavioral Economics concept is Bounded Rationality, which recognizes that individuals possess limited cognitive abilities, information, and time, leading to "good enough" (satisficing) rather than optimal decisions. The complexity of solar PV technology, its financing, and uncertain returns can lead potential adopters to rely on simpler decision rules or heuristics (Parsad et al., 2020). Complementing this, Prospect Theory (Kahneman & Tversky, 1979) highlights that individuals evaluate outcomes relative to a reference point (e.g., current electricity bills) and are typically loss-averse — losses loom larger than equivalent gains. This is highly relevant when considering subsidy removal or solar PV incentives; the perceived "loss" of a subsidy or the upfront solar PV cost can evoke a strong negative reaction,

potentially outweighing the perceived long-term gains for some (Faiers & Neame, 2006; Kahneman & Tversky, 1979).

Given these cognitive limitations, individuals often use mental shortcuts (heuristics) that can lead to systematic errors (biases). These biases, such as myopia (short-term focus), inertia (preference for the status quo), and herding (imitating others), are principal reasons why consumers may avoid long-term investments like solar panels, even when they are financially attractive and socially beneficial (Kunreuther et al., 2022). For instance, the Availability Heuristic might cause an overestimation of events that are easily recalled (e.g., high bills, visible local installations), while Anchoring Bias involves over-reliance on initial information such as early cost estimates. The status-quo bias, a preference for the current state, can create inertia against adopting PV, even with clear benefits (Al-Sharafi et al., 2023; Daiyabu et al., 2022). Herd Behavior following group actions also underscores the influence of social norms and peer effects on individual choices (Mundaca & Samahita, 2020), bridging individual cognition with social dynamics.

The decision to adopt solar PV is also profoundly shaped by the multifaceted Perceived Risks. Financial Risk includes uncertainty regarding investment returns and subsidy stability (Al-Sharafi et al., 2023). leading some to view solar PV as expensive despite its long-term benefits (Ruokamo et al., 2023). Performance/technical risks relate to concerns about reliability and maintenance (Alnaser et al., 2018; Al-Sharafi et al., 2023). Furthermore, Social Risk involves the perception of adoption might be viewed by peers, whereas Psychological Risk can stem from conflicts with existing beliefs or perceived operational complexity (Al-Sharafi et al., 2023). These risks are often interconnected, and present significant barriers to adoption.

However, Perceived Benefits such as lower energy costs and environmental contributions can counteract these risks (Schulte et al., 2022). especially when coupled with individual financial capabilities and pro-environmental attitudes (Chanda et al., 2025). Government incentives, such as subsidies and tax credits, are designed to mitigate financial risks (Ahmed et al., 2022; Mundaca & Samahita, 2020; Parsad et al., 2020), although policy uncertainty itself can be a deterrent (Margolis & Zuboy, 2006). The perception of these incentives is also critical; for low-income individuals, financial and knowledge barriers are often the primary hindrances to adoption, and incentives are most effective when paired with clear information and social support to build confidence (Rahardja et al., 2022).

Ultimately, Behavioral Economics principles are indispensable for understanding how households perceive and act upon incentive mechanisms and subsidy reforms. The Framing of policy information, for instance, whether incentives are presented as gains achieved or losses avoided, can dramatically alter their uptake, a direct implication of Prospect Theory. Successful strategies often work with rather than against these natural decision biases, for example, by using default options or guarantees to overcome inertia (Kunreuther et al., 2022). This underscores a critical takeaway for Bahraini policymakers: energy policy communication is as important as the policy itself. Policies that actively simplify complex choices, provide transparent and easily digestible information, and make the benefits of solar PV adoption salient and relatable are far more likely to overcome the identified behavioral barriers (bounded rationality, loss aversion, status quo bias). These nuanced Behavioral Economics insights—spanning bounded rationality, loss aversion, the influence of heuristics and biases, the

multifaceted nature of perceived risks and benefits, and the power of framing— are systematically integrated into the agent decision-making logic within this study's conceptual framework (Section 2.5) and subsequently operationalized in the Agent-Based Model (Chapter 3). This integration allows for a more realistic simulation of household adoption decisions in response to the various policy interventions in Bahrain.

2.1.3 Social Capital Theory (Coleman, Putnam)

Social Capital Theory posits that resources embedded within social networks, such as trust, norms, and information channels, can facilitate collective action and significantly influence individual behavior (Coleman, 1988; Putnam, 1995). The role of social capital is multifaceted in the context of residential solar PV adoption, shaping how information is disseminated, how peer influence operates, and how community-level actions emerge.

A primary mechanism through which social capital operates is via Social Networks and Information Diffusion. These networks serve as crucial conduits for information regarding solar PV, encompassing the technical specifications, costs, benefits, and experiences of existing adopters (Irfan et al., 2021). Notably, information disseminated through trusted network members—friends, family, neighbors, or community leaders—often carries greater weight than information from formal institutional channels (J. Liu et al., 2024; Noll et al., 2014). Conversely, a deficit in information or significant information asymmetry can act as a substantial barrier to solar PV adoption (Rai & Beck, 2015). Thus, effective information strategies that leverage existing social capital are pivotal for promoting solar energy uptake (Chanda et al., 2025).

Beyond information flow, Peer Effects and Social Influence are powerful indicators of social capital. The adoption decisions of individuals within a social network can sway others considerably, a phenomenon often termed 'social contagion.' This influence can manifest through Observational Learning, where seeing solar panels on neighboring rooftops (a form of visibility or observability, as also noted in DOI theory) enhances awareness and normalizes technology (Chanda et al., 2025; J. Liu et al., 2024; Ruokamo et al., 2023). Similarly, Word-of-Mouth Communication involving the sharing of positive or negative experiences by early adopters can significantly influence potential adopters (J. Liu et al., 2024; Parsad et al., 2020); indeed, direct conversations with solar PV owners are often highly impactful (Parsad et al., 2020).

Peer interactions contribute to the formation and reinforcement of Social Norms. When solar PV system adoption becomes widespread or highly regarded within a community (a descriptive norm), individuals may feel social pressure to conform or may choose to adopt it as a signal of pro-environmental values or social standing (an injunctive norm) (Ajzen, 1991; Chanda et al., 2025; Nolan et al., 2008). Research has consistently affirmed that peer influence significantly impacts solar PV adoption (Bollinger & Gillingham, 2012; Mundaca & Samahita, 2020; Ruokamo et al., 2023); for example, knowing acquaintances with solar PV systems increases the likelihood of adoption (Mundaca & Samahita, 2020). Recent research confirms that social influence is a significant positive predictor of the intention to adopt new energy technologies like electric vehicles (Kurniawan et al., 2025). Such social influence, operating through peer networks, can alter information flows, thereby boosting technology uptake (Reeves et al., 2022).

Trust is central to the efficacy of social mechanisms. Trust in installers, technology providers, government policies, and information sources is crucial for reducing the perceived risks and facilitating adoption. Social networks can effectively foster trust through sharing experiences and recommendations. A study on residential solar PV adoption found that social networks indirectly increased villagers' willingness to adopt by reducing their perceived risk and enhancing the perceived usefulness of the technology, which was mediated through peer communication (Wang et al., 2022). Conversely, lack of trust constitutes a major barrier (Ahmed et al., 2022; Chanda et al., 2025). Enhancing the perceived security and safety of renewable energy systems, along with clear and transparent communication, is vital for bolstering consumer trust (Ahmed et al., 2022).

Finally, social capital can underpin Collective Action and Community Engagement, thereby facilitating community-led solar initiatives. Strong community ties and shared norms often encourage participation in group-purchasing schemes or community solar projects, which can lead to significant cost reductions and increased adoption rates (Y. Liu & Bah, 2021; Narjabadifam et al., 2024; Walker & Devine-Wright, 2008). Community ownership and active participation are vital for the long-term sustainability of solar PV initiatives (Chanda et al., 2025), with initiatives such as Solar Community Organizations (SCOs) leveraging social interaction to enhance adoption (Noll et al., 2014). A recent review highlights that social capital—comprising trust, norms, and networks—is a critical factor for the success of such community energy projects, as it facilitates cooperation and collective action among members (Giacovelli, 2022).

In essence, Social Capital Theory underscores that solar PV adoption is not merely an individual economic or technical calculus, but is deeply embedded within social structures and relationships. Policies aiming to promote solar PV should therefore consider leveraging these social dynamics by supporting community initiatives, encouraging peer-to-peer information sharing, and actively building trust within the solar ecosystem. These dimensions of social influence are the key components of the conceptual framework guiding this study (Section 2.5).

A critical examination of these theoretical frameworks reveals their complementary nature in understanding residential solar PV adoption, particularly within Bahrain's distinctive market context. Each framework provides unique insights while addressing the inherent limitations of the others. DOI theory provides a crucial understanding of adoption patterns and innovation characteristics, although its assumptions about rational decision making require modification in subsidized markets (Rogers, 2003). Behavioral economics enriches this understanding by illuminating the psychological mechanisms and cognitive biases that influence adoption decisions, particularly in contexts where traditional economic incentives are distorted by subsidies (Parsad et al., 2020).

Social Capital Theory further enhances this theoretical foundation by explaining how social networks and community structures mediate both information flows and adoption decisions. This perspective is particularly valuable in Bahrain's socially interconnected context, in which community influence significantly shapes technology acceptance (Mundaca & Samahita, 2020). The integration of these theoretical perspectives provides a more

comprehensive conceptual framework than any single theory that can be offered independently.

This theoretical synthesis has significant implications for both the research methodology and policy development. First, effective modeling approaches must incorporate multiple theoretical perspectives to adequately capture the complexity of adoption decisions. Second, policy design should consider not only economic incentives but also social dynamics and psychological factors. Third, it highlights the importance of adapting theoretical insights to specific market contexts, particularly in subsidized environments, where traditional adoption drivers may operate differently.

The subsequent section builds upon this theoretical foundation to examine the specific determinants of solar PV adoption and evaluate their relative importance and interactions in Bahrain's distinctive energy market context. This analysis demonstrates how theoretical insights manifest in practical adoption dynamics, while incorporating empirical evidence from comparable markets.

2.2. Determinants of Residential Solar PV Adoption

The theoretical frameworks established in the previous section provide crucial conceptual foundations; however, their practical application requires a detailed understanding of how adoption determinants manifest in specific contexts. Empirical research reveals that residential solar PV adoption emerges from complex interactions among multiple factors, often operating differently across various market environments. This complexity becomes particularly pronounced in subsidized energy markets such as Bahrain, where traditional adoption drivers may function distinctively.

While the extensive literature examines solar PV adoption determinants in developed markets (Ruokamo et al., 2023), understanding remains limited in contexts with substantial energy subsidies. These unique market conditions create distinctive adoption dynamics that challenge the conventional assumptions about economic and social incentives. Bahrain's experience proves particularly instructive, as its subsidized electricity market, cultural characteristics, and climate conditions create a unique environment in which to examine how adoption determinants interact (Alsabbagh, 2019).

This section critically analyzes the key adoption determinants through two lenses: their general influence on solar PV adoption and their specific manifestation in subsidized energy markets. This analysis serves two purposes: informing effective policy design and providing empirical grounding for subsequent Agent-Based Modeling. By examining how various factors influence adoption decisions in Bahrain's distinct context, we can better understand both universal patterns and context-specific variations in solar PV adoption dynamics (Alnaser et al., 2023).

2.2.1 Economic Factors

Economic considerations have consistently emerged as pivotal drivers and significant barriers to the adoption of residential solar PV systems. These factors directly influence a household's financial calculus when considering such investments.

The most prominent economic determinants are Upfront Costs and the associated Payback Period. The initial capital outlay required for solar PV systems is frequently cited as a substantial barrier for many households (Fauzi et al., 2023; Juliusson, 2024). Indeed, high upfront costs can act as a more

potent deterrent to adoption than potential future revenues act as an incentive (Schulte et al., 2022). This is particularly evident in Bahrain, where capital costs have been identified as a major challenge for purchasing and installing solar panels, representing the most commonly cited barrier by residents (Alsabbagh, 2019). This challenge is not unique to Bahrain, with recent studies identifying high installation and maintenance costs as a primary barrier to solar adoption in nearby Oman (Mishrif & Khan, 2024) and across developing countries more broadly (Oliva & Atehortua Santamaria, 2025). Although the global cost of solar PV has declined over time, potentially mitigating this barrier to some extent (Juliusson, 2024), this remains a key consideration for prospective adopters. Closely linked to the initial cost, the investment payback period is another critical economic factor that shapes adoption decisions (Alsabbagh, 2019). Herein lies a central challenge for Bahrain, which this thesis directly confronts: the payback period is often perceived as prohibitively long, rendering solar PV economically unfeasible for many homeowners (EzzEldin et al., 2022). Crucially, as Alnaser (2018) highlighted that this extended payback is not solely due to solar PV costs, but is inextricably linked to the low prevailing electricity tariffs resulting from government subsidies. This fundamental interaction means that addressing upfront costs in isolation without tackling the underlying distortion from subsidies may yield limited success in accelerating widespread solar PV adoption.

The prevailing electricity price plays a crucial role. Rising electricity costs can serve as a significant catalyst for solar PV adoption, as households increasingly seek to reduce their energy expenditure (Juliusson, 2024; Tetteh, 2021). Consequently, retail electricity prices often exhibit a positive

correlation with solar adoption rates. However, the Bahraini residential sector presents the opposite scenario: historically, high subsidies create an artificially low electricity tariff, which acts as a fundamental barrier to solar PV adoption by severely diminishing the financial attractiveness of self-generation (Sanfilippo et al., 2024; SEU, 2017). This effect is so pronounced that surveys in Qatar have found residents are largely unencouraged by potential savings on electricity bills, precisely because electricity is already heavily subsidized or free (Alrawi et al., 2022). Quantitative analysis further confirms that subsidy status is a powerful determinant of behavior, with subsidized households in Qatar consuming drastically more electricity and being far less motivated by cost savings than their non-subsidized counterparts (Zaidan et al., 2025). The stark disparity between the subsidized residential tariff (as low as $0.008/kWh) and the government's cost of electricity (around $0.074/kWh)(Alnaser, 2015), dramatically illustrates this distortion. As Alsabbagh (2019) and EzzEldin et al. (2022) demonstrate that this low tariff environment renders even supportive policies like net metering less effective and extends solar PV payback periods to economically unviable lengths (e.g., 83.5 years versus 9.6 years at a cost-reflective tariff). This critical finding underscores the core premise of this thesis: sustainable and widespread solar PV adoption in Bahrain likely necessitates not just add-on incentives but a more fundamental reform of the electricity pricing structure itself, coupled with mechanisms to manage the transition for households.

The household Income level has a more complex influence on adoption. Several studies have identified a positive correlation, suggesting that higher-income households are more likely to adopt such policies because of their greater capacity to absorb upfront costs (G. Jones et al., 2025; Schulte et al.,

2022; Zander et al., 2019). For instance, in Bahrain, Alsabbagh (2019) observed a significant association between household income and willingness to pay for residential PV, with a considerable portion of survey respondents falling within an income bracket close to the national average. However, the universal significance of income as a direct driver is debated, and some studies indicate that its influence might be less critical or can be effectively mitigated by targeted policies aimed at low- and medium-income (LMI) households (Schulte et al., 2022; Tetteh, 2021). Other studies, possibly conducted in different socioeconomic contexts or with varying policy landscapes, have found no significant direct effect of income on adoption rates (Balta-Ozkan et al., 2013; Zander, 2020). This variability suggests that the role of income is likely moderated by other factors, including the availability of financing and specific policy support.

Consequently, Financial Incentives—such as subsidies, tax credits, loans, and Feed-in Tariffs (FITs)—are widely recognized as crucial instruments for promoting solar PV adoption (Tetteh, 2021; Zander et al., 2019). These mechanisms aim to overcome the barrier of high upfront costs and enhance the overall financial attractiveness of solar PV systems (Juliusson, 2024; Rai & Sigrin, 2013; San-Martín & Elizalde, 2024). Indeed, a recent study in Oman concluded that the potential for growth in the solar sector is directly dependent on the government's capacity to provide substantial incentives and financial support (Mishrif & Khan, 2024). In Bahrain, public interest in solar PV installation was notably higher when full government subsidization was posited, with nearly half of the survey respondents expressing such conditional interest (Alsabbagh, 2019). This finding underscores the explicit emphasis that Bahraini residents place on government financial support,

particularly for covering initial capital costs. Policy proposals in Bahrain have included considerations for a residential sector FIT, with one study suggesting a specific rate (Alnaser, 2018), and another proposed a FIT combined with a government subsidy on capital costs (Haji et al., 2017). However, traditional policy instruments common in other regions may have limited applicability in the Gulf. For instance, incentive policies based on tax reductions are ill-suited for the tax-free, subsidized economies of the GCC, necessitating the design of alternative frameworks (Qadir et al., 2023). The Bahraini government also initiated plans for solar PV installations in government-built houses, commencing with a pilot project in 2018. However, the effectiveness of such subsidies is not guaranteed and can be undermined if they are not carefully designed, or if the specific socioeconomic attributes of the target population are overlooked (Tetteh, 2021). For instance, a subsidy might be insufficient for very low-income households or poorly communicated to eligible groups. Furthermore, some analysts suggest that, as the baseline costs of solar PV technology continue to decrease, the direct impact of subsidies on the adoption decisions of certain adopter segments might lessen over time (Juliusson, 2024). This implies that, while subsidies are critical for market initiation and for specific demographics, their long-term necessity or form might evolve. For instance, the non-residential sector may respond more strongly to incentives that reduce upfront costs through mechanisms such as tax base reductions, reflecting different financial priorities compared with individual households (San-Martín & Elizalde, 2024). Therefore, while various incentives are important, this thesis posits that their ultimate effectiveness in Bahrain hinges on addressing the larger structural issue of electricity subsidies through comprehensive reform, a pathway that this research explores in detail.

2.2.2 Socio-Demographic Factors

Beyond economic calculations, the socio-demographic characteristics of households also play a discernible role in shaping their propensity to adopt residential solar PV systems. These factors provide context for the decision-making unit and can interact with economic and psychological determinants.

One frequently considered characteristic is the age of householders. The influence of age on solar PV adoption varies notably across empirical studies. Research by Lemay et al. (2023) demonstrates a positive correlation in their analysis of residential solar adoption patterns, suggesting that older householders exhibit a greater inclination towards adoption, potentially due to their accumulated financial stability and established homeownership tenure. In contrast, Dharshing's (2017) examination of German households found age to have minimal predictive power, while Karytsas et al.'s (2019) study of Mediterranean regions revealed more complex relationships, where age effects were significantly moderated by other socioeconomic factors. Recent studies from the GCC region reflect this complexity; research in Oman suggests younger generations are more willing to adopt solar in the future (Mishrif & Khan, 2024), while other work from Qatar has found age to be significantly related to awareness levels (Alrawi et al., 2022). A systematic review of developing countries suggests this variation may be due to younger households facing more acute affordability constraints despite higher environmental awareness, while older households may prioritize more practical benefits (Oliva & Atehortua Santamaria, 2025). These contrasting findings from different geographical and cultural contexts suggest that the impact of age on solar PV adoption is not uniform, but rather depends heavily

on the specific socioeconomic environment and life circumstances of the individuals involved.

By contrast, educational level is more frequently associated with a greater likelihood of solar PV adoption (Jan et al., 2020; G. Jones et al., 2025; Niamir et al., 2020; San-Martín & Elizalde, 2024; Zander, 2020). It is often posited that more educated individuals may possess a better understanding of the complex financial and environmental benefits associated with solar PV systems, or they may have greater access to and ability to process relevant information (Simpson & Clifton, 2017). This general trend aligns with the findings from Bahrain, where Alsabbagh (2019) reported a significant association between willingness to pay for residential solar PV and education level. Notably, the majority of those willing to bear the full cost held bachelor 's degrees, and approximately 40% of all study participants had a bachelor's degree as their highest educational attainment. This regional finding aligns with broader trends, as lower overall education rates in developing nations can create barriers to understanding the technology (Oliva & Atehortua Santamaria, 2025), and studies in Qatar have also linked education level to solar energy awareness (Alrawi et al., 2022). Nevertheless, it is important to acknowledge that some studies, potentially from different cultural or economic settings, where information access or priorities differ, report no significant influence of education on adoption decisions (Karytsas et al., 2019). This suggests that, while education is often positively correlated, its role might be nuanced by other contextual variables.

Other demographic factors with particular relevance in the GCC context include gender and citizenship status. For instance, a study in Qatar found that gender had a notable impact on the level of knowledge about solar energy

(Alrawi et al., 2022). More critically, the distinction between citizen and non-citizen residents—a defining feature of GCC societies—can be a powerful, yet often overlooked, socio-demographic determinant. Policies, particularly energy subsidies, are often applied differently to these groups, which profoundly shapes consumption patterns, economic incentives, and ultimately, the propensity to adopt new energy technologies (Zaidan et al., 2025).

Household Size and Structure are also features of adoption models, although their direct influence can be multifaceted. For instance, factors such as mean house size (which often correlates with energy demand) and overall family income (which is related to both household structure and affordability) are considered potential influences on the decision to invest in solar PV systems (San-Martín & Elizalde, 2024). Larger households might perceive a greater potential for savings from solar PV owing to higher energy consumption, but they might also face more complex internal decision-making processes or competing financial priorities. The specific interplay between these elements within household dynamics warrants further investigation in diverse contexts.

2.2.3 Policy & Regulatory Factors

The policy and regulatory landscape exerts a critical influence in shaping the residential solar PV market and directly impacts household adoption rates. These frameworks establish the operational and financial conditions under which the solar PV technology can be adopted and integrated.

Net Metering Rules represent a fundamental policy instrument for promoting residential solar energy adoption. These regulations establish a framework through which homeowners can receive credit for surplus electricity exported

to the grid, creating a direct financial incentive for solar PV installation (Lemay et al., 2023; San-Martín & Elizalde, 2024). However, the effectiveness of net metering policies critically depends on their specific design and implementation. Research shows that changes to these provisions, particularly those reducing homeowner compensation, can significantly diminish the financial viability of solar PV investments and, consequently, impede adoption rates (Lemay et al., 2023). Bahrain's experience provides an illustration of how net metering effectiveness interacts with broader energy policy structures. Although the country introduced net metering in 2017 as part of its renewable energy initiative, its impact has been notably constrained. The primary limiting factor is the prevailing low residential electricity tariffs, which substantially reduce the value of exported electricity, and thus undermine the financial incentives that net metering is designed to create (Alnaser, 2023b). This case clearly demonstrates how the success of specific renewable energy policies can be fundamentally contingent on a wider energy policy environment, particularly existing subsidy structures.

Beyond compensation mechanisms, clear and efficient Grid Connection Policies are essential to facilitate solar PV adoption. Procedural challenges or complexities in accessing the electricity grid can significantly influence homeowners' decisions to invest in solar PV systems (Schulte et al., 2022). In developing contexts, such as Ghana, the fundamental aspects of electricity access and the ease of grid connection are foundational for analyzing renewable energy adoption trajectories (Tetteh, 2021). In Bahrain, the National Renewable Energy Action Plan (NREAP) explicitly aims to promote renewable energy, including decentralized urban solar power generation. The Sustainable Energy Unit (SEU) plays a coordinating role among various

energy stakeholders to streamline the processes related to this goal (SEU, 2017), although the perceived ease and speed of connection remain important practical considerations for potential adopters.

Furthermore, overall Policy Stability and Certainty surrounding the renewable energy sector are paramount. The stability and predictability of support policies, including subsidies and incentives, significantly influence investor confidence and adoption momentum. Frequent or unexpected changes to these policies, such as abrupt alterations in subsidy amounts or eligibility criteria, can create market uncertainty and negatively affect adoption trends (Juliusson, 2024). This is a particularly acute barrier in developing countries, where inconsistent policy support often hinders widespread solar PV adoption (Oliva & Atehortua Santamaria, 2025). Recent research from the GCC region reinforces this point, with one study on Oman concluding that the growth of the solar industry is highly dependent on the government's ability to introduce a clear and stable solar energy policy (Mishrif & Khan, 2024). Moreover, policy design must be tailored to the unique economic context; frameworks successful elsewhere may not apply in the GCC, where heavily subsidized electricity and the absence of income tax render policies like tax credits ineffective, necessitating the design of novel, context-specific incentive structures (Qadir et al., 2023). For long-term success, policy measures should ideally be designed holistically, considering the intricate interplay of economic, geographic, cultural, and social factors that influence adoption (Fauzi et al., 2023). Bahrain made a significant stride in this direction when its Cabinet endorsed the first national renewable energy action plan in 2017. The subsequent establishment of the SEU led to the development of both the NREAP and the National Energy Efficiency Action Plan (NEEAP), which, for

the first time, set clear renewable energy and energy efficiency targets for the country, thereby providing a strategic direction (SEU, 2017). Perceived commitment to long-term targets can foster a more stable environment for solar PV investment.

2.2.4 Social & Network Factors

The diffusion of residential solar PV technology is significantly shaped by social interactions and network effects, operating beyond individual household characteristics or economic evaluations. These factors underscore the inherent social nature of the adoption decisions.

The dominant social mechanisms are Peer Effects and Neighbor Influence. The adoption decisions of peers, friends, and neighbors can strongly influence a household's likelihood of installing solar PV (Juliusson, 2024; Min, 2025; Varun Rai et al., 2016; Wang et al., 2023). This phenomenon, often described as "social contagion" or a "snowball effect," effectively accelerates the spread of solar PV technology through interpersonal communication and direct observation (Curtius et al., 2018; Wang et al., 2023). A recent systematic review highlights that peer effects are particularly prevalent in developing countries, where strong community ties mean that observing a neighbor's successful installation serves as a powerful signal of the technology's trustworthiness and feasibility (Oliva & Atehortua Santamaria, 2025). This has been quantified in other contexts, with recent econometric analysis from Spain confirming that neighboring peer effects are a statistically significant and positive determinant of residential solar PV adoption (San-Martín & Elizalde, 2024). Such peer effects can provide valuable and trusted information, thereby reducing perceived uncertainties and potentially shortening the decision-making period for prospective adopters (Rai &

Robinson, 2013). The mere visibility of solar PV systems in neighbors' homes can act as a powerful signal, enhancing awareness and normalizing the technology, thus encouraging further adoption (Wolske et al., 2017).

Social Norms form an intricate layer of influence that operates in tandem with peer effects to shape adoption behavior. Wang et al. (2023) demonstrate how community awareness and prevailing social norms significantly influence both the broader implementation of solar PV projects and individual adoption decisions. These collective behavioral patterns, which Negro et al. (2012) characterize as "soft" institutions, serve as powerful determinants of the evolution and trajectory of renewable energy technology adoption across society. This is particularly critical in the GCC, where a lack of widespread implementation has created a public awareness gap that hinders the formation of pro-adoption norms (Alrawi, 2023). Recent surveys in both Qatar and Oman identify this lack of awareness as a primary barrier to adoption, suggesting that current social norms do not yet actively encourage the shift to solar energy (Alrawi et al., 2022; Mishrif & Khan, 2024). The interplay between these social norms and individual decision making creates a dynamic feedback loop in which community values and practices both shape and are shaped by adoption patterns. Understanding local social norms is therefore crucial; for instance, prior to a study by Albuflasa (2018), public acceptance of residential solar panels had not been systematically researched in Bahrain, highlighting a knowledge gap concerning local attitudes and norms related to this specific technology. That study specifically aimed to explore these public perspectives, recognizing their potential influence on adoption pathways.

Community Initiatives also represent an important facet of social influence and can broaden access to solar energy. For example, community solar

programs offer a viable alternative for individuals who may be unable to install rooftop solar due to housing type (e.g., renters) or financial constraints, potentially expanding the benefits of renewable energy, particularly to low-income households (Dillman-Hasso & Sintov, 2025). Beyond formal programs, social influence can manifest more informally, as early adopters inspire others within their community to consider solar PV (Juliusson, 2024). In Bahrain, a clear desire for community-level engagement was evident in survey participants' requests for fully funded demonstration projects distributed across different areas of the country, with a stipulation that the results should be communicated publicly (Alsabbagh, 2019), underscoring the value placed on shared learning and visible local examples. This aligns with findings from Oman, where awareness campaigns using social media, workshops, and community events were identified as essential for promoting solar energy (Mishrif & Khan, 2024).

2.2.5 Psychological & Behavioral Factors

Individual psychological attributes and ingrained behavioral patterns are key determinants of how households perceive and decide on the adoption of solar PV systems. These factors often interact with the economic and social factors.

Environmental Awareness and Attitudes are frequently cited as significant motivators for many households to adopt solar PV (G. Jones et al., 2025; Juliusson, 2024; Qureshi et al., 2017; San-Martín & Elizalde, 2024; Zander, 2020). Aspiration to reduce personal carbon footprints and actively contribute to a more sustainable future often drives adoption decisions, even when financial benefits are considered (Juliusson, 2024). However, the link between attitude and action is not always direct; some studies note an "attitude-behavior gap," where generally favorable environmental attitudes do not

consistently translate into actual adoption behaviors (Dharshing, 2017). This gap can be attributed to various other barriers such as cost and perceived complexity. This is particularly true in the GCC, where a persistent awareness gap has been identified as a primary barrier to adoption (Alrawi, 2023; Mishrif & Khan, 2024). Research on the public perception of solar PV systems in Bahrain has revealed a significant knowledge gap regarding their environmental advantages. Multiple studies have highlighted that while Bahraini residents show interest in solar technology, they demonstrate a limited understanding of its environmental implications (Alsabbagh, 2019). Despite the documented potential for significant CO2 reduction - approximately 4.637 tons annually per household with a 7.8 kW system - survey participants rarely mentioned environmental benefits unprompted (Alnaser et al., 2023; Haji et al., 2021). This disconnect between environmental benefits and public awareness is particularly noteworthy, given that successful renewable energy adoption typically correlates with high levels of environmental consciousness (SEU, 2017). Recent regional surveys confirm this challenge; a study in Qatar found that only 16% of the public had a full understanding of solar energy uses, and another in Oman identified a lack of awareness as one of the top two barriers to adoption (Alrawi et al., 2022; Mishrif & Khan, 2024). This awareness deficit, which exists despite high general interest in solar technology, presents a substantial barrier to achieving Bahrain's renewable energy targets and underscores the critical need for enhanced public education and awareness campaigns.

Assessment of Perceived Benefits versus risks is another critical psychological component. Households are demonstrably more likely to adopt solar PV if they perceive it as useful and beneficial, particularly in terms of

reducing energy costs and enhancing the reliability of their energy supply (Schulte et al., 2022; Tetteh & Kebir, 2022). Conversely, perceived risks, such as uncertainties about the long-term performance of the technology or actual financial returns, can act as significant barriers to adoption (Varun Rai et al., 2016). Indeed, household risk preference is a critical variable in renewable energy investment decisions (Qadir et al., 2023). In the GCC, the perception of benefits is fundamentally altered by the subsidy environment. For example, a study of households in Qatar found that cost savings, a key benefit, were a primary motivation for energy conservation for 72% of non-citizens but only 35% of subsidized citizens, demonstrating how subsidies can reshape behavioral motivations (Zaidan et al., 2025). Research on public perception of solar PV in Bahrain reveals a complex relationship between adoption interest and perceived barriers. While Alsabbagh (2019) found substantial public interest in solar panel adoption, her findings warrant careful examination in the broader context of renewable energy implementation. Although scientifically unfounded, the identified health concerns reflect a critical gap in public understanding that other researchers have observed in similar contexts (Alnaser et al., 2023; Haji et al., 2021). These perceived health risks align with broader patterns of misconceptions about renewable energy technologies documented across the Gulf Cooperation Council (GCC) region (Albuflasa et al., 2022). However, Alsabbagh's methodology in assessing these perceptions could have benefited from a more detailed investigation of the origins of these health concerns, particularly given that subsequent studies have emphasized the importance of addressing such misconceptions through targeted educational initiatives (SEU, 2017). This analysis suggests that future research should focus more explicitly on the

relationship between public education and barrier perceptions in Bahrain's renewable energy transition.

Trust in Technology and Installers is a vital psychological factor. A high degree of trust in the reliability of the solar PV technology itself, as well as in the competence and integrity of installers and providers, is important for encouraging adoption. This is especially true in developing country contexts, where trust in both developers and suppliers is paramount for households to make a significant investment (Oliva & Atehortua Santamaria, 2025). Conversely, a generalized distrust in established utility companies has, in some contexts, been linked to increased interest in solar energy as a means for households to gain greater energy independence and control (Horne et al., 2021). In Bahrain, a "lack of trust in PV" was explicitly identified as a barrier by some residents (Alsabbagh, 2019), indicating that building confidence in technology and its ecosystem is crucial.

Finally, access to information and knowledge play a fundamental role in the decision-making process. Access to clear, reliable, and easily understandable information is crucial for potential adopters (Fauzi et al., 2023; Juliusson, 2024; Varun Rai et al., 2016). A lack of sufficient information or misinformation from suppliers can act as a significant barrier by increasing the perceived complexity and effort required for adoption (Juliusson, 2024; Schulte et al., 2022). This challenge was particularly evident in Bahrain, where the "lack of necessary information on PV" was the second most commonly cited barrier to adoption in Alsabbagh's (2019) study. More than half of the participants in the Bahraini survey reported having little or no specific knowledge about solar energy as it pertains to Bahrain, a factor that significantly influenced their willingness to pay for solar PV systems. This

information gap is a consistent theme across the region (Alrawi et al., 2022; Mishrif & Khan, 2024). Different information channels, including professional installers and peer networks, play vital roles in various stages of the adoption journey (Varun Rai et al., 2016; Wolske et al., 2017). In Bahrain, the preferred channels for receiving information on solar energy include social media, television, and newspapers (Alsabbagh 2019).

2.2.6 Technical & Physical Factors

The physical characteristics of a property and various technical aspects of the solar PV system are fundamental, often non-negotiable, determinants of adoption feasibility and attractiveness.

Roof Suitability encompassing factors such as size, orientation, and shading is paramount. The appropriateness of a building's roof structure, considering its available dimensions, its directional facing (with south-facing often being optimal in the Northern Hemisphere), and the absence of significant shading from nearby structures or vegetation, plays a vital role in the viability of solar PV system installation (G. Jones et al., 2025; Juliusson, 2024; Schulte et al., 2022). Recent literature reinforces this by using variables such as mean house size as a proxy for available roof space in econometric models (San-Martín & Elizalde, 2024). Unsurprisingly, buildings with optimal roof features are more inclined to successfully implement solar PV (Juliusson, 2024). Additionally, local insolation, which refers to the amount of solar energy available at a specific geographic location, is a crucial technical element that directly affects potential energy generation (Lemay et al., 2023). The spatial constraints of solar PV installation in Bahrain present unique challenges that distinguish it from other markets. While Alsabbagh's (2019) study identified limited roof space as a barrier, subsequent research has expanded this finding's

significance in the Bahraini context. For instance, Ezzelden et al. (2022) found that the architectural and structural features in Bahraini buildings typically leave only 35% of the roof area available for solar PV installation. This spatial limitation contrasts sharply with the experiences of other regions; for example, studies in the UAE and Saudi Arabia have reported significantly higher usable roof areas (Elshurafa et al., 2019). Furthermore, the challenge extends beyond mere space availability; Alnaser et al. (2023) demonstrated that Bahraini homes must balance solar PV installation with cultural practices of roof space utilization, particularly during moderate weather periods that constitute approximately 70% of the year. These findings suggest that successful solar PV implementation in Bahrain requires solutions specifically tailored to the local architectural and cultural contexts.

Expectations regarding System Performance, including anticipated energy output and long-term reliability, significantly influence adoption decisions (Tetteh, 2021). Misinformation or unrealistic expectations concerning system performance can act as a barrier if potential adopters feel misled (Juliusson, 2024). The perceived reliability and durability of solar panels are especially important in developing nations, where technical support may be limited and complexity can be a major deterrent (Oliva & Atehortua Santamaria, 2025). Studies conducted in Bahrain have provided varied estimates of residential solar PV performance. For instance, an early study by Alnaser (2015) suggested that a system could meet approximately 12% of a typical house's demand, while a subsequent study by Alnaser (2018) found that the actual generation could be 26-37% less than initially estimated under certain conditions. Environmental factors prevalent in GCC countries, including Bahrain, such as dust accumulation and high humidity, can theoretically

reduce the solar PV efficiency (Mas'ud et al., 2018). However, it is important to contextualize this; specific research conducted in Bahrain by Alnaser et al. (2018) calculated that the overall negative impact of these ambient weather conditions on solar PV efficiency was relatively low, estimated at only around 7.2%.

Finally, Maintenance Concerns regarding the operation and maintenance (O&M) of solar PV systems can be a significant factor in adoption calculus. These concerns can particularly influence the choice between outright purchasing a system versus leasing or opting for a third-party ownership model, where the provider typically handles maintenance (Varun Rai et al., 2016). Maintenance concerns have emerged as a significant barrier to solar PV adoption in Bahrain, warranting careful analysis within the local context. This is a consistent finding across the region, with a recent survey in Oman also identifying high maintenance costs and a lack of technical support as major barriers to adoption (Mishrif & Khan, 2024). Although Alsabbagh (2019) identified maintenance as the third most significant barrier, subsequent studies have provided deeper insights into the practical implications of these concerns. For instance, Alnaser et al. (2023) demonstrated that regular cleaning of solar PV panels, required every 15 days in Bahrain's dusty environment, significantly impacts the system performance and efficiency. This finding is supported by empirical evidence from the first domestic solar PV installation in Bahrain, where the performance varied by up to 16.3% between cleaned and uncleaned panels (Alnaser, 2018). Haji et al. (2021) calculated that maintenance costs, including monthly cleaning and inverter replacement, constitute approximately 0.5-1% of the total installation costs annually. These maintenance requirements present particular challenges in

Bahrain's climate, where dust accumulation and high temperatures can significantly reduce the system efficiency (Ezzelden et al., 2022). Notably, these concerns persist even when the initial installation costs are subsidized, suggesting that public policy must address both upfront and long-term operational costs to encourage widespread adoption.

A critical examination of adoption determinants reveals several significant insights regarding residential solar PV adoption in Bahrain's distinctive market environment. Three key findings emerged from this analysis. First, the presence of electricity subsidies fundamentally alters conventional economic adoption drivers, creating market dynamics that deviate substantially from those observed in unsubsidized environments (Sanfilippo et al., 2024). This market distortion necessitates careful reconsideration of traditional policy approaches.

Second, economic determinants operate through complex social and cultural mechanisms. Empirical evidence suggests that community networks and trust relationships significantly mediate adoption decisions, particularly in Bahrain's socially interconnected context. These social dynamics are particularly salient when considering policy interventions in established subsidy systems (Wang et al., 2023).

Third, technical and infrastructural constraints interact with behavioral factors in distinctive ways within Bahrain's environment. Local climate conditions, architectural practices, and cultural considerations create unique adoption parameters that require careful consideration for both policy design and implementation strategies (EzzEldin et al., 2022). These findings suggest that successful adoption frameworks must address multiple interrelated barriers while acknowledging the local contextual factors.

This analysis has significant implications for policy development and modeling. The observed complexity of the interactions between determinants indicates that effective interventions must simultaneously address multiple adoption barriers while recognizing their interdependencies. Moreover, the distinctive characteristics of Bahrain's energy market suggest that policy mechanisms require careful adaptation to local conditions rather than the direct application of approaches that have been successful elsewhere.

The subsequent section examines specific policy mechanisms, particularly focusing on subsidy reform and compensation approaches based on this empirical foundation. This examination illuminates how understanding the intricate relationships between adoption determinants can inform more effective and contextually appropriate policy designs.

2.3. Energy Subsidy Reform and Compensation Mechanisms

Energy subsidy reforms represent a fundamental paradigm shift in global energy policy, intersecting critically with sustainable development objectives and fiscal sustainability imperatives. The pervasiveness of energy subsidies, particularly in fossil-fuel-dependent economies, has created deeply entrenched market distortions that significantly influence both economic behavior and technological transitions (Solaymani, 2021). These distortions are especially pronounced in GCC countries, where historically low energy prices have shaped consumption patterns and investment decisions (Al-Saidi, 2020).

The complexity of reform processes, particularly in contexts with long-established subsidy systems, necessitates sophisticated policy approaches that

address multiple, often competing objectives. Within this context, cash transfer (CT) programs have emerged as prominent policy instruments, although their effectiveness critically depends on design parameters and implementation strategies aligned with local socioeconomic conditions. Bahrain's distinctive market environment, characterized by substantial electricity subsidies and ambitious renewable energy targets, provides a particularly relevant context for examining these dynamics (Alabbasi, 2021). This section systematically examines the theoretical foundations and practical implications of energy subsidy reform and the associated compensation mechanisms, with a particular focus on their relevance to residential solar PV adoption in Bahrain's market context.

2.3.1 Rationale for Subsidy Reform

Arguments advocating for the reform of energy subsidies are compelling and multifaceted, primarily focusing on the pursuit of economic efficiency, fiscal sustainability, and substantial environmental benefits. These rationales underscore the detrimental effects of subsidies and potential gains from their removal or restructuring.

A core argument revolves around Economic Distortions created by subsidies. By artificially lowering energy prices, subsidies distort market signals, which, in turn, lead to an inefficient allocation of resources and often result in the overconsumption of subsidized fuels (Boersma & Griffiths, 2016; Solaymani, 2021). A recent case study from Jordan provides a stark, quantitative example of this effect, revealing that households receiving electricity subsidies consumed, on average, 615 kWh/month—more than double the 296 kWh/month consumed by non-subsidized households in the same environment (Albatayneh et al., 2023). This environment actively discourages

investment in energy efficiency measures and cleaner energy alternatives, as conventional energy sources that benefit from subsidies appear deceptively more economically attractive (Alabbasi, 2021; Solaymani, 2021). In the specific context of Bahrain, the nation's heavy dependence on subsidized fuel for power generation has been identified as a key factor obscuring the true cost of electricity production. Consequently, unsubsidized investments in renewable energy appear comparatively costly, necessitating supportive policies to level the playing field (Alabbasi, 2021). Therefore, the fundamental aim of removing these subsidies is to correct these distorted price signals, thereby fostering a more efficient energy market and encouraging a societal shift towards more sustainable energy consumption patterns (Zarepour, 2022).

Beyond market inefficiencies, energy subsidies impose a significant Fiscal Burden on the government. These subsidies divert substantial public funds that could otherwise be channeled into essential public services, such as healthcare, education, or critical infrastructure development (Al-Saidi, 2020; Boughanmi & Khan, 2019; Solaymani, 2021). In many oil-exporting nations, including those within the GCC, these subsidies often manifest as lost export revenue rather than direct budgetary outlays; however, the economic cost to the nation remains substantial, regardless of the accounting method (Al-Saidi, 2020; Moayed et al., 2021). Prior to recent reform efforts, energy subsidies in GCC countries such as Bahrain were among the highest globally (Al-Saidi, 2020). To illustrate the scale, UAE subsidies in 2013 were estimated at over $20 billion, while Bahrain's specific total for that period is not detailed in the same comparative figure; the regional context clearly highlights the potential magnitude of such expenditures. Facing economic pressure exacerbated by declining oil prices in 2014, Bahrain initiated restructuring of its electricity

tariffs. Although these reforms were somewhat limited in scope, they resulted in government savings of approximately £261 million between 2015 and 2018 (Alabbasi, 2021), clearly indicating both the fiscal strain subsidies imposed and the potential savings achievable, even through partial reforms. Furthermore, an analysis of Bahrain suggests that the foregone consumption tax revenue due to subsidies is higher than the direct environmental cost of these subsidies, pointing to a significant loss of government revenues that could be redirected to beneficial public spending (Boudekhdekh, 2022). Despite initiated reforms, subsidization levels often remain high across regions (Al-Saidi, 2020). It is also noteworthy that the primary motivations for some reforms can vary; for instance, Iran's 2010 Subsidy Removal and CT program was reportedly aimed at managing national energy consumption and achieving a more equitable distribution of national wealth rather than being driven solely by fiscal consolidation objectives (Boersma & Griffiths, 2016; Zarepour, 2022).

Finally, the environmental impacts of energy subsidies are a major concern. These subsidies contribute significantly to environmental degradation by promoting the increased consumption of fossil fuels. These include elevated greenhouse gas (GHG) emissions, which drive climate change, as well as increased local air pollution and associated public health problems (Belhadj et al., 2022; Boersma & Griffiths, 2016; Solaymani, 2021). Consequently, subsidy reform is recognized as a key policy instrument for achieving international climate-change mitigation targets and improving local environmental quality (Solaymani, 2021). For example, Tunisia's energy mix remains heavily reliant on subsidized fossil fuels, a dependency that actively hinders its ability to meet GHG reduction commitments (Belhadj et al., 2022).

In Bahrain, the significant projected costs associated with global warming are considered a strong impetus for pursuing energy subsidy reforms (Boudekhdekh, 2022). The country's Intended Nationally Determined Contributions (INDCs) submitted under the UNFCCC also signify a commitment that aligns with reducing reliance on subsidized fossil fuels, although it is noted that Bahrain's capacity to fulfill these commitments is highly dependent on receiving international support (Griffiths, 2017). Numerous studies suggest that the removal or reduction of energy subsidies can lead to tangible reductions in the overall energy consumption and associated emissions (Solaymani, 2021).

2.3.2 Challenges of Reform

Despite the compelling rationale for the energy subsidy reform discussed in the previous section, the implementation of such reforms presents significant challenges that span political, social, economic, and administrative dimensions. Understanding these challenges is crucial for designing effective reform strategies that can achieve their intended objectives, while maintaining social stability and political feasibility.

The potential for strong opposition has been demonstrated across various MENA countries, notably Ecuador, where subsidy removal attempts have triggered significant public resistance (Al-Saidi, 2020; Schaffitzel et al., 2020). This is not unique to developing nations; even advanced economies like France have experienced major social protests in response to energy price increases, highlighting that such reforms must be carefully adapted to the unique political and social fabric of the country in question (B. Jones & and Cardinale, 2023). In the GCC, the pace of reform has varied significantly, with countries like Kuwait facing strong parliamentary opposition that has delayed

changes, while fiscal pressures have forced more rapid action in others (Moerenhout, 2022). Therefore, successfully implementing reforms requires not only strong and sustained political commitment but also carefully crafted communication strategies to build public understanding and support (Boersma & Griffiths, 2016; Moayed et al., 2021; Solaymani, 2021).

A second critical challenge concerns Social Impact and Potential Regressivity. The immediate consequence of subsidy removal is invariably an increase in energy prices, which can adversely affect household welfare, particularly among low- and middle-income families that typically allocate a larger proportion of their income to essential energy services (Boughanmi & Khan, 2019; Solaymani, 2021; Zarepour, 2022). While energy subsidies often disproportionately benefit wealthier households in absolute terms, owing to their higher consumption levels, the removal of these subsidies can be regressive in relative terms if not accompanied by adequate compensatory measures (Boughanmi & Khan, 2019). For example, one study in Jordan found that 40% of energy subsidies benefited the top 20% of high-income households (Albatayneh et al., 2023). The resulting increase in living costs can potentially exacerbate existing poverty and inequality (Zarepour, 2022). In Bahrain, electricity tariffs have historically been maintained at low levels for both social and economic reasons, with the domestic sector receiving highly subsidized electricity (55-80%) (Albuflasa, 2018). The country has demonstrated some awareness of its social implications. For instance, when removing meat price subsidies, Bahrain implemented compensation for local citizens (although notably not for expatriates) to cushion the impact (Boersma & Griffiths, 2016), highlighting the need to protect certain population segments during the reform processes.

GCC nations have employed distinct strategies to manage the social impact of subsidy reforms. The UAE, an early reformer, saw its expatriate workforce bear a significant portion of adjustment costs (Alsayegh et al., 2025). Tariff designs in the Emirates, such as Abu Dhabi, include social considerations, offering highly subsidized initial consumption blocks for low-income citizens (Alsayegh et al., 2025). Oman uses a tiered tariff system based on citizenship, account numbers, and consumption (Alsayegh et al., 2025). The absence of explicit, broad CT programs in both the UAE and Oman, unlike Saudi Arabia, makes the full extent of welfare protection less clear. In Kuwait, the potential for profound social disruption from reforming near-free electricity tariffs underscores the historical reluctance to change residential pricing without robust compensation (Alsayegh et al., 2025).

The Macroeconomic Impacts of subsidy reform present another significant challenge, particularly in the short-term. Price increases can trigger inflationary pressures, while a broader adjustment process may temporarily dampen economic growth (Solaymani, 2021; Zarepour, 2022). Iran's experience with its 2010 reform provides an instructive example, where the changes resulted in both short-term negative impacts on GDP and persistent inflationary effects that extended into the longer term (Zarepour, 2022). While specific macroeconomic impact studies for Bahrain's limited electricity tariff reforms are not extensively detailed in the literature, a regional analysis by the IMF suggests that the inflationary impact of higher energy prices in the GCC context might be relatively contained (Boughanmi & Khan, 2019), although this assessment requires careful consideration given each country's unique economic circumstances.

Finally, Implementation Challenges can significantly undermine reform effectiveness, even when political issues exist. The success of reforms can be compromised by incomplete or poorly managed implementation processes (Solaymani, 2021). A particularly demanding aspect involves the practical difficulties of designing and delivering compensatory measures, which necessitate robust data systems, effective targeting mechanisms, reliable payment channels, and significant administrative capacity, institutional elements that are often underdeveloped in many countries (Al-Saidi, 2020; Moayed et al., 2021). Bahrain's approach to electricity tariff restructuring, which involved categorizing subscribers based on citizenship status and the number of accounts, illustrates the administrative complexity involved, as such differentiation requires substantial institutional capacity for effective implementation (Alabbasi, 2021; Albuflasa, 2018).

The need for advanced administrative systems is evident across GCC subsidy reforms. Both Oman and the UAE have implemented complex, multi-tiered electricity tariffs based on consumption, citizenship, account numbers, and sometimes income (Alsayegh et al., 2025). While aiming for precise targeting, these designs require robust data management and administrative capacity. Kuwait's primary implementation hurdle has been the political and social difficulty of moving from its extremely low flat-rate residential tariff rather than administrative complexity, despite the proposed reform scenarios (Alsayegh et al., 2025).

2.3.3 Role of Cash Transfers (CTs)

Cash transfers have emerged as a cornerstone strategy in energy subsidy reform efforts, serving both to mitigate the negative consequences of reform and enhance their public and political acceptability. These transfers represent

a direct mechanism for addressing the social and political challenges identified in the previous section, while facilitating the achievement of reform objectives.

A primary function of cash transfers is to mitigate the adverse welfare impacts on households affected by subsidy reform. These transfers provide direct financial assistance to households, helping cushion the impact of higher energy prices on their budgets and purchasing power (Boughanmi and Khan, 2019; Moayed et al., 2021; Schaffitzel et al., 2020; Solaymani, 2021). Iran's 2010 reform offers an instructive example; their universal CT program was specifically designed to compensate households for the income effects resulting from subsidy removal, demonstrating how such mechanisms can be integrated into comprehensive reform strategies (Boersma & Griffiths, 2016; Zarepour, 2022). Although Bahrain has not yet implemented a broad energy-related CT program comparable to Saudi Arabia's Citizen's Account, its targeted compensation to citizens following the removal of meat subsidies provides a relevant precedent for direct financial recompense within the country's specific context (Boersma & Griffiths, 2016). This experience suggests both the feasibility of such approaches in Bahrain and the government's recognition of the need for compensatory measures during the subsidy reform.

Beyond their direct welfare effects, cash transfers play a crucial role in Enhancing Social Acceptance and Political Feasibility of subsidy reforms. By directly addressing welfare concerns through tangible compensation, CTs can significantly improve both the social acceptability and political viability of potentially contentious reform processes (Boersma and Griffiths, 2016; Moayed et al., 2021; Schaffitzel et al., 2020). For example, Indonesia

successfully implemented a series of difficult price rises partly due to the introduction of the Bantuan Langsung Tunai (BLT), a direct cash transfer program that was supported by a strong government communication campaign to explain the necessity of the reforms (Jones & Cardinale, 2023). International experience consistently suggests that reforms accompanied by well-designed compensation mechanisms, particularly cash transfers, are more likely to succeed and encounter less public opposition than are uncompensated reforms (Moayed et al., 2021). The timing of these transfers emerges as a critical factor; delivering compensation either before or concurrently with price increases can help build public trust and ensure that vulnerable households are not exposed to immediate financial hardship during the transition period (Al-Saidi, 2020; Moayed et al., 2021). This aligns with broader policy recommendations that advocate for the gradual implementation of reforms accompanied by well-targeted social safety nets (Boughanmi & Khan, 2019), allowing for adjustment periods and fine-tuning of support mechanisms based on observed impacts.

This dual role of cash transfers, which provides direct welfare support while enhancing reform feasibility, makes them a particularly valuable tool in the complex process of energy subsidy reform. Their effectiveness, however, depends critically on proper design, implementation, and considerations, which will be explored in subsequent sections.

2.3.4 Review of Cash Transfer (CT) Designs: Universal vs. Targeted Approaches and International Experiences

Globally, CTs have become prominent policy instruments for mitigating the adverse welfare impacts of subsidy reform, particularly electricity subsidy reform, which affects virtually all households and businesses (Aldubyan and

Gasim, 2021; Atalla et al., 2018). Electricity subsidies are especially challenging to reform, given their universal consumption and direct impact on household budgets, making CTs critical for political feasibility and social acceptance (Hasanov et al., 2020; Moayed et al., 2021). The designs of these CT programs vary significantly, with universal and targeted approaches representing the two main archetypes, each presenting distinct advantages and disadvantages.

Universal or near-universal transfers, exemplified by Iran's 2010 comprehensive energy reform that included electricity subsidies, offer administrative simplicity as they avoid complex means-testing procedures, which can garner broad initial public support (Mukherjee et al., 2023; Solaymani, 2021; Zarepour, 2022). However, such schemes can impose a substantial fiscal burden, particularly in the long term, and their effectiveness may diminish over time if inflation erodes the real value of fixed transfer amounts (Mukherjee et al., 2023; Solaymani, 2021). For example, Iran's experience involved distributing savings from energy subsidy removal as a universal, unconditional CT equivalent to approximately 8% of per capita GDP (Zarepour, 2022). While it has shown some initial positive impacts on poverty and inequality (Solaymani, 2021; Zarepour, 2022), the analysis suggests that it ultimately led to a net decline in real household consumption for many, as the transfer failed to fully compensate for price increases and inflation (Zarepour, 2022; Zarepour & Wagner, 2022). Furthermore, the expected environmental benefits have been questioned (Zarepour, 2022), and the long-term impact of the reform on energy consumption has been debated (Solaymani, 2021; Zarepour, 2022). From the perspective of achieving multifaceted goals, such as equitable compensation, renewable energy

promotion, and fiscal sustainability, such outcomes highlight the inherent trade-offs of overly broad universal schemes.

By contrast, targeted transfers attempt to allocate resources more efficiently by focusing on the most needy or vulnerable populations. The aim is generally to improve distributional equity and generate potential fiscal savings compared with universal schemes (Feltenstein & Datta, 2022; Mukherjee et al., 2023), potentially maximizing benefits for the lowest-income groups (Hanna & Olken, 2018). Evidence from reforms in countries such as Indonesia, which adjusted electricity and fuel subsidies (Widiyanto, 2016), and Pakistan's energy pricing adjustments highlights both the promise and pitfalls of such targeted approaches (Feltenstein & Datta, 2022). Practical challenges frequently associated with targeting include administrative complexity, the high cost of accurate means testing, the significant risk of exclusion errors (failing to reach eligible households, especially those in the informal sector lacking documentation), and occasional political resistance due to perceived unfairness (Moayed et al., 2021; Mukherjee et al., 2023; Solaymani, 2021). Consequently, the success of targeted schemes often depends on the availability of robust data systems, comprehensive social registries, and reliable payment channels, which may be lacking in various contexts (Moayed et al., 2021; Mukherjee et al., 2023). While promising for equity and fiscal prudence, the challenge for targeted CTs, particularly in the context of this research, lies in designing them to also effectively stimulate desired behaviors such as solar PV adoption, rather than solely acting as a social safety net. Bahrain has demonstrated the capacity of targeted approaches in its subsidy policies. For instance, its 2014 electricity tariff restructuring aimed at two specific categories: Bahraini subscribers with more

than one account and non-Bahraini subscribers (Alabbasi, 2021). Similarly, when meat subsidies were removed, compensation was provided specifically to local citizens, excluding expatriates (Boersma and Griffiths, 2016). Electricity and water tariffs in Bahrain also differentiate between Bahraini and non-Bahraini consumers and employ consumption-based thresholds, indicating a targeted subsidization system (Albuflasa, 2018).

In the GCC context, Saudi Arabia's Citizens' Account Program (CAP) offers the most direct regional precedent for using cash transfers to facilitate electricity subsidy reform. Launched in December 2017 explicitly to address "electricity tariffs adjustment," the program strategically disbursed its first payments just before significant electricity price increases took effect in January 2018, ensuring that households received financial support beforehand. The importance of this sequencing was clear, as the government had publicly stated that no further energy price reforms would be implemented until the Citizen's Account cash transfer program was fully operational (Moerenhout, 2022). The CAP targets low- and middle-income Saudi households, with benefits varying based on household size and income level, and reaching approximately 50% of the population (Al-Saidi, 2020; Atalla et al., 2018). Research indicates that the 2018 electricity reforms in Saudi Arabia, supported by the CAP, achieved significant annual welfare gains and contributed to electricity demand reductions (Aldubyan & Gasim, 2021; Hasanov et al., 2020). These studies specifically highlight that cash transfers were essential in making the reforms progressive rather than regressive, effectively protecting vulnerable households from price shocks. Generally, CT programs in the GCC region are increasing; however, for these programs to effectively provide a reliable form of social protection against price rises for

vulnerable households in GCC countries facing poverty issues (such as Oman, Saudi Arabia, and Bahrain), they must be sustained over the long term (Al-Saidi, 2020).

However, while CT programs in the GCC, exemplified by Saudi Arabia's CAP, have been successful in cushioning the immediate impact of energy price increases, such approaches—and potentially those implemented or under consideration in countries such as Oman and Kuwait—often exhibit inherent limitations. For instance, the Saudi program uses categorical tiers for benefits, which can create "welfare cliffs" at income or household size thresholds (Fattouh et al., 2018). Additionally, transfer amounts are frequently administratively determined, rather than precisely calculated, based on individual household subsidy losses, potentially limiting their compensatory accuracy. Critically, from the perspective of broader energy transition goals, CT systems in the region tend to function primarily as social protection mechanisms against higher energy bills, without explicit designs to incentivize renewable energy adoption or facilitate the transition to technologies such as solar PV (Fattouh et al., 2018). This common gap across various national contexts underscores the potential value of exploring alternative CT designs such as the tiered approach examined in this thesis, which aims to simultaneously address equity concerns and promote renewable energy uptake.

Indeed, the limitations identified in sophisticated programs, such as the Saudi CAP, and pertinent to the design and evaluation of CT mechanisms in Oman, Kuwait, and similar economies—particularly the predominant focus on social protection at the expense of direct renewable energy incentivization–are reflective of a broader pattern observed across the spectrum of CT

mechanisms reviewed in the literature. While various universal and targeted CTs effectively mitigate the adverse welfare impacts and enhance the social acceptability of reforms by compensating households for increased energy prices, a significant gap persists. The literature reveals a scarcity of CT designs that are explicitly engineered as integrated policy instruments to simultaneously (1) provide precise and equitable compensation tailored to diverse household needs post-subsidy removal, (2) actively stimulate the adoption of renewable energy technologies, such as residential PV, and (3) ensure long-term governmental fiscal sustainability. Most analyses and existing schemes tend to focus on the compensatory and social protection aspects of CTs, often overlooking their potential as dynamic, multifaceted tools within a comprehensive strategy to accelerate sustainable energy transitions. Therefore, this doctoral research directly confronts this lacuna by developing and evaluating a novel CT design that holistically addresses these interconnected objectives.

2.3.5 Linking CTs to Energy Policy Goals Beyond Simple Compensation

While cash CTs in subsidy reform have traditionally served primarily as social protection mechanisms, there is a growing recognition of their potential to advance broader energy policy objectives through strategic design and implementation. This evolution in thinking represents a significant shift from viewing CTs merely as compensation tools to understanding their potential as instruments for energy transition.

The strategic design of cash transfers can actively promote the adoption of preferred technologies, particularly residential solar PV systems, by directly addressing affordability barriers. The National Renewable Energy Action Plan

(NREAP) of Bahrain, established in 2017, set ambitious targets for renewable energy integration, including specific provisions for decentralized solar installations (SEU, 2017). While the plan does not currently specify direct CTs for solar PV adoption, its framework suggests the potential for enhancement through such financial mechanisms (Alabbasi, 2021; Alsabbagh, 2019).

CTs can also play a vital role in advancing the energy efficiency and conservation goals. This connection is demonstrated by Iran's reform experience, in which the program explicitly aimed to reduce energy consumption through price signals, with CTs making these changes more socially acceptable (Zarepour & Wagner, 2022). Bahrain's dual-policy approach, encompassing both the National Energy Efficiency Action Plan (NEEAP) and NREAP (SEU, 2017), provides a foundation for the simultaneous promotion of both efficiency and renewable adoption.

Integrating renewable energy objectives into CT programs represents a particularly promising direction. While existing programs, such as Saudi Arabia's CAP, primarily focus on social protection, the opportunity exists to design more sophisticated mechanisms that explicitly support renewable energy adoption. Although Saudi Arabia has established more ambitious renewable energy targets than Bahrain, the rationale for Bahrain's approach lies in its unique socioeconomic context and the need for tailored solutions that address local barriers to adoption. The NREAP specifically identifies opportunities for decentralized rooftop solar installations in existing residential buildings (SEU, 2017), a goal that could be accelerated if savings from subsidy reform were redirected into supportive financial mechanisms for adoption.

A crucial consideration in designing such integrated CT programs is to ensure that funds effectively support the intended energy policy goals. The challenge with unconditional CTs lies in the potential dispersion of funds across various household needs, potentially diluting their impact on energy-related investments or behavioral changes.

2.3.6 Assessing Equity and Distributional Impacts of Subsidy Reform and Cash Transfers

2.3.6.1 Introduction to Equity Considerations

Assessing distributional equity is paramount when evaluating energy subsidy reforms and the accompanying compensatory CT programs. This analysis becomes particularly crucial, given the complex relationship between subsidies, welfare, and social justice in energy policy implementation.

Energy subsidies, while originally intended to make essential goods affordable, often fail to achieve social welfare objectives. Groot and Oostveen (2019) demonstrate that these subsidies frequently function as inefficient and inequitable means of poverty relief. Their analysis reveals a particularly troubling pattern where substantial benefits "leak" to higher-income groups, undermining the policy's intended redistributive effects. This misallocation of resources becomes especially problematic when considering the fiscal burden that these subsidies place on government budgets.

The removal or reduction of these subsidies presents a set of equity challenges. Boughanmi and Khan's (2019) analysis shows that reforms can disproportionately harm vulnerable populations if not carefully designed. Their research identifies significant negative effects on the real income and welfare of poorer households, particularly due to sudden price increases for

necessities, such as fuel and electricity. This impact is especially severe for households that spend a large fraction of their income on energy services.

The Iranian Subsidy Removal and CT program offers an instructive example of attempting to address these equity concerns. According to Salehi-Isfahani et al. (2015), the program aimed not only to reduce energy consumption, but also to distribute the remaining support more equitably. This dual objective exemplifies how subsidy reforms can potentially serve both efficiency and equity goals when properly structured.

CTs have emerged as a primary mechanism to mitigate the adverse impacts of price increases on vulnerable households. Zarepour (2022) demonstrates how these transfers can effectively compensate households for welfare losses, while simultaneously building public support for broader reforms. Bahrain's experience of compensating citizens after removing meat subsidies, as documented by Boersma and Griffiths (2016), provides a relevant example of this approach.

The ultimate success of subsidy reform in achieving more equitable resource distribution depends critically on the design and implementation of these CT programs. Evidence suggests that careful attention to program structure, targeting mechanisms, and delivery systems is essential for ensuring that reforms protect those most in need, while advancing broader energy policy objectives.

2.3.6.2 Common Metrics for Assessing Distributional Equity

The evaluation of subsidy reforms and CT programs requires robust quantitative metrics to assess their distributional impacts. The following metrics were selected based on their demonstrated effectiveness in capturing

different dimensions of equity and their widespread use in empirical research on energy subsidy reform (Groot and Oostveen, 2019; Zarepour, 2022). These measures complement each other by addressing distinct aspects of distributional equity, namely overall inequality, compensation adequacy, welfare impact, and benefit distribution across social groups.

The Gini coefficient serves as a foundational metric for quantifying the overall distributional outcomes. This measure is particularly valuable in subsidy reform analysis because it captures both pre-existing inequalities and reform-induced changes in income distribution (Zarepour and Wagner, 2022). By comparing the Gini coefficients before and after policy implementation, researchers can evaluate whether reforms achieve equity objectives or exacerbate existing disparities.

Building on this broad measure of inequality, the Compensation-to-Subsidy Ratio (CR) provides specific insights into reform effectiveness at the household level. This metric directly addresses the crucial question of whether compensation adequately offsets subsidy removal impacts (Groot & Oostveen, 2019). The CR's clear thresholds ($< 1, = 1, > 1$) make it particularly useful for policymakers to assess and adjust compensation levels to achieve the desired welfare outcomes.

The Transfer-to-Income Ratio (T2I) complements CR by examining transfers within the broader context of household finance. This measure is especially relevant for evaluating reform impacts on vulnerable populations, as demonstrated by studies on Iran's subsidy reform, where transfers constituted a significant portion of low-income household budgets (Salehi-Isfahani et al., 2015). The T2I helps policymakers understand the relative importance of transfers in supporting household welfare.

The Benefit Incidence Analysis rounds out the analytical framework by providing detailed insights into how reforms affect different socioeconomic groups. This approach is crucial for identifying potential inequities in both subsidy distribution and reform impacts (Breton & Mirzapour, 2016). Its ability to reveal whether policies are progressive or regressive makes it invaluable for designing targeted interventions to protect vulnerable populations.

Together, these metrics form a comprehensive framework for evaluating distributional equity in subsidy reforms. The Gini coefficient provides an overview of system-wide inequality, whereas CR and T2I offer detailed insights into household-level impacts. Benefit incidence analysis allows for a nuanced examination of effects across different social groups. This integrated approach enables policymakers to assess both the overall fairness of reforms and their specific impacts on various segments of society, thus facilitating the design of more equitable and effective policy interventions.

2.3.6.3 Application in Evaluating Subsidy Reform and CT Programs

The practical application of these equity metrics in evaluating subsidy reforms and CT programs reveals distinct patterns in diverse contexts. These empirical assessments demonstrate how different metrics complement each other to provide a comprehensive understanding of reform impacts and compensation effectiveness (Moayed et al., 2021; Schaffitzel et al., 2020).

Benefit incidence analysis typically initiates reform evaluations by revealing pre-existing distributional patterns. In Ecuador, it costs $20 to transfer $1 to the bottom quintile using gasoline subsidies, compared to $5 using Liquefied

Petroleum Gas subsidies, highlighting the inefficiency of untargeted subsidies (Schaffitzel et al., 2020). Similarly, in Indonesia, an analysis showed that the removal of fuel subsidies could generate sufficient fiscal space to alleviate poverty while costing less than the current subsidy expenditure (Moayed et al., 2021).

Post-reform evaluation employs multiple metrics to capture various impact dimensions. In Iran, the Gini coefficient dropped eight points from 0.42 to 0.34 following reform implementation (Moayed et al., 2021). However, despite significant cash transfers, real household consumption has declined by 7-9% (Zarepour & Wagner, 2022). This contrasts with Ghana's experience, where enhanced cash transfers through Livelihood Empowerment Against Poverty programs effectively mitigated the adverse effects of subsidy reform (Gyekye and Danso, 2024).

The adequacy of compensation varies significantly across different contexts. In Ecuador, analysis showed that increasing the Bono de Desarrollo Humano by US$46 per month could raise bottom quintile income by 9% while reducing deficit by US$1.3 billion (Schaffitzel et al., 2020). The Dominican Republic has successfully protected public transport drivers through targeted compensation, demonstrating the importance of identifying specific vulnerable groups (Moayed et al., 2021).

Challenges in implementation persist across countries. The GCC states' experience shows how reforms between 2014-2016 achieved varying levels of subsidy reduction, from 6% in Oman to 77% in Qatar, highlighting the role of the political economy in reform success (Moayed et al., 2021). Mexico and Indonesia's experiences emphasize the importance of timing-delivery of

compensation before or simultaneously with price increases, which is crucial for public acceptance (Moayed et al., 2021).

Evidence suggests that successful reforms require the careful orchestration of multiple elements. Iran's universal transfer program reached 97% coverage within six months, demonstrating the potential of broad-based approaches (Moayed et al., 2021). However, experiences from Ecuador and Iran in 2019 show that failing to address specific vulnerable groups can jeopardize reform sustainability (Moayed et al., 2021).

This cross-country analysis reveals that effective reform implementation requires balancing immediate compensation with long-term investment. Countries such as Indonesia, Ghana, and the Philippines have successfully leveraged subsidy savings for health and education programs while maintaining social protection (Moayed et al., 2021). This integrated approach, which combines targeted support with structural improvements, appears to be most effective in achieving sustainable reform outcomes.

2.3.6.4 Relevance to This Thesis

The established metrics for assessing distributional equity—specifically the Gini coefficient for analyzing the distribution of cash transfers, the Compensation-to-Subsidy Ratio (CR) to evaluate the adequacy of compensation related to solar PV adoption incentives, the Transfer-to-Income Ratio (T2I) to understand the significance of financial support, and benefit incidence analysis (e.g., adoption rates of solar PV, net welfare changes, or CT reception by income quintile)— are instrumental in this thesis. These metrics are employed within the agent-based modeling framework to quantitatively assess and compare the distributional equity implications of the

different simulated subsidy reforms and CT scenarios aimed at optimizing residential solar PV adoption in Bahrain. This approach will allow for a nuanced understanding of how various policy designs impact different socioeconomic groups, thereby informing the development of more equitable and effective energy policies for Bahrain, building upon its existing experiences with targeted support and tariff differentiation (Alabbasi, 2021; Boersma & Griffiths, 2016).

A systematic examination of energy subsidy reform and compensation mechanisms reveals several critical insights pertinent to residential solar PV adoption in Bahrain's distinctive market environment. The analysis illuminates three fundamental theoretical and practical implications that warrant careful consideration for both policy development and implementation strategies.

First, successful reform initiatives necessitate a nuanced balance between multiple, often competing, objectives: fiscal sustainability, social protection, and renewable energy promotion. Evidence from comparable markets demonstrates that well-designed compensation mechanisms can simultaneously address reform impacts while creating enabling conditions for accelerated solar PV adoption (Alabbasi, 2021). This finding suggests that policy frameworks must evolve beyond simple trade-offs to embrace more sophisticated, integrated approaches that recognize the interconnected nature of these objectives.

Second, implementation efficacy fundamentally depends on institutional capacity and policy coordination mechanisms. Research indicates that successful transitions require robust institutional frameworks capable of managing complex compensation schemes, while simultaneously promoting

renewable energy adoption (Boersma & Griffiths, 2016). This insight is particularly significant in Bahrain, where existing institutional structures may require enhancement to support comprehensive reform initiatives.

Third, the integration of subsidy reforms with solar PV adoption policies presents distinctive opportunities for policy innovation. Empirical evidence suggests that carefully structured compensation mechanisms can generate positive feedback loops between reform benefits and renewable energy transitions (Zarepour & Wagner, 2022). This dynamic is especially relevant in Bahrain's context, where existing subsidy structures significantly influence adoption patterns.

These findings have substantial implications for theoretical understanding and practical policy development. From a theoretical perspective, they suggested the need for integrated frameworks that can adequately capture the complex interactions between market reforms, social protection mechanisms, and technology adoption patterns. In practical terms, successful policy design necessitates sophisticated compensation mechanisms that support both social protection and solar PV adoption, while maintaining robust institutional frameworks capable of managing complex transitions. Furthermore, effective implementation requires clear policy coordination strategies across multiple domains supported by advanced monitoring systems and adaptive approaches that respond to emerging challenges.

The subsequent section examines Agent-Based Modeling (ABM) as a methodological framework for analyzing these complex interactions. This approach offers particular value in understanding the dynamic relationships between subsidy reform, compensation mechanisms, and solar PV adoption patterns in Bahrain's unique market context. Through this methodological

lens, this study seeks to illuminate how various policy configurations might influence adoption outcomes across different market segments and temporal scales.

2.4. Agent-Based Modeling in Energy Policy and Technology Diffusion

The transition to sustainable energy systems driven by concerns over climate change and energy security necessitates innovative policy design and a deep understanding of technology adoption dynamics. Residential solar PV systems are pivotal in this transition; however, their widespread adoption is a complex process influenced by a multitude of interacting factors. Traditional top-down modeling approaches, although valuable, often fail to capture the nuanced, individual-level behaviors and social interactions that significantly shape these dynamics (Moglia et al., 2017; Nurwidiana et al., 2021). ABM has emerged as a powerful bottom-up computational methodology, offering a granular lens to simulate how individual decisions aggregate to produce system-wide patterns, making it particularly well-suited for analyzing energy policy and technology diffusion (Akhatova et al., 2022; Hesselink & Chappin, 2019). This section presents a systematic examination of the ABM, encompassing its fundamental principles, methodological advantages, and inherent limitations within the context of energy transition research. Through a critical analysis of ABM applications in energy policy and focused evaluation of studies examining solar PV adoption, this section establishes the methodological foundation for the subsequent empirical investigation. Particular attention is devoted to the distinctive capabilities of ABM in capturing complex sociotechnical transitions, thereby informing the conceptual framework employed in this thesis.

2.4.1 Overview of Agent-Based Modeling: Principles, Strengths, and Limitations

The ABM represents a sophisticated computational approach that fundamentally differs from traditional modeling methods from a bottom-up perspective on complex systems. This methodology simulates system behavior by modeling the autonomous actions and interactions of constituent entities, known as agents, within a defined environment (Bonabeau, 2002; Macal & North, 2010). Unlike conventional Equation-Based Models (EBM), which rely primarily on aggregate variables and average behaviors, ABM distinguishes itself through its emphasis on emergence: macro-level system behaviors and patterns arise organically from the micro-level decisions and interactions of heterogeneous agents (Van Dyke Parunak et al., 1998; Vuthi et al., 2022). Each agent is characterized by specific attributes (such as income, preferences, or knowledge), decision-making rules (ranging from simple heuristics to complex cognitive models), and the capacity to interact dynamically with other agents and their environment (Hesselink & Chappin, 2019; Vuthi et al., 2022).

2.4.1.1 Key Strengths in Energy Transition Modeling

The capabilities of ABM make it particularly well suited for modeling energy transitions and technology adoption processes. First, its ability to represent Agent Heterogeneity is of paramount importance (Akhatova et al., 2022; Hesselink & Chappin, 2019; Nurwidiana et al., 2021). Individual households vary significantly in their financial resources, risk attitudes, environmental values, information access, and social networks, which crucially influence their decisions regarding energy technologies, such as solar PV (Yao et al., 2023). While traditional EBMs often simplify or aggregate these differences,

ABM allows for an explicit representation (Moglia et al., 2017; Vuthi et al., 2022). This capability is essential for designing targeted policies and for understanding differential adoption patterns across diverse societal segments (Hansen et al., 2019; Yao et al., 2023).

Another crucial strength is the ability to model Complex Interactions. ABM can explicitly simulate the intricate web of communication, social influences, peer effects, and observational learning that characterize real-world technology diffusion (Hesselink & Chappin, 2019; Nurwidiana et al., 2021; Vuthi et al., 2022). These social dynamics, recognized as powerful drivers of technology diffusion (Rogers, 2003), can be captured through defined network structures and interaction protocols. For instance, the influence of a household's solar PV installation on neighboring properties can be precisely modeled and analyzed (Moglia et al., 2017; Palmer et al., 2015).

Perhaps most distinctively, ABM excels in capturing the emergent phenomenon —complex, often nonlinear system-level behaviors that arise from relatively simple individual-level rules and interactions (Vuthi et al., 2022). This capability enables researchers to identify unexpected system dynamics, potential policy-side effects, or critical tipping points in technology adoption that might remain obscured in more aggregated modeling approaches (Hansen et al., 2019).

Furthermore, ABM offers remarkable flexibility in decision making, accommodating diverse theoretical frameworks from multiple disciplines. Models can incorporate psychological perspectives (e.g., Theory of Planned Behavior), economic principles (e.g., utility maximization and bounded rationality), and sociological concepts (e.g., social norm adherence) to create

rich representations of agent decision-making processes (Akhatova et al., 2022; Hesselink & Chappin, 2019).

2.4.1.2 Critical Limitations and Challenges

Despite these substantial strengths, ABM has several significant limitations that warrant careful consideration. The Data Requirements for properly calibrating and validating these models are often extensive and require detailed empirical data on agent characteristics, behaviors, and interaction patterns (Hesselink & Chappin, 2019; Moglia et al., 2017). This challenge becomes particularly acute when modeling novel technologies or specific sociocultural contexts, such as Bahrain, where such detailed data may be scarce.

The computational Complexity presents a substantial challenge. The simulation of large numbers of heterogeneous agents and their interactions over extended periods can impose significant computational demands, requiring considerable processing power and time (Hesselink & Chappin, 2019; Vuthi et al., 2022). This can constrain the scale and scope of the analyses, particularly when exploring multiple scenarios or conducting sensitivity analyses.

The validation challenge is noteworthy. Establishing the credibility and accuracy of an ABM, ensuring that its outputs reliably reflect real-world processes and that emergent patterns are not mere artifacts, requires sophisticated methodological approaches (Hammond, 2015; Hesselink & Chappin, 2019; Moglia et al., 2017). This often necessitates multifaceted validation strategies, including face validation, parameter validation, and pattern-oriented modeling (Grimm & Railsback, 2012).

Finally, issues of Model Complexity and Transparency require careful management. While ABM's ability to incorporate complexity is valuable, overly intricate models risk becoming "black boxes" where the drivers of simulation outcomes become obscured. Clear documentation, often utilizing standardized protocols like ODD (Overview, Design concepts, and details), is crucial for ensuring transparency and enabling replication (Hesselink & Chappin, 2019; Vuthi et al., 2022).

2.4.2 Applications in Energy Transitions: Modeling Consumer Behavior, Policy Analysis, and Technology Adoption Dynamics

Building upon the foundational principles discussed in the previous section, the capacity of Agent-Based Modeling to handle heterogeneity, complex interactions, and emergent phenomena makes it particularly valuable for studying the multifaceted nature of energy transitions. These transitions encompass intricate shifts across multiple dimensions: technological infrastructure, institutional frameworks, policy landscapes, and perhaps most crucially, human behavior patterns (Akhatova et al., 2022; Hansen et al., 2019).

Modeling Consumer Behavior represents a primary application domain in which the strengths of ABM are especially evident. Understanding and influencing consumer decisions are fundamental to driving successful energy transitions, and ABM enables nuanced modeling of consumer behavior concerning both energy consumption and technology adoption (Hesselink & Chappin, 2019). The flexibility of the methodology allows for the integration of diverse theoretical frameworks, such as psychological theories and the

Theory of Planned Behavior (Ajzen, 1991). Sociodemographic factors, economic considerations (such as perceived costs and benefits), and social influences. This integrated approach enables researchers to simulate how households make complex decisions about adopting energy-efficient appliances, renewable energy technologies, or modifying their energy usage patterns (Hesselink & Chappin, 2019; Nurwidiana et al., 2021). For example, Rai and Robinson (2015) empirically grounded the ABM for solar PV adoption, demonstrating this capability by successfully integrating social, behavioral, economic, and environmental factors, showcasing the methodology's strength in representing the diverse influences that shape consumer choices (Hesselink & Chappin, 2019; Nurwidiana et al., 2021).

In terms of Policy Analysis, ABM serves as a sophisticated virtual "policy laboratory," enabling researchers and policymakers to conduct detailed ex-ante evaluations of various policy interventions (Hesselink & Chappin, 2019; Nurwidiana et al., 2021). Through the simulation of "what-if" scenarios—involving variations in subsidy levels, tax incentives, information campaigns, or regulatory standards—ABMs can project potential impacts across multiple dimensions: technology adoption rates, energy demand patterns, market dynamics, and even distributional equity considerations (Adepetu et al., 2018; Hesselink & Chappin, 2019). This capability helps to identify more effective and efficient policy designs, anticipate potential unintended consequences, and tailor interventions to specific contexts or target groups (Hansen et al., 2019; Yao et al., 2023). A notable example is Chappin et al.'s (2017) use of EMLab, an ABM platform, to simulate climate and energy policy impacts, demonstrating the utility of this methodology in evaluating strategic policy options (Hansen et al., 2019).

In modeling Technology Adoption Dynamics, ABM provides a particularly robust framework for simulating the complex, dynamic process of technology diffusion, particularly for innovations such as solar PV (Hesselink & Chappin, 2019; Nurwidiana et al., 2021). This approach overcomes the significant limitations of traditional diffusion models (such as the Bass model), which often rely on assumptions of population homogeneity and neglect the micro-foundations of adoption decisions (Moglia et al., 2017; Nurwidiana et al., 2021). ABM can explicitly model the various stages outlined in Rogers' (2003) Diffusion of Innovations theory—from awareness through persuasion, decision, implementation, and confirmation—while accounting for how these stages are influenced by individual characteristics, communication channels, and social system structures (Nurwidiana et al., 2021). Notably, the empirically observed S-shaped diffusion curve often emerges naturally in ABM simulations because of agent interactions, learning processes, and threshold effects (Nurwidiana et al., 2021). Palmer et al. (2015) have effectively demonstrated this capability by modeling residential solar PV diffusion through the lens of both financial attractiveness and social influence dynamics (Hesselink & Chappin, 2019; Nurwidiana et al., 2021).

2.4.3 Review of Specific ABM Studies on Solar PV Adoption

The application of the ABM has proven particularly useful for simulating the complex dynamics of residential solar PV adoption. Understanding these dynamics requires sophisticated modeling approaches capable of handling heterogeneous populations and feedback loops, making the ABM a powerful tool (Danielis et al., 2023; Rai & Robinson, 2015). Unlike equation-based models that rely on aggregate assumptions, ABM captures the nuanced decision-making processes of individual households, accounting for diverse

factors, such as income, consumption patterns, risk preferences, and social influence (Castro et al., 2020; Rai & Henry, 2016).

Previous ABM studies on solar PV adoption have explored several key themes. The predominant theme is the critical role of financial incentives and economic viability. High upfront costs are consistently identified as a major barrier, making factors such as payback period (PBP), Net Present Value (NPV), subsidies, and Feed-in Tariffs (FiTs) central to adoption decisions (Hesselink & Chappin, 2019; Nurwidiana et al., 2021). Many ABM studies operationalize household decisions using multi-criteria utility functions, often incorporating these economic considerations alongside household income or budget constraints (Iachini et al., 2015; M. Lee & Hong, 2019; Mohandes et al., 2018; Palmer et al., 2015; Pearce & Slade, 2018; Zhao et al., 2011). In addition, Irsyad et al. (2019), Zhao et al. (2011), and Palmer et al. (2015) used ABM to assess the impact of various financial policies on solar PV uptake, generally finding them to be significant drivers. However, their effectiveness can be nuanced depending on policy design and the specific context (Adepetu et al., 2018; Pearce & Slade, 2018). For instance, Pearce & Slade (2018) evaluated FIT policies for solar microgeneration in Great Britain using an ABM framework, while Mittal et al. (2017) highlighted how policy changes, such as modifications to net metering, can drastically impact adoption rates.

Social influence and network effects represent another frequently modeled and highly significant driver. A substantial body of research has focused on the critical role of peer effects, neighbor influence, and information diffusion through social networks as key accelerators (or inhibitors) of solar PV adoption (Moglia et al., 2017; Nurwidiana et al., 2021). Researchers have used ABM to model how observing solar PV adoption by neighbors or within social

networks increases an individual's likelihood of adoption, demonstrating how these interactions drive diffusion patterns (Bollinger & Gillingham, 2012; Palmer et al., 2015; Rai & Robinson, 2015; Wolske et al., 2020; Zhang & Vorobeychik, 2019). For example, Palmer et al. (2015) modeled the effect of communication with other agents alongside economic factors in Italy, whereas Zhao et al. (2011) incorporated word-of-mouth effects in the USA. Rai & Robinson (2015) and Mittal et al. (2019) emphasized the importance of social influence in ABMs.

The theoretical underpinnings of agent decision making in these models are often drawn from established behavioral science. The Theory of Planned Behavior (TPB) and Rogers' (2003) diffusion of innovation (DoI) theory are commonly integrated to structure the logic behind agents' choices (Hesselink & Chappin, 2019; Nurwidiana et al., 2021). These frameworks help incorporate psychological factors, such as attitudes, subjective norms, perceived behavioral control, and the perceived characteristics of the innovation (such as relative advantage or complexity) into the simulation.

Beyond these core themes, ABM studies consider a wide array of other influencing factors, including socio-demographic attributes (income, education, and household characteristics), technical aspects of solar PV systems (efficiency and installation costs), household awareness levels, and environmental concerns or attitudes (Nurwidiana et al., 2021; Vuthi et al., 2022). Furthermore, some studies emphasize spatial dynamics, modeling how adoption clusters geographically due to localized peer effects or shared neighborhood characteristics (Zhang et al., 2016).

Regarding methodological approaches, many ABM studies on solar PV adoption have focused on empirical grounding, utilizing survey data, publicly

available statistics, and historical adoption data to define agent populations, parameterize decision rules, and perform model calibration and validation (Adepetu et al., 2018; Danielis et al., 2023; Hesselink & Chappin, 2019; Mehta et al., 2019; Zhang et al., 2016). Integration with other tools is also common, such as Geographic Information Systems (GIS) to model spatial aspects (Rai & Robinson, 2013, 2015) or data-driven techniques such as logistic regression to inform adoption probability functions (Zhang et al., 2016).

Reviews of this growing body of literature highlight both the strengths of ABM in capturing complexity and areas where further research is required. Hesselink and Chappin (2019) reviewed ABMs for energy efficiency adoption more broadly and found a predominant focus on a subset of barriers (e.g., lack of capital, high upfront cost, and lack of information) and policies (mainly subsidies and information campaigns), suggesting opportunities to explore other barriers (such as institutional factors) and more diverse policy instruments. Nurwidiana et al. (2021), focusing specifically on solar PV adoption ABMs, noted that while financial and social interaction aspects are well covered, factors such as environmental awareness and the role of the local solar industry ecosystem (installers and maintenance services) are often under-addressed, particularly in the context of developing countries. They also observed a geographical research gap, with most studies originating in developed countries. Akhatova et al. (2022) further noted the diversity in model objectives and outputs, categorizing them broadly into "diffusion ABMs" and "exploratory ABMs". A clear pattern emerges regarding the strong emphasis on economic drivers and social influence, often framed by the TPB or DoI. However, inconsistencies exist in how other factors are

incorporated, and the rigor of the calibration and validation procedures can vary, sometimes making cross-study comparisons difficult (Hansen et al., 2019).

While insightful, existing ABM research on solar PV adoption exhibits certain gaps relevant to the present study. Few studies have specifically applied the ABM within the unique context of heavily subsidized electricity markets, such as those found in the GCC region, where conventional economic drivers are significantly distorted (Al-Marri et al., 2018). Moreover, previous ABM studies on solar PV adoption have primarily focused on peer effects, spatial patterns, or standard economic incentives but have generally not integrated the complex interplay of comprehensive electricity subsidy reform coupled with alternative compensatory CT mechanisms into their agent decision frameworks or policy evaluations (M. Lee & Hong, 2019; Mohandes et al., 2018; Palmer et al., 2015; Zhang et al., 2016). This thesis seeks to extend the application of the ABM to address these gaps, providing insights relevant to navigating energy transitions in subsidy-dependent economies.

2.5. Conceptual Framework

This study employs an integrated conceptual framework (Figure 2.1), synthesized from the core theoretical principles detailed in Section 2.1, to guide the investigation of residential solar PV adoption under varying policy environments in Bahrain. This framework explicitly translates tenets from Diffusion of Innovation (DOI) theory, Behavioral Economics, and Social Capital Theory into a cohesive, operational model. It provides a structured representation of how policy interventions, supporting factors, and agent characteristics collectively influence the household adoption decision process,

leading to emergent system-level outcomes. The subsequent sections deconstruct this framework, explaining each component in sequence.

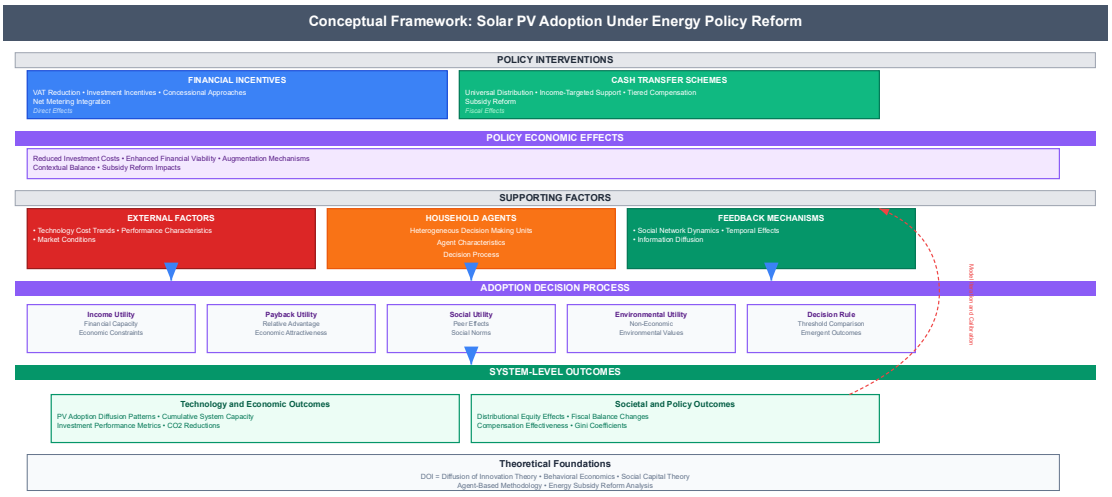


Figure 2.1: Integrated Conceptual Framework: Solar PV Adoption Under Energy Policy Reform

2.5.1 Policy Interventions

At the highest level of the framework, we model two distinct categories of Policy Interventions that represent the primary levers tested in this research.

- Financial Incentives: These policies are designed to enhance the economic viability of solar PV systems within the existing market structure. Strategies investigated include VAT reduction to lower upfront capital costs and innovative loan schemes to improve financing affordability. The existing Net Metering policy in Bahrain is also included as a foundational support mechanism.
- Cash Transfer (CT) Schemes: These policies are analyzed in conjunction with comprehensive electricity subsidy reform. The study evaluates a baseline reform-only scenario against three distinct compensatory designs: a Universal per-capita transfer, an Income-

Targeted support scheme, and a novel Tiered mechanism that links compensation to household size and estimated subsidy loss.

2.5.2 Policy Economic Effects

The modeled policy interventions produce direct and immediate Policy Economic Effects at the household level. Financial incentives primarily function by reducing the upfront investment or ongoing financing costs of solar PV adoption. In contrast, subsidy reform exposes households to unsubsidized electricity prices, creating a financial loss. This negative impact is then offset to varying degrees by the specific compensation provided under the different CT schemes.

2.5.3 Supporting Factors

The agent's decision-making environment is shaped by a set of Supporting Factors, which include both external market conditions and dynamic feedback loops that evolve within the system.

- External Factors: Agent decisions are influenced by several exogenous conditions. These include the projected cost trajectory of solar PV systems (PV System Cost), which reflects technological progress; the annual performance degradation rate of panels, which affects long-term returns; and each household’s unique electricity consumption pattern. As shown in Figure 2.1, these factors directly influence the calculation of an agent's financial returns (Payback Utility).
- Feedback Mechanisms: The framework explicitly incorporates feedback loops that drive the system's dynamics. Social Network Dynamics represent a critical feedback mechanism, operationalized in the model by updating each agent's dynamic attributes (e.g., Social

Influence, Awareness Level) based on the adoption status of their neighbors. This process simulates the "social contagion" effect. Temporal effects, such as the increasing visibility of savings from early adopters, also create a reinforcing loop by influencing the awareness of non-adopters over time.

2.5.4 Household Agents

Central to the ABM are the heterogeneous Household Agents, which represent the Bahraini owner-occupied population. Each agent is defined by a set of attributes influencing their decision-making:

- Static Attributes: These are stable characteristics assigned at initialization, including annual income, family size, education, physical roof suitability, building type, and baseline environmental attitudes.
- Dynamic Attributes: These attributes evolve during the simulation as a result of the feedback mechanisms. They include the agent's Awareness and Knowledge Levels regarding solar PV technology, their perceived Social Influence within their network, and their individual Adoption Threshold.

2.5.5 Adoption Decision Process

The core of each agent's behavior is the Adoption Decision Process, modeled via a Multi-Attribute Utility Framework. This is where the foundational theories are operationalized. The overall utility (U) an agent derives from adopting solar PV is a weighted sum of four components:

- Income Utility: Represents the household's financial capacity and economic constraints.

- Payback Utility: Operationalizes the DOI concept of Relative Advantage, capturing the economic attractiveness of the solar PV investment based on its payback period and financial returns.
- Social Utility: Draws from Social Capital Theory and DOI's Observability, operationalizing peer effects and social norms based on an agent's network interactions.
- Environmental Utility: Incorporates non-economic motivations from Behavioral Economics, reflecting the household's environmental values.

The agent's final decision is governed by a probabilistic Decision Rule, where the calculated utility is compared against the agent's individual threshold. This operationalizes the concept of Bounded Rationality, as agents make decisions based on a weighted consideration of these key factors.

2.5.6 System-Level Outcomes

The aggregation of individual agent decisions and their interactions gives rise to emergent, System-Level Outcomes. These macro-level results are the primary outputs for policy evaluation:

- Technology & Economic Outcomes: This category includes metrics such as the overall solar PV Adoption Diffusion Patterns, Cumulative System Capacity, average Investment Performance Metrics (e.g., payback period), and environmental co-benefits like CO_2 reductions.
- Societal & Policy Outcomes: This focuses on the equity and welfare impacts of the policies. Key metrics include Distributional Equity Effects (e.g., adoption by income quintile, Gini coefficients), the net

Fiscal Balance Changes for the government, and the Compensation Effectiveness of the different CT schemes.

This integrated conceptual framework provides a robust and theoretically grounded approach for simulating the complex interplay between policy, behavior, and social dynamics to assess strategies for promoting residential solar PV adoption in Bahrain.

A comprehensive review of the literature on theoretical foundations, determinants, and policy mechanisms reveals several interconnected themes and research gaps. Table 2.1 synthesizes these key findings, their implications for Bahrain's context, and identifies critical areas requiring further investigation.

2.6. Literature Review Synthesis, Research Gaps, and Thesis Contribution

This chapter examined multiple theoretical frameworks and empirical evidence underpinning residential solar PV adoption, encompassing the Diffusion of Innovation, Behavioral Economics, and Social Capital Theory. The synthesis presented in Table 2.1 integrates these findings, revealing critical patterns and research opportunities at the intersection of theory, policy, and methodology.

As shown in Table 2.1, while these distinct areas are well-researched individually, significant gaps emerge at their intersection, particularly within subsidized energy markets such as Bahrain. The synthesis reveals that theoretical frameworks, although complementary in explaining adoption through economic rationality, psychological biases, and social network effects, require context-specific adaptation. Methodologically, traditional

approaches often struggle to capture the dynamic, non-linear interactions inherent in technology diffusion, highlighting the need for more sophisticated modeling techniques.

Building on this comprehensive analysis, three critical research opportunities have emerged.

1. Context-Specific Application in GCC/Bahrain: Most empirical studies have focused on developed Western nations or large developing economies. A notable research gap exists in examining solar PV adoption within the GCC countries' unique socio-economic contexts, particularly Bahrain's subsidized energy market. This gap extends the understanding of how established theoretical frameworks translate into these distinctive market conditions.

2. Integrated Dynamic Policy Modeling and Innovative Compensation Design: While theories are frequently discussed in conjunction, the formal integration of diverse theoretical mechanisms into dynamic modeling frameworks remains limited. This integration is crucial for simulating complex policy packages, particularly those that involve electricity subsidy reforms. Furthermore, the literature, as discussed in section 2.3.4, reveals a specific gap in the design of compensatory CT mechanisms. There is a scarcity of CT approaches explicitly engineered to simultaneously optimize equitable household compensation, actively incentivize renewable energy adoption (such as PV), and ensure long-term governmental fiscal viability within the dynamic context of such reforms. Current models and policy discussions often focus on CTs primarily for social protection or analyze policy elements in isolation, thereby missing opportunities to leverage innovative, multi-objective

CT designs as integral components of a comprehensive energy transition strategy.

3. Methodological Advancement Through ABM: Agent-Based Modeling offers powerful capabilities for understanding complex adoption dynamics, yet its application in subsidized markets remains underdeveloped. The methodology's potential for integrating heterogeneous agent behaviors, policy interactions, and emergence patterns presents significant opportunities for advancing the understanding of solar PV adoption in Bahrain's context.

This thesis strategically addresses these gaps through several key contributions. First, it develops a sophisticated and empirically grounded ABM framework tailored to Bahrain's unique market conditions. This framework integrates theoretical mechanisms from multiple perspectives into a unified dynamic simulation, thereby providing comprehensive insights into adoption drivers. Second, it offers a context-specific analysis of adoption dynamics and policy impacts within Bahrain's under-researched subsidized energy market. Third, it explicitly models complex policy interactions, investigating both financial incentives and the multifaceted impacts of electricity subsidy reforms coupled with different compensation mechanisms.

This research advances the understanding of subsidized energy markets by integrating established theories into a context-specific agent-based model. Through simulating complex policy interactions, the investigation analyzes distributional and fiscal impacts, contributing significantly to the academic literature and providing practical tools to foster sustainable energy transitions in Bahrain and similar nations.

Table 2.1: Synthesis of Literature Review: Key Findings and Research Implications

Research Domain	**Key Findings & Consensus in Literature**	**Identified Research Gaps (especially for GCC/Bahrain)**	**How This Thesis Addresses the Gap**
Economic & Policy Factors	High upfront costs are a major barrier; subsidies distort markets and hinder PV adoption.	Limited empirical studies on the unique economic dynamics of subsidized *and* tax-free GCC markets.	Develops an ABM specifically calibrated to Bahrain's subsidized electricity tariffs and socioeconomic context.
Social & Network Factors	Peer effects and social norms are significant drivers of adoption.	Lack of research on the specific social network dynamics within the GCC context.	The ABM incorporates social influence and network effects to test their impact under different Bahraini policy scenarios.
Compensation Mechanisms	Cash Transfers (CTs) are critical for the political feasibility of subsidy reform.	Most literature treats CTs as welfare tools, not as active instruments to drive renewable energy adoption. A lack of novel, multi-objective CT designs.	Introduces and evaluates a novel Tiered Cash Transfer (S3) mechanism designed to simultaneously promote equity, accelerate PV adoption, and ensure fiscal balance.
Modeling Methodology	Traditional models struggle to capture household heterogeneity and emergent social dynamics.	ABM is under-utilized for integrated policy analysis (incentives vs. reform) in the GCC.	Employs a comprehensive ABM framework to compare two distinct policy paradigms and their complex, intersecting impacts on the Bahraini market.

The comprehensive synthesis presented in Table 2.1 establishes clear directions for addressing current knowledge gaps through an integrated approach combining theoretical advancement, context-specific policy analysis, and sophisticated Agent-Based Modeling techniques. This conclusion demonstrates how this thesis bridges critical research gaps while advancing both theoretical understanding and practical policy design for promoting solar PV adoption in subsidized energy markets.

The identified gaps in the literature, particularly the need for context-specific modeling of policy impacts in subsidized markets and the limited application of ABM to explore comprehensive reform packages with varied cash transfers, highlight the requirement for a sophisticated and tailored research methodology. Chapter 3 will, therefore, detail the ABM framework developed specifically to address these research questions and investigate the dynamics of solar PV adoption under different policy scenarios in Bahrain.

Chapter 3: Methods and Procedures

This chapter outlines the research methodology employed to address the research questions posed in Chapter 1 and the gaps identified in the literature review (Chapter 2), particularly concerning the dynamic interactions of policy interventions in subsidized markets. The investigation of residential solar photovoltaic (PV) adoption in subsidized electricity markets requires a methodological approach that captures complex sociotechnical interactions. This chapter presents a comprehensive research framework that examines how policy interventions, particularly electricity subsidy reform and compensatory mechanisms, influence solar PV adoption patterns in Bahrain's residential sector.

The methodology employs Agent-Based Modeling (ABM), which is selected for its capacity to simulate heterogeneous household decisions while capturing emergent system-level outcomes. This approach enables a detailed examination of how different policy mechanisms influence adoption patterns across diverse household segments, incorporating the economic rationality, social influences, and behavioral factors identified in the literature review.

This chapter progresses systematically through the interconnected sections that establish the analytical framework. Beginning with philosophical underpinnings and research design considerations, it advances to detail the ABM architecture, including agent characteristics, decision rules, and interaction mechanisms. Particular attention has been paid to the empirical grounding of the model, describing data sources, calibration procedures, and validation approaches specific to Bahrain's context.

The methodology integrates the economic analysis of household adoption decisions, assessment of social network effects, and evaluation of distributional impacts across income groups. This comprehensive approach enables a rigorous evaluation of how different policy interventions might accelerate sustainable energy transitions, while ensuring equitable outcomes. Through this structured framework, this chapter establishes the analytical foundation necessary for generating policy-relevant insights about residential solar PV adoption in subsidized electricity markets.

To provide a comprehensive overview of the research approach employed in this thesis, Figure 3.1 presents a complete methodology flowchart, illustrating the systematic progression from philosophical foundations to research outcomes. The flowchart follows a structured sequence beginning with the post-positivist research philosophy and ABM methodology selection, proceeding through data collection and integration phases, model development and validation processes, and concluding with the experimental design and analysis procedures. This visual representation demonstrates how the various methodological components—from the ODD (Overview, Design concepts, Details) protocol framework to sensitivity analysis—interconnect to form a cohesive research strategy for investigating residential solar PV adoption policies in Bahrain's subsidized electricity market.

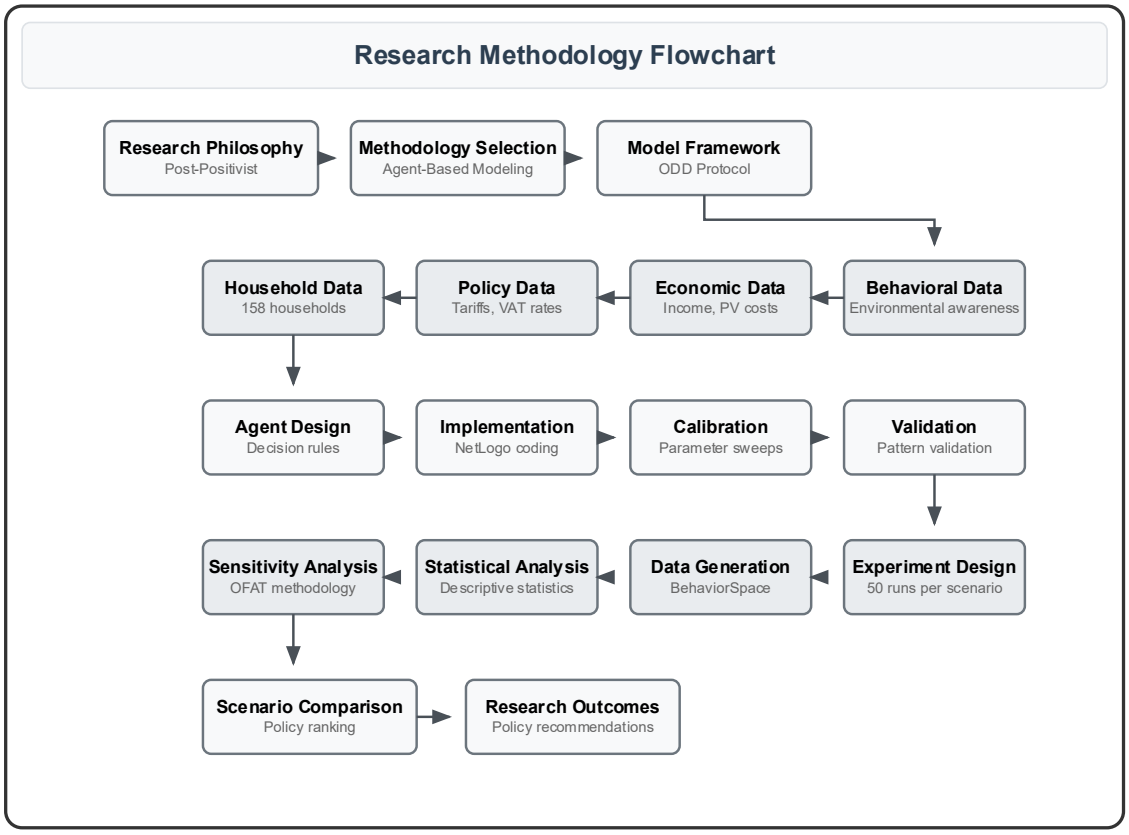


Figure 3.1: Research Methodology Flowchart

3.1. Research Philosophy and Approach

The foundation of any rigorous scholarly inquiry lies in its research philosophy and methodological approach, which collectively delineates the researcher's assumptions about the nature of reality (ontology), knowledge (epistemology), and systematic process of investigation (Sætra, 2017). This section discusses and justifies the philosophical stance and research strategy adopted for this thesis, which aims to investigate the optimization of residential solar PV adoption in Bahrain through the design of incentive mechanisms and subsidy reforms using ABM. A transparent and well-reasoned methodological framework is crucial for ensuring the credibility,

validity, and relevance of research findings, particularly when addressing complex socio-technical systems and informing public policy.

The research philosophy embraced in this study was post-positivism. Post-positivism emerged as a critique of classical positivism, which espouses the existence of an objective reality that can be fully understood through empirical observation and the discovery of universal deterministic laws (Anderson & Whall, 2011; Rieder et al., 2024). While post-positivism retains the scientific ideal of striving for objectivity and utilizing empirical evidence, it acknowledges that our understanding of reality is inherently imperfect, and that all knowledge is conjectural and fallible (Priori, 2022). According to this view, researchers are not detached observers but can influence and are influenced by the phenomena under study. Consequently, post-positivism emphasizes critical realism, asserting that, while an objective reality exists, it can only be apprehended probabilistically and imperfectly (Miller, 2015). This philosophical stance is particularly well-suited for studying complex social systems, such as energy adoption dynamics, where human behavior, social interactions, and contextual factors introduce significant uncertainty and variability (Henrickson & McKelvey, 2002). In this thesis, a post-positivist approach means that while the ABM aims to model the Bahraini residential solar PV adoption system as accurately as possible based on available data and established theories, the insights generated are considered plausible explanations and contingent predictions rather than absolute truths (Epstein, 2006). The focus is on understanding underlying generative mechanisms and exploring "how-possibly" explanations for observed phenomena and potential policy outcomes (Priori, 2022; Rieder et al., 2024), which aligns with the practical goal of providing robust yet nuanced policy recommendations.

While this thesis adopts a post-positivist/critical-realist stance, it also draws on the pragmatic spirit common in ABM scholarship, valuing models as iteratively improvable tools for ‘what-works’ policy exploration. Both paradigms share a fallibilist outlook: Simulations are provisional and subject to refinement as new data or insights emerge.

Congruent with this post-positivist philosophy, this research employs a quantitative approach, primarily through the application of computational simulation, specifically ABM. A quantitative approach is characterized by the systematic collection and analysis of numerical data to identify relationships and explore the dynamics of systems (Mittal et al., 2019). ABM is a powerful computational methodology that operationalizes this approach by creating artificial societies of interacting, autonomous "agents" (e.g., households) whose behaviors are governed by predefined rules derived from theory and empirical data (Anderson & Whall, 2011; Karimi & Vaez-Zadeh, 2021). These agents can be heterogeneous, reflecting the diversity present in real-world populations, and their interactions can lead to emergent, often non-linear, macro-level patterns such as technology adoption curves or market responses to policy (Jung et al., 2025; Mittal et al., 2019)

The selection of the ABM is particularly apposite for the objectives of this thesis for several reasons. First, it allows for the explicit modeling of heterogeneity among Bahraini households in terms of their socioeconomic characteristics, energy consumption patterns, environmental attitudes, and responsiveness to financial incentives (Gallegati, 2018; Mittal et al., 2019). Second, ABM excels in capturing complex interactions and feedback loops, such as social influence effects (e.g., peer effects on adoption) and the dynamic interplay between adoption rates, electricity tariffs, and government

subsidy expenditure (Anderson & Whall, 2011). Third, it provides a "virtual laboratory" for policy experimentation, enabling the systematic testing of various incentive designs and subsidy reform scenarios to assess their potential impacts on solar PV adoption rates and other performance indicators in Bahrain before costly real-world implementation (Axtell et al., 2001; Karimi & Vaez-Zadeh, 2021). This bottom-up approach, in which macro-level outcomes emerge from micro-level agent behaviors and interactions, aligns well with the post-positivist goal of understanding complex causal mechanisms, rather than merely identifying statistical correlations (Anderson & Whall, 2011; Rieder et al., 2024). The data-driven nature of the ABM involves initialization with empirical data (Collado, 2017) and ongoing validation against real-world patterns (Mittal et al., 2019), further supporting the simulations in the empirical reality of Bahrain and enhancing the credibility and policy relevance of the findings.

To ensure empirical grounding, this research will first conduct expert validation to critically review the model structure, rule definitions, and scenario assumptions. Second, a systematic sensitivity analysis will be performed—both one-factor-at-a-time sweeps and Monte Carlo parameter sampling—to gauge how variations in key inputs affect emergent adoption, equity, and fiscal metrics. These steps demonstrate the robustness and plausibility of the ABM results.

In essence, the synergy between a post-positivist philosophy and quantitative ABM approach provides a robust framework for this research. Post-positivism acknowledges the complexities and uncertainties inherent in studying solar PV adoption, guiding the development of models that are seen as useful tools for understanding and prediction rather than definitive representations of

reality. The quantitative ABM methodology provides analytical power to explore these complexities, simulate dynamic processes, and evaluate the potential efficacy of different policy interventions aimed at promoting residential solar PV adoption in Bahrain. This integrated approach was designed to yield scientifically sound and practically actionable insights to support Bahrain's sustainable energy transition.

3.2. Modeling Methodology: Agent-Based Modeling (ABM)

This section elucidates the modeling methodology employed in this thesis, specifically the ABM. It commences by establishing the rationale for selecting ABM, drawing upon the extant literature to underscore its suitability for addressing the research questions related to residential solar PV adoption. Subsequently, the selection of NetLogo as a specific modeling platform is justified, with an outline of its capabilities and appropriateness for the complexities inherent in this study..

3.2.1 Rationale for Choosing Agent-Based Modeling

To effectively address the multifaceted research objectives outlined in Chapter 1 and the critical research gaps identified in Chapter 2, particularly the need to model dynamic policy interactions, heterogeneous household decisions, and emergent adoption patterns within Bahrain's unique subsidized energy market, this study employs ABM as its core analytical methodology. The choice of ABM is driven by its distinct advantages in addressing these specific challenges. The adoption of energy technologies, particularly renewable systems such as residential solar PV, is a complex socio-technical process that is influenced by a multitude of interacting factors (Hansen et al., 2019;

Nurwidiana et al., 2021). Traditional modeling approaches often struggle to capture the nuances of these systems. The ABM offers a powerful alternative, providing a bottom-up approach that simulates the actions and interactions of autonomous agents (e.g., households) to understand emergent system-level behaviors (Mittal et al., 2019; Moglia et al., 2017; Van Dyke Parunak et al., 1998). At its core, ABM is a computational technique wherein individual software entities, or "agents," are situated in a virtual environment and endowed with specific attributes, objectives, and behavioral rules (Karimi & Vaez-Zadeh, 2021; Mittal et al., 2019). These agents are characterized as being autonomous, self-contained, interactive, and often adaptive, capable of learning and modifying their behaviors based on experience (Karimi & Vaez-Zadeh, 2021; Mittal et al., 2019). This methodology is increasingly recognized for its capacity to explore complex adaptive systems, making it particularly well-suited for investigating energy policy design and technology diffusion (Hesselink & Chappin, 2019; Yao et al., 2023). The ABM is concerned with understanding possible future scenarios based on given situations and sets of assumptions, which aligns with the exploratory nature of policy design (Hansen et al., 2019).

As established in the literature review (Chapter 2), conventional Equation-Based Modeling (EBM) approaches, which are useful for predicting aggregate adoption trends, often fall short of studies requiring a granular understanding of individual behaviors and policy impacts (Moglia et al., 2017; Nurwidiana et al., 2021). The EBM typically categorizes decision makers into homogenous groups, thereby omitting the rich tapestry of individual preferences, circumstances, and decision-making heuristics (Nurwidiana et al., 2021). Consequently, EBM may inappropriately explain dramatic changes

in adoption or specific decisions made by individuals (Nurwidiana et al., 2021).

In contrast, ABM excels in representing household heterogeneity, which is a critical factor in solar PV adoption (Hesselink & Chappin, 2019). In this study, heterogeneity manifests across multiple crucial dimensions that characterize how agents differ from one another. At the socioeconomic level, agents vary in their income levels (across different quintiles), family sizes, dwelling characteristics (including roof size and suitability for PV), and electricity consumption patterns.

Behaviorally, agents exhibit different levels of risk aversion in financial decision making, varying degrees of environmental awareness, distinct sensitivities to peer influence, and diverse time preferences for investment returns. Their decision-making processes incorporate individual adoption thresholds, different weights assigned to various factors, and various responses to financial incentives. Furthermore, agents differ in their access to resources, including available roof spaces, financial capacity for upfront investment, and access to financing options.

This multidimensional heterogeneity allows ABM to capture the diversity inherent in real-world systems (Gallegati & Kirman, 2012; Mittal et al., 2019). By incorporating these dimensions, the model simulates how different household segments respond to policy interventions, accounting for their unique combinations of characteristics and constraints. This comprehensive representation of household diversity is crucial for understanding adoption patterns and assessing the distributional equity impacts of different policy scenarios in Bahrain's residential sector.

Beyond heterogeneity, ABM facilitates the modeling of interactions and social influences. Solar PV adoption is significantly influenced by social factors including peer effects, neighbor influence, social norms, and information diffusion through networks (Moglia et al., 2017; Nurwidiana et al., 2021). ABM provides a natural framework for explicitly modeling these agent-to-agent interactions and feedback loops, including the "social pressure to adopt" and the role of communication, which significantly impacts technology diffusion and is often difficult to capture adequately in aggregate models (Hesselink & Chappin, 2019; Moglia et al., 2017; Palmer et al., 2015).

Furthermore, the ABM allows for the incorporation of complex decision-making processes. The decision to adopt a solar PV system is not purely economic; it is influenced by the interplay of financial considerations (e.g., payback period and net present value), social influences (e.g., peer effects), psychological factors (e.g., attitudes, perceived behavioral control, bounded rationality, and loss aversion), and awareness of environmental benefits (Mittal et al., 2019). ABM can integrate these multifaceted influences, embedding theoretical frameworks, such as the Theory of Diffusion of Innovations (DOI), within agent decision rules to provide a robust theoretical underpinning (Nurwidiana et al., 2021; Rai & Robinson, 2015). The ABM captures the effects of bounded rationality and social interactions, which are often simplified or ignored in other modeling paradigms (Jung et al., 2025; Mittal et al., 2019).

A fundamental tenet of ABM and a key strength of this research is its ability to capture emergence, where system-wide behaviors (such as adoption trajectories, market dynamics, and aggregate policy impacts) arise from the nonlinear interactions of heterogeneous agents, which are often difficult to

predict solely from the properties of individual agents (Alfaro, 2014; Hansen et al., 2019; Mittal et al., 2019; Vuthi et al., 2022).

Finally, a significant advantage of ABM for this thesis is its utility as a "policy laboratory" or a "low cost test bed for policy and planning scenarios" (Axtell et al., 2001) for exploring the potential impacts of various interventions (Hesselink & Chappin, 2019; Nurwidiana et al., 2021). This study leverages the ABM to simulate and compare different policy scenarios, such as varying financial incentives (VAT reduction, loans), subsidy reforms, and different cash transfer (CT) designs (universal, targeted, tiered), observing their effects on adoption rates and patterns across a heterogeneous population (Adepetu et al., 2018; Hesselink & Chappin, 2019). The application of ABM in energy systems is prominent; for example, Mittal et al. (2019) developed an ABM to predict consumer adoption of residential renewable energy, considering various stakeholders, while Karimi and Vaez-Zadeh (2021) used an ABM for electric energy policy assessment. Alfaro (2014) also highlighted ABM's utility of ABMs in planning renewable energy deployment in developing countries. This "computational laboratory" approach enables an ex-ante evaluation of policy effectiveness, helping to identify interventions that are most likely to achieve the desired outcomes in the specific context of Bahrain (Sopha et al., 2017).

Therefore, given the need to model heterogeneous households, their complex decision-making influenced by economic and social factors, the dynamic interactions between them, and the objective of comparing intricate policy scenarios within the specific context of Bahrain's subsidized energy market, ABM was deemed to be the most appropriate and powerful methodological approach. Although ABM offers significant strengths in capturing agent

interactions and emergent behaviors, it is important to acknowledge certain methodological challenges. These include sensitivity to the underlying assumptions and validation complexities in contexts with limited historical data. To address these limitations, this research employs a comprehensive sensitivity analysis across key model parameters and utilizes available real-world data from Bahrain's electricity sector for calibration. Furthermore, the model's validation strategy incorporated multiple approaches, including pattern-oriented validation and expert consultation, to ensure robust and reliable results. This balanced methodological approach enables the leveraging of ABM's strengths while systematically addressing its limitations, thereby providing a rigorous framework for analyzing solar PV adoption policies in Bahrain's unique market context.

3.2.2 Modeling Platform: NetLogo

Following a comprehensive evaluation of the available agent-based modeling platforms, NetLogo (Version 6.4) was selected as the implementation framework for this study based on several critical criteria: computational capabilities, model complexity requirements, and specific research objectives. NetLogo is a multi-agent programmable modeling environment designed to simulate complex natural and social phenomena (Tisue & Wilensky, 2004; Wilensky, 1999), with demonstrated effectiveness in energy policy and technology diffusion research.

The selection of NetLogo was based on a systematic evaluation of its technical capabilities aligned with the research requirements. Its architecture efficiently handles the modeled population size (158 household agents) and supports the implementation of complex decision-making algorithms required for this study. The platform's ability to represent heterogeneous agents and their

interactions within defined environments, whether spatial or networked, directly addresses the core modeling requirements for simulating Bahraini household behaviors and social influence networks. The integrated BehaviorSpace functionality enables systematic parameter sweeps and sensitivity analyses, which are essential for the robust validation of the model outcomes.

However, it is important to acknowledge the limitations of the NetLogo. The platform faces scalability challenges when modeling very large agent populations, and has constraints in integrating external data sources in real time. To address these limitations, this study implemented several mitigation strategies: optimization of model parameters to manage computational load, careful structuring of data input processes, and development of external data processing pipelines using Python for advanced analytics. Additionally, although NetLogo's built-in validation tools are valuable, supplementary validation techniques have been implemented to ensure robust results.

The ABM, implemented through NetLogo, provides an appropriate framework for investigating residential solar PV adoption dynamics while acknowledging inherent methodological constraints. The platform's capabilities in modeling household heterogeneity, decision-making processes, and social interactions align with the research objectives, although certain limitations persist. Future work could address these limitations through integration with more sophisticated data-management systems and advanced computational resources. The current implementation balances methodological rigor with practical constraints, providing a foundation for analyzing policy interventions in Bahrain's residential solar PV market while maintaining transparency regarding both capabilities and limitations.

To ensure a transparent, comprehensive, and replicable description of the ABM developed for this research, the widely adopted ODD (Overview, Design concepts, Details) protocol (Grimm et al., 2006, 2010) is employed, as detailed in the following sections.

3.3. Model Description

This section provides a detailed description of the ABM developed in this study. To ensure clarity, completeness, and reproducibility, the description adheres to the ODD protocol, a widely adopted standard for documenting individual- and agent-based models (Grimm et al., 2006, 2010; Polhill et al., 2008). The ODD protocol is utilized because it offers a structured framework that enhances model communication and comprehension, which is crucial for complex simulations, such as those presented here (Grimm et al., 2017; Szangolies et al., 2024). By providing a standardized layout, ODD helps to ensure that all essential aspects of the model are described, thereby improving the potential for replication and comparison with other models (Grimm et al., 2010, 2017; Polhill et al., 2008). The use of such a protocol is particularly important in fields such as economics to improve transparency and to allow others to critique and build upon the model (Alvarez & Grimm, 2024).

Additionally, the hierarchical structure of ODD, beginning with an overview and then exploring specifics, enhances readability and enables readers to engage with information at their preferred level of detail (Grimm et al., 2010, 2017). The protocol also serves as a comprehensive checklist, promoting rigorous model formulation by ensuring that key design decisions are explicitly addressed and that essential elements are less likely to be forgotten (Grimm et al., 2010, 2017). Given this thesis's focus on simulating human decision-making (i.e., household solar PV adoption), the principles of the

ODD+D extension, which refines ODD to describe human decisions in ABMs (Müller et al., 2013), are also implicitly and explicitly incorporated. This is particularly relevant for detailing aspects such as the theoretical basis of decisions, cognitive factors, and individual sensing and prediction, which are crucial when modeling human agents in the social sciences (Müller et al., 2013; Polhill et al., 2008).

The ODD protocol was followed to provide a clear and structured description of the ABM (Grimm et al., 2006, 2010). Figure 3.2 illustrates the main components of the ODD protocol of the developed model, summarizing its core elements and processes.

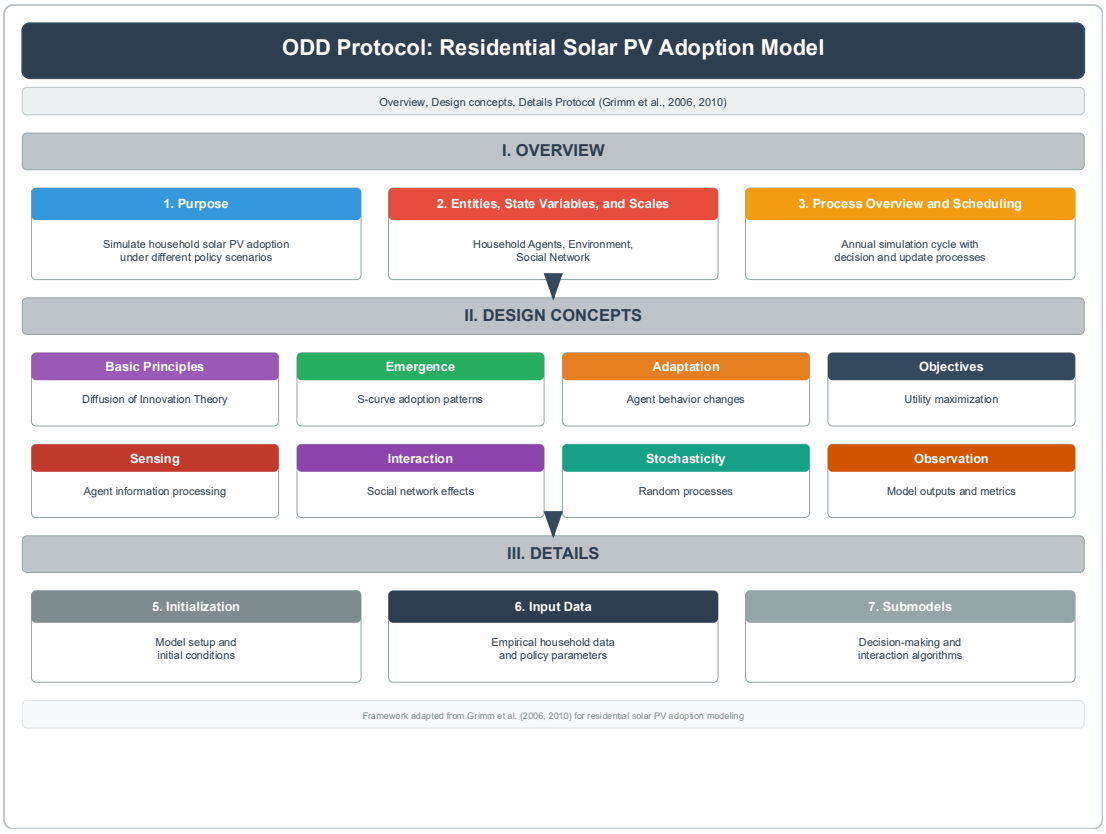


Figure 3.2: Structure of the ODD (Overview, Design concepts, Details) protocol used to describe the agent-based model

3.3.1 Purpose

The first element of the ODD protocol, 'Purpose,' requires a concise statement of the model's objectives (Grimm et al., 2006, 2017). This is crucial for understanding the model's scope and rationale behind including certain aspects of reality while omitting others (Grimm et al., 2010, 2017). Accordingly, the primary purpose of this ABM is to simulate the adoption decisions of residential households in Bahrain regarding rooftop solar PV systems operating within the country's approved net metering framework (EWA, 2017) under different energy policy scenarios. Specifically, the model aims to explore and compare the impacts of (a) financial incentives (VAT reduction, innovative loans) within the existing subsidized electricity market and (b) comprehensive electricity subsidy reform coupled with various compensatory CT mechanisms (universal, targeted, tiered). The goal is to assess the effects of these policies on solar PV adoption diffusion rates, distributional equity across households, overall governmental fiscal balance, household economic outcomes, and associated environmental benefits (CO2 reduction and natural gas savings) over the period 2025-2050.

3.3.2 Entities, State Variables, and Scales

Following the 'Purpose,' the ODD protocol delineates the description of 'Entities, State Variables, and Scales' (Grimm et al., 2006, 2017). This component elucidates the model's elements, their characteristics, and spatiotemporal context. Within the ODD framework, state variables encompass not only numerical attributes, but also behavioral characteristics, strategies, and parameters that differentiate agents (Grimm et al., 2010).

3.3.2.1 Entities

1) Household Agents: The model comprises 158 owner-occupied households representing a diverse cross-section of the Bahraini residential sector, derived from empirical data collected through collaboration with external stakeholders. The sample size was determined on the basis of several methodological considerations and data availability constraints. The household dataset provides detailed monthly electricity consumption profiles for the year 2024, along with comprehensive household characteristics, including residence area/location, building age and type, number of rooms, family size, dwelling/plot size, and number of air-conditioning units. The richness of this dataset enables the initialization of heterogeneous agents with realistic energy-use patterns and socio-physical attributes. While this sample size may appear modest, it proves adequate for the study's objectives for several reasons. First, the dataset captures significant variations across key household characteristics that influence solar PV adoption decisions, including income level, electricity consumption pattern, and dwelling attributes. Second, the sample provides sufficient heterogeneity to explore diverse behavioral responses and emergent patterns under different policy scenarios, consistent with established ABM practices (Grimm & Railsback, 2012; Wilensky & Rand, 2015). Furthermore, the detailed nature of the data allows for the robust calibration of agent behaviors and validation of model outcomes. The representativeness of the sample was enhanced through careful calibration against national statistics, particularly in terms of income distribution and household characteristics. This approach ensures that,

while working with a manageable sample size for computational efficiency, the model maintains its ability to generate insights applicable to broader policy implications for Bahrain's residential solar PV adoption patterns.

2) Environmental Context: The Environmental entities encompass a broader contextual framework influencing agent decisions, comprising three interconnected components: the national policy environment (electricity tariffs, renewable energy incentives, and CT rules as defined by policy scenarios), external market dynamics (solar PV system cost trajectories), and a stochastic social network structure facilitating agent interactions. While geographically situated within Bahrain, the model employs network-based rather than spatially explicit interactions, with the initial network formation potentially informed by geographical proximity considerations. This specification enables a systematic examination of policy effects, while maintaining computational tractability and an analytical focus on household-level adoption dynamics.

3.3.2.2 State Variables

1) Household Agent Attributes: Each agent possesses a comprehensive set of state variables that are systematically categorized as follows:

a) Static Attributes: Variables derived from empirical data were maintained constant throughout the simulation runs. These include annual income, family size, roof size/suitability (determining potential solar PV capacity), building type and age, location (governorate), and the initial environmental awareness score.

b) Dynamic Attributes: Variables subjected to modification during simulation execution

- Economic State: Calculated financial metrics including current payback period (PBP) estimates for solar PV investment, subsidy loss under reform, applicable compensation ratio (CR), and CT amount received (P).
- Social State: Current awareness level regarding solar PV technology and policies (influenced by information acquisition and network interactions), perceived social influence from network neighbors, and observed neighborhood adoption rate.
- Behavioral/Decision State: Individual adoption threshold, solar PV adoption status (Boolean: Adopted-solar?), and time since adoption.

2) Environmental Variables: Global variables encompass the current simulation year, projected cost per kilowatt peak (kWp) of solar PV systems (declining temporally), panel degradation rate, and prevailing policy parameters, including electricity tariffs, VAT rate, loan terms, and CT rules corresponding to the active scenario.

3.3.2.3 Scales

1) Temporal Scale: The simulation is conducted from 2025 to 2050, with this time frame carefully selected to align with multiple strategic considerations. First, the 25-year simulation horizon matches the typical lifetime of solar PV systems, enabling a comprehensive assessment of long-term adoption patterns and return on investment calculations for households. Second, this timeframe allows for the evaluation of gradual policy implementation effects, which is

particularly important for subsidy reform scenarios where impacts evolve over extended periods. The primary decision-making cycle occurs annually, with each "tick" representing one year. Nonetheless, certain calculations, such as solar PV energy generation, electricity billing, and emissions, are executed or aggregated according to the monthly patterns within each annual interval.

3) Spatial Scale: The model encompasses households throughout Bahrain, but does not employ a detailed geographical grid to specify agent locations or resource variations. Spatial characteristics are implicitly represented through agent attributes, such as location or governorate, and potentially within the social network structure.

3.3.3 Process Overview and Scheduling

The 'Process Overview and Scheduling' element of ODD outlines what entities do, in what order, and how time is modeled, providing a high-level view of the model's dynamics (Grimm et al., 2006, 2017). A clear and precise description of the schedule, including the sequence of entity processing and state variable updates, is essential for model reimplementation and understanding (Grimm et al., 2010).

The simulation proceeded in discrete annual steps from 2025 to 2050. Within each year (tick), the following sequence of events typically occurred:

1) Environment Update: Global variables are updated (e.g., solar PV system cost decreases based on projected trajectory, panel efficiency decreases owing to degradation). Policy parameters were set according to the active scenario.

2) Agent Financial Calculation: For each household agent, key financial metrics relevant to the solar PV adoption decision are recalculated based on the current environmental state (solar PV cost and electricity tariffs) and agent attributes (consumption pattern). This includes potential bill savings, payback period (PBP), and possible rate of return (RoR).

3) CT Calculation (Scenarios S_1, S_2, S_3): If a CT scenario is active (from 2026 onwards), the applicable transfer amount is calculated for each household based on a specific algorithm (universal, targeted, or tiered) and the relevant agent attributes (income, family size, subsidy loss). (See Sub-model 3.3.7.4).

4) Adoption Decision: Each non-adopting household agent evaluates the utility of adopting solar PV based on its current state, perceived financial benefits (influenced by incentives or CTs), social influence, and environmental preferences. The agent makes a probabilistic decision to adopt based on comparing its calculated utility to its threshold. (See Sub model 3.3.7.1).

5) State Update: Agents who adopt solar PV change their 'Adopted-solar?' status. Future financial calculations should reflect solar PV ownership. Dynamic attributes, such as awareness, may be updated based on the decision process or new information.

6) Social Network Update: The social network potentially evolves. New links may form (e.g., non-adopters connecting with nearby adopters), existing links may decay stochastically, and awareness/influence propagates through the network. (See Sub model 3.3.7.3).

7) Monthly Calculations (Aggregated Annually): Within each annual step, processes based on monthly data were executed or aggregated. This includes calculating the monthly solar PV energy output (based on system size and yield), calculating monthly electricity bills (considering tiered tariffs, net metering, and solar PV generation), and calculating the associated CO2 emissions and natural gas savings based on displaced grid electricity.

8) Data Logging: Key state variables and outcomes (adoption count, total capacity, average PBP, equity metrics, fiscal balance, and environmental savings) are recorded at the end of each time step.

9) Simulation End: The simulation stops after completing the final year (2050).

3.3.4 Design Concepts

The Design Concepts section of the ODD protocol is intended to articulate the fundamental principles and modeling choices underlying the ABM (Grimm et al., 2006, 2017). This helps to expose the theoretical underpinnings and adaptive mechanisms within the model, facilitating comparison along various dimensions (Grimm et al., 2010; Polhill et al., 2008). The concepts employed in this thesis align with those typically reported in ODD descriptions. Furthermore, as this model centrally involves human decision-making, the conceptualization also draws from the ODD+D extension (Müller et al., 2013), which provides a more detailed framework for describing aspects, such as individual decision logic, objectives, sensing, prediction, and heterogeneity in decision-making within social simulations (Müller et al., 2013).

1) Basic Principles (Theoretical Underpinnings): The model's design is grounded in the established theories reviewed in Chapter 2. The principles of Rogers (2003) Diffusion of Innovation theory inform the understanding of adoption patterns, the role of perceived innovation attributes (implicitly within utility components), and adopter heterogeneity. Concepts from Behavioral Economics, such as bounded rationality in decision-making and the influence of perceived costs, benefits, and risks (including loss aversion in subsidy reform scenarios), are embedded in the agent decision logic. Social Capital Theory (Coleman, 1988; Putnam, 1995) underpins the modeling of social network structures, trust, and mechanisms of social influence and information diffusion.
2) Emergence: Defined in ODD as key results arising from individual adaptive traits or behaviors that are not explicitly programmed at the system level (Grimm et al., 2017). In this model, macro-level outcomes, such as the S-shaped diffusion curve of solar PV adoption, overall fiscal impact, and patterns of distributional equity, are not pre-programmed, but emerge from the micro-level interactions and decisions of heterogeneous household agents.
3) Adaptation: This concept concerns the rules that agents use to make decisions or change behavior in response to changes in themselves or their environment (Grimm et al., 2017). Agents adapt their behavior based on their internal and external environments. The primary adaptation is the decision to adopt solar PV triggered when the calculated utility surpasses the agent's threshold, reflecting changing perceptions of economic viability, social norms, or awareness.

4) Objectives: ODD requires specifying agent objectives if they are programmed to meet certain goals or to rank alternatives based on criteria (Grimm et al., 2017). Müller et al. (2013), in ODD+D, further emphasize detailing the decision model, including its theoretical basis, and how agents measure success. Agents are modeled as having objectives that are primarily framed through a multi-attribute utility function. They implicitly seek to maximize this utility by balancing economic factors (payback), social considerations, environmental preferences, and financial capacity (income utility).
5) Sensing: Part of the ODD design concept, sensing, refers to what agents can perceive or know about their environment and other agents (Grimm et al., 2010; Polhill et al., 2008). ODD+D refines this by asking about the information agent uses and how they acquire it (Müller et al., 2013). Agents in this model sense current solar PV costs, electricity tariffs, active policies (incentives, CTs), and the adoption status of their network neighbors.
6) Interaction: ODD highlights how agents connect and influence each other (Grimm et al., 2010; Polhill et al., 2008). Agents primarily interact through their social network structures. These interactions drive the diffusion of information/awareness and exert social influence (peer effects), thereby impacting individual adoption probabilities. Agents also interact indirectly via their collective impact on aggregate statistics (e.g., the overall adoption rate influencing perceived norms).
7) Stochasticity: The incorporation of random processes is a standard design concept in ODD that reflects the uncertainty and variability in real-world systems (Grimm et al., 2010; Polhill et al., 2008). Randomness is incorporated in several processes: the probabilistic

nature of the adoption decision itself (based on the logistic function comparing utility to threshold), potentially in the formation or decay of social network links, and in the initial attribute assignment within defined distributions.

8) Observation (Model Output): This ODD element details the data collected from the model for analysis (Grimm et al., 2010; Polhill et al., 2008). Key system-level outputs (e.g., adoption rates, installed capacity, PBP distributions, equity metrics, fiscal balance, and environmental savings) and selected agent-level data were observed and recorded by the simulation at each time step for subsequent analysis, as detailed in Section 3.8.

3.3.5 Initialization

The initialization section in ODD outlines the model's starting conditions, detailing initial values for state variables and any data necessary to establish the simulation environment (Grimm et al., 2006, 2010, 2017). The model was set up to depict the state of the system at the onset of 2025.

1) Household Agents: A total of 158 household agents were generated, and each assigned static attribute, such as income, family size, roof size, and location, was derived from an empirical dataset. Initial values for dynamic attributes, such as awareness level and adoption threshold, are determined, possibly based on distributions or assumptions informed by the literature or calibration. The 'Adopted-solar?' was initially marked as 'false' for all agents.
2) Network: A random social network structure was initially created to connect the agents. This involves each agent being randomly linked to

a set number of other agents to form a network that facilitates the spread of social influence and awareness.

3) Environment: Global variables were initialized to their 2025 starting values, such as the initial solar PV cost and policy parameters for the specific scenario being executed.

All parameters in the ABM were systematically initialized using empirical data, literature benchmarks, or scenario-specific assumptions. These parameters include monetary values, such as solar PV system costs, tariff rates, CT amounts, and household energy expenditures, and non-monetary variables, such as behavioral thresholds, social influence factors, and household demographic attributes. The careful selection and calibration of these parameters ensures that the model accurately reflects real-world dynamics and policy environments pertinent to the case study. Appendix A provides a comprehensive list of all initialized parameters, complete with their units, default values, and descriptions, to ensure the full transparency and reproducibility of the simulation experiments.

3.3.6 Input Data

ODD defines 'Input Data' as external information utilized by the model to depict processes or environmental conditions that change over time, distinct from parameters or initial state variable values, which are addressed under 'Initialization' or 'Sub models' (Grimm et al., 2006, 2010). The model employs several essential datasets for initialization and parameterization, as outlined in Section 3.5: Household Data, which consists of empirical data from 158 households to inform agent attributes; Income Data, representing household economic strata; and solar PV System Data, including technical specifications and cost data from local installers and literature. Key time-varying inputs

include the projected future cost reduction of solar PV systems. Policy Information, such as tariff structures (EWA, 2021; SEA, 2021), and the standard Value-Added Tax (VAT) rate (NBR, 2023). Importantly, the rules governing the current Net Metering scheme (EWA, 2017) serve as a constant underlying assumption for all simulated scenarios in this thesis, providing a fundamental mechanism for grid interaction and compensation for surplus electricity exported by households with adopted solar PV systems. The parameters for the various policy interventions examined (e.g., specific VAT reduction rates, innovative loan interest rates and terms, and the algorithms and parameters defining the Universal, Targeted, and Tiered CT schemes) were based on the detailed scenario designs presented in Section 3.4. The detailed validation of the input data's representativeness is provided in Section 3.7.2.1.

3.3.7 Sub models

The 'Details' block of the ODD protocol culminates in the 'Sub-models' section, which provides complete and detailed descriptions of all processes outlined in the 'Process Overview and Scheduling' (Grimm et al., 2006, 2010, 2017). The ODD recommends a clear separation between the factual description of sub-models (e.g., equations and algorithms) and the justification or rationale behind their design, including the selection of parameters and sub-models tested (Grimm et al., 2010; Polhill et al., 2008). For models involving human decision-making, the ODD+D extension (Müller et al., 2013) provides further guidance, particularly for detailing the 'individual decision-making' process within the design concepts, which then translates into specific submodel structures. This includes articulating the theoretical and empirical background, cognitive aspects, and decision rules

(Müller et al., 2013). The ODD+D also encourages describing how parameter values were chosen and the testing and calibration of submodels (Polhill et al., 2008).

The overall ABM incorporates several key submodels that define specific processes.

3.3.7.1 Household Agent Decision Model

This core sub-model defines how individual household agents make choices regarding solar PV adoption and is central to the ABM. Its detailed description aligns with the ODD protocol's requirement for comprehensive submodel documentation, particularly the ODD+D emphasis on clearly articulating human decision-making processes (Müller et al., 2013).

The model deployed in this study uses a multi-criteria 'utility function' framework within an ABM to simulate how a household decides on solar PV adoption in Bahrain's subsidized electricity market, as described in section 2.5. This methodology is consistent with the conventional methods of modeling energy technology diffusion (Palmer et al., 2015; Pearce & Slade, 2018; Rai & Robinson, 2015). First, it deals with heterogeneous decision-making by decision-makers who are, for the most part, not perfectly informed about costs and benefits (Kiesling et al., 2012), while introducing application elements that are also relevant, though more specific, to subsidized energy markets. Under such conditions, a utility-based approach offers a logical framework to represent individual choices. Other researchers have applied similar methods in the social construction of renewable energy technologies, as illustrated in Table 3.1, which summarizes factors considered in utility

functions from previous ABM studies on solar PV (Iachini et al., 2015; J.-S. Lee et al., 2015; Palmer et al., 2015; Pearce & Slade, 2018).

Table 3.1: Summarizes factors considered in utility functions from previous ABM studies on solar PV

Reference	**Investigation Focus**	**Factors Considered in Utility Function**
Pearce & Slade. (2018)	Effect of feed-in-tariff subsidy (Great Britain)	household income, social network, total capital cost, and the payback period
Palmer et al. (2015)	Effect of support schemes (Italy)	Payback period, Environmental benefit, Household income, Communication with other agents
Zhao et al. (2011).	Effect of support schemes (USA)	Payback period, Household income, Word of mouth, Advertisement effect
(Iachini et al., 2015)	Effect of social and economic factors (Italy)	Payback period, Household budget, Neighborhood influence, Environmental benefit

In this model, households are agents who decide independently on the basis of the calculated utility of adopting PV. If an agent's total utility exceeds a predetermined individualized adoption threshold, the agent adopts a solar PV system (Rai & Robinson, 2015). This approach allows for the consideration of multiple interacting factors in decision making, providing flexibility in calibrating the model based on empirical data and theoretical understanding (Kiesling et al., 2012). The model aims to forecast key outcomes, including the number and characteristics of adopting households, installation timing,

and cumulative capacity, which can inform broader economic and policy assessments. Realistic agent characteristics, including demographic variables, are integrated to inform the decision-making processes.

The household agent decision process at each annual step for each non-adopting agent involves the following steps:

1) Payback Utility (u_{pay})

$$u_{pay}(pp) = \begin{cases} 0.8, & pp \leq 3 \\ 0.8 - 0.05(pp - 3), & 3 < pp \leq 7 \\ 0.6 - 0.04(pp - 7), & 7 < pp \leq 12 \\ 0.4 - 0.04(pp - 12), & 12 < pp \leq 17 \\ 0.2\dfrac{20 - pp}{3}, & 17 < pp < 20 \\ 0, & pp \geq 20 \end{cases} \quad (3.1)$$

The payback utility quantifies the attractiveness of the investment payback period (pp, in years).

Where:

pp: Payback period in years

2) Income Utility (u_{inc})

Income utility increases with normalized household income.

$$x = \frac{I_h - I_{min}}{I_{max} - I_{min}} \quad (3.2)$$

$$u_{inc} = safe\_logistic(x, k_{inc}, 0.5) \quad (3.3)$$

Where:
I_h: Household annual income
I_{min}, I_{max} : Minimum/maximum income in the population

k_{inc} : Slope parameter for income utility

3) Environmental Utility (u_{env})

Environmental utility combines income and environmental awareness

$$y = 0.5 \left(\frac{I_h - I_{min}}{I_{max} - I_{min}} \right) + 0.5 \cdot \text{env-awareness} \quad (3.4)$$

$$u_{env} = \text{safe\_logistic}(y, k_{env}, mid_{env}) \quad (3.5)$$

Where:

env-awareness: environmental awareness score (range 0–1)

k_{env} : logistic slope, mid_{env} : logistic midpoint

4) Social Utility (u_{soc})

Social utility aggregates social capital, influence, and neighbor awareness.

$$z = \alpha_{sc} \cdot \text{social-capital} + \alpha_{si} \cdot \text{social-influence} + \alpha_{ana} \cdot \text{avg-neighbor-awareness} \quad (3.6)$$

$$u_{soc} = safe\_logistic(z, k_{soc}, mid_{soc}) \quad (3.7)$$

Where:

$\alpha_{sc}, \alpha_{si}, \alpha_{ana}$: Weights for social-capital, social-influence, and neighbor-awareness (sum to 1), k_{soc} : logistic slope, mid_{soc}: logistic midpoint

5) Logistic Function

The safe logistic function is used to normalize all subutilities except payback.

$$\text{safe\_logistic}(x, k, m) = \frac{1}{1 + \exp(-k(x - m))} \tag{3.8}$$

Where:

k: slope parameter, m: logistic midpoint

6) Total Utility (U)

The final utility score is the weighted sum of the subutilities:

$$U = w_{inc}u_{inc} + w_{pay}u_{pay} + w_{soc}u_{soc} + w_{env}u_{env} \tag{3.9}$$

Where:

$w_{inc}, w_{pay}, w_{soc}, w_{env}$: utility weights (sum to 1)

7) Logistic Adoption Probability

The adoption probability is determined by the gap between the utility and the threshold:

$$P(\text{adopt}) = \frac{1}{1 + \exp\left(-k_{logistic}(U - \text{threshold})\right)} \tag{3.10}$$

Where:

$k_{logisitic}$: logistic slope for adoption, threshold: agent-specific threshold

8) Adoption Rule

Adoption is triggered if the utility exceeds the threshold of the agent.

$$U > \text{individual-threshold} \tag{3.11}$$

Where:

individual−threshold: agent-specific value, reflecting heterogeneity

3.3.7.2 Financial Calculation Model

This sub-model implements comprehensive computational algorithms for the essential financial metrics underlying household adoption decisions.

1) Electricity Bill Computation: The model calculates monthly and annual electricity expenditures based on household-specific consumption patterns, applicable tiered tariff structures (encompassing either subsidized baseline tariffs or unsubsidized reform tariffs contingent upon scenario specification), and net metering credits derived from solar PV generation output.
2) Solar PV System Cost Analysis: Total upfront investment costs are computed based on the system capacity specifications and prevailing cost per kilowatt-peak (kWp), incorporating value-added tax (VAT) implications under relevant policy scenarios. The model additionally calculates potential loan repayment schedules under innovative financing mechanisms.
3) Payback Period (PBP) determination: The algorithm computes the temporal duration required for cumulative savings (comprising reduced electricity bills and potential CT effects) to recover initial investment costs, incorporating discount rate considerations where applicable. This metric served as the primary input parameter for the Payback Utility component (u_pay).
4) Rate of Return (RoR) calculation: The model generates the rate of return metrics for the adopted systems, facilitating comprehensive financial performance analysis and comparative evaluation across scenarios.
5) Net Metering Credit Assessment: The sub-model implements Bahrain's regulatory net metering framework to calculate credits for surplus energy

exported to the national grid, ensuring compliance with established policy parameters and tariff structures.

3.3.7.3 Social Network Dynamics Model

This sub-model governs agent interactions as follows:

1) Link Management: Defines rules for how social links between agents are formed (e.g., based on initial proximity or randomly) and potentially decay over time.
2) Information/Awareness Propagation: Simulates how awareness of solar PV technology, costs, benefits, and policies spreads through the network from adopters or other sources to non-adopters.
3) Peer Influence Calculation: Quantifies the effect of network neighbors' adoption status or opinions on an agent's Social Utility (u_soc) component.

3.3.7.4 Cash Transfer Calculation Model

Implementing specific algorithms for the CT scenarios (S_1, S_2, S_3).

1. Universal Cash Transfer S_1:

A universal transfer provides each household with a base and per person amount scaled to the available pool (S):

$$P_i = \text{Base Amount} + (\text{Per-Person Amount} \times \text{family members}) \tag{3.12}$$

$$\text{scaling factor} = \frac{f \cdot S}{\sum_{i=1}^{N} P_i} \tag{3.13}$$

$$\text{Cash Transfer}_i = P_i \times \text{scaling factor} \tag{3.14}$$

Where:

f: fraction of pool, S: total subsidy pool, N: number of eligible households

9) Targeted Cash Transfer S_2

$$\text{phase-out factor} = \begin{cases} 1, & \text{if income} \leq T \\ 1 - \dfrac{\text{income} - T}{\text{phase-out range}}, & T < \text{income} < T + \text{phase-out range} \\ 0, & \text{if income} \geq T + \text{phase-out range} \end{cases} \tag{3.15}$$

A phase-out factor ensures transfer tapers with higher income.

$$P_i = [\text{Base Amount} + (\text{Per-Person Amount} \times \text{family members})] \times \text{phase-out factor} \tag{3.16}$$

$$\text{Cash Transfer}_i = P_i \times \text{scaling factor} \tag{3.17}$$

Where:

T: income cutoff

phase−out range: range over which the transfer is phased out

10) Tiered Cash Transfer S_3

$$F_i = \begin{cases} 1, & \text{if income} \leq T_{min} \\ \dfrac{T_{max} - \text{income}}{T_{max} - T_{min}}, & T_{min} < \text{income} < T_{max} \\ 0, & \text{if income} \geq T_{max} \end{cases} \tag{3.18}$$

$$H_i = 1 + \text{household-size-factor} \times \max(0, \text{family members} - 4) \tag{3.19}$$

$$\text{Cash Transfer}_i = \text{subsidy-loss}_i \times F_i \times H_i \times \text{scaling factor} \tag{3.20}$$

Where:

T_{min}, T_{max}: tier income thresholds, H_i : household size adjustment

$subsidy - loss_i$: loss of subsidy per household

3.3.7.5 Policy Scenario Implementation Model

This sub-model defines how the different policy scenarios analyzed are activated within the simulation. This involves setting specific global parameters or agent rules based on the scenario being run, such as

- Changing electricity tariff structures (subsidized versus unsubsidized).
- Adjustment of the applicable VAT rate in solar PV systems.
- Making an innovative loan option available or unavailable to agents.
- Activating the relevant CT calculation algorithm (S_0, S_1, S_2, or S_3) and setting the fraction *f* of total subsidy savings to be redistributed.

These sub-models interact dynamically within the annual simulation loop to generate the overall system behavior and outcomes evaluated in this study. The clear articulation of these sub-models, their parameters, and their underlying logic is a core tenet of the ODD protocol aimed at ensuring that the model is understandable and ideally replicable (Grimm et al., 2006; Polhill et al., 2008).

3.4. Scenario Design

To evaluate the potential impact of different policy approaches on residential solar PV adoption in Bahrain, a series of distinct scenarios were designed and simulated. A fundamental premise across all scenarios is that any household adopting a solar PV system does so under the terms and conditions of Bahrain's current approved net metering policy (EWA, 2017), which governs the interaction and compensation for surplus energy exported to the grid.

3.4.1 Baseline Scenarios

Given that this thesis investigates both interventions *within* the current subsidy system and the effects of *reforming* that system, two distinct baseline or reference scenarios are defined:

3.4.1.1 Baseline (Traditional Tariff)

This scenario represents a continuation of the current energy policy landscape for Bahraini nationals' primary residences. It assumes that existing tiered, subsidized electricity tariffs remain in place throughout the simulation period ($0.008/kWh for 0-3000 kWh/month, $0.024/kWh for 3001-5000 kWh/month, and $0.042/kWh above 5000 kWh/month, compared to a production cost of approx. $0.077/kWh). Standard VAT rates apply to solar PV systems, and no specific financial incentives beyond the existing net metering are assumed. This baseline (Traditional Tariff) serves as a reference point for evaluating the financial incentive scenarios described below.

3.4.1.2 S_0 (Subsidy Removal Baseline)

This scenario represents a hypothetical future in which existing electricity subsidies for Bahraini nationals' primary residences are completely removed from the start of the simulation. Households face a full, unsubsidized, cost-reflective electricity tariff ($0.077/kWh) for all consumption. Crucially, this scenario assumes that no compensatory measures (such as cash transfers) are implemented alongside the subsidy removal. This baseline serves as the reference point for evaluating subsequent subsidy reforms and cash transfer schemes.

3.4.2 Financial Incentive Scenarios (Current Subsidy Context)

Building on the baseline, the following scenarios were simulated to assess the impact of specific financial incentives operating *within* the existing subsidized market framework:

3.4.2.1 VAT Reduction Scenario

This scenario introduces a reduction in the Value-Added Tax (VAT) levied on residential solar PV system hardware and installation costs. The standard 10% VAT is reduced (e.g., initially to 5%, potentially evolving as specified in the model parameterization) to directly lower the upfront capital cost barrier for adopters. All other conditions matched the baseline (traditional tariffs).

3.4.2.2 Innovative Loan Scenario

This scenario models the availability of a new concessional loan program, specifically for financing residential solar PV systems. The key feature is that the monthly loan repayment amount is structured to be equal to or less than the household's typical monthly electricity bill before solar PV adoption, effectively making the investment cash flow neutral or positive from the outset. Assume a specific interest rate (e.g., 7%). All other conditions matched the baseline (traditional tariffs).

3.4.2.3 Combined VAT + Loan Scenario

This scenario investigates the synergistic effect of implementing VAT reduction (as in the VAT Reduction Scenario) and the innovative loan scheme (as in the Innovative Loan Scenario). All other conditions matched the baseline (traditional tariffs).

3.4.3 Subsidy Reform and Cash Transfer Scenarios

Building upon the Subsidy Removal Baseline (S_0), the following scenarios were simulated to assess the impact of pairing subsidy removal with different compensatory cash transfer (CT) mechanisms:

3.4.3.1 S_1 (Universal Cash Transfer Scenario)

Subsidy removal (as in S_0) is accompanied by universal cash transfer provided to households. The transfer amount is primarily based on household size, potentially with a base amount plus a per-person amount, as detailed in the CT algorithm specified in Section 3.3.7.4. The total pool for transfers is funded by a predefined fraction (85%) of the total calculated government savings from the subsidy removal.

3.4.3.2 S_2 (Income-Targeted Cash Transfer Scenario)

Subsidy removal (as in S_0) is accompanied by cash transfers targeting lower- and middle-income households. The transfer amount is based on household size but includes an income phase-out factor, as detailed in the CT algorithm (Section 3.3.7.4). Funding is based on recycling a fraction of the subsidy savings.

3.4.3.3 S_3 (Tiered Household-Size Cash Transfer Scenario)

Subsidy removal (as in S_0) is accompanied by a tiered cash transfer. The transfer amount is calculated based on the household's estimated subsidy loss but adjusted by factors considering income tiering and household size, as detailed in the CT algorithm (Section 3.3.7.4). Funding is based on recycling a fraction of the subsidy savings.

3.4.4 Justification for Scenario Design

This suite of scenarios was carefully designed to systematically address the core research questions of this thesis and to enable meaningful comparisons between different policy approaches.

The Baseline (Traditional Tariff) and subsequent Financial Incentive Scenarios allow for the assessment of interventions within the current subsidized system, directly addressing RQ1 regarding the effectiveness of specific incentives such as VAT reduction and innovative loans.

The Subsidy Removal Baseline (S_0) creates the necessary counterfactual for understanding the impact of subsidy removal alone (RQ2).

The Cash Transfer Scenarios (S_1, S_2, S_3), when compared against S_0, permit the evaluation of how different compensatory designs influence adoption, household economics, and equity following reform (RQ3). Comparing S_1, S_2, and S_3 against each other reveals the relative merits of universal, targeted, and tiered compensation strategies.

Comparing outcomes across relevant scenarios (e.g., the combined financial incentive scenario vs. the reform plus compensation scenarios) enables an assessment of the comparative fiscal implications and environmental co-benefits of different strategic pathways for promoting solar PV adoption (RQ4).

This multifaceted scenario design provides a robust framework for exploring the complex trade-offs involved in promoting residential solar PV in Bahrain, considering both incremental interventions and fundamental policy reforms.

3.5. Data Sources and Parameterization

The development and execution of the ABM for this thesis relies on a combination of empirical data, information from official sources, relevant literature, and parameters determined through model calibration. This section details the data sources used to initialize the model state and the parameters defining the agent characteristics, environmental conditions, policy scenarios, and behavioral rules. The key parameters are summarized in the tables presented in this chapter.

3.5.1 Data Sources

1) Household Data: The core of the agent population is based on an empirical dataset representing 158 owner-occupied households across the Bahraini governorates. This dataset, obtained through data collection efforts, includes detailed monthly electricity consumption profiles (for the year 2024), along with household characteristics such as residential area/location, building age and type, number of rooms, family size, dwelling/plot size (used to estimate roof suitability), and number of air-conditioning units. This rich data allows the initialization of heterogeneous agents with realistic energy use patterns and socio-physical attributes. For instance, the roof-size obtained from the household dataset is crucial for determining potential solar PV system capacity. The model calculates usable-roof-area as 25% of the total roof-size. While some local studies indicate a higher average potential (e.g., Ezzelden et al., 2022 reporting ~35% usable area in Bahrain), a more conservative 25% was adopted for this model to account for potential variations in roof suitability, obstructions, or suboptimal orientations not explicitly detailed in the input dataset. Other key variables derived or used include income levels

(calibrated against national statistics), family size, building type and age, and initial environmental awareness scores.

Table 3.2: Key Household Agent Variables and Characteristics

Variable	Description	Source
Income	Annual income, used to determine affordability and CT eligibility	(SIO, 2024) Income is a significant determinant of adoption capability and response to incentives (Alsabbagh, 2019 for Bahrain context)
Family size	Number of residents affects the CT level and consumption	Household dataset provided by external collaborator (2024)
Roof size	Determines feasible solar PV system size	Household dataset provided by external collaborator (2024)
Monthly load profile	12-month electricity demand pattern	Household dataset provided by external collaborator (2024)
Building type & age	Used in adoption thresholds and eligibility	Household dataset provided by external collaborator (2024)
Environmental awareness	Household environment awareness about solar PV	Informal survey

This table summarizes the static attributes of the agents based on household data such as income categories, family size distribution, dwelling types, and environmental awareness score distribution.

2) Income Data: As direct income data were not part of the household dataset, representative annual household incomes were assigned and calibrated against national statistics. The initial assignment was based on correlations with dwelling attributes (building type/size, AC units, energy use), and the distribution was then scaled to align with Bahrain's national mean and median monthly salary figures reported by the SIO (2024), ensuring realistic economic heterogeneity while maintaining consistency with aggregate national data.
3) Solar PV System Costs and Technical Specifications: Data on the costs and technical characteristics of residential solar PV systems relevant to the Bahraini market were obtained from the local installers and manufacturers. This included the baseline overnight capital cost per kilowatt-peak (kWp) (e.g., $663.2/kWp in 2023), typical panel degradation rates (e.g., 0.5%), expected specific yield in Bahrain's climate (e.g., approx. 1,685 kWh/kWp/year, consistent with studies like Haji et al. 2021), and estimated Operation and Maintenance (O&M) costs (e.g., $3.32/month/household based on Haji et al. 2021). Projected future declines in solar PV system costs were incorporated into the model to reflect ongoing technological advancements and market maturation. This is represented by the parameter yearly_decrement, set at 2.2% (0.022) per annum in the model. This rate aligns with general observations of solar PV cost reductions noted in the literature (e.g., Juliusson, 2024; Wang et al., 2023, as cited in Chapter 2) and is consistent with expectations from external energy outlooks.
4) Policy Parameters: Parameters defining existing policies were sourced from official Bahraini entities. This includes the tiered electricity tariff structure for subsidized households, the cost-reflective tariff used in reform scenarios (sourced from the Electricity and Water Authority, EWA, 2021),

the standard Value-Added Tax (VAT) rate (NBR, 2023), and the rules governing the existing Net Metering scheme (EWA, 2017). The parameters for the simulated policy interventions (e.g., reduced VAT rate, innovative loan interest rate and terms, and parameters defining the Universal, Targeted, and Tiered Cash Transfer algorithms) are based on the specific scenario designs detailed in Section 3.4, informed by the analysis in foundational papers.

5) Environmental Data: Coefficients used to calculate the environmental co-benefits of solar PV adoption, such as the displacement of natural gas (e.g., 7.213 scf/kWh) and the avoidance of CO2 emissions (e.g., 0.000446 t CO_2/kWh), are based on standard conversion factors, potentially derived from IPCC guidelines or local energy authority data.
6) Environmental awareness: Environmental awareness data were collected through an informal survey conducted with a small group of acquaintances (n=20). This approach aligns with established qualitative research practices, where informal surveys and unstructured interviews are recognized for their ability to capture nuanced, context-rich data (Jackson & Vitacco, 2012). Such methods are particularly valuable in exploratory contexts, where formal data collection methods may not be feasible or practical.

Table 3.3: Core Model Constants, Economic, and Technical Parameters

Parameter	**Value**	**Source**
Electricity tariff (Tier 1, 3000 kWh)	0.008 $/kWh	(EWA, 2020)
Electricity tariff (Tier 2, 3001 – 5000 kWh)	0.024 $/kWh	(EWA, 2020)
Electricity tariff (Tier 3, above 5,000 kWh)	0.042 $/kWh	(EWA, 2020)
Cost per kWp	663.2 $/kWp	Local installer data 2023

Solar PV cost decline rate (yearly_decrement)	2.2% / yr	Model parameter; supported by literature trends (e.g., Juliusson, 2024; Wang et al., 2023)
Loan interest rate	7%	Proposed policy
VAT rate	10%	National Bureau for Revenue (NBR, 2023)
Unsubsidized tariff	$0.077/kWh	(EWA, 2021)
Solar PV yield	1,685 kWh/kWp	(Haji et al., 2021)
Panel degradation	0.5%/yr	(Jordan & Kurtz, 2013)
O&M cost	$3.32/month	(Haji et al., 2021)
CO2 displacement	0.000446 t/kWh	(IPCC, 2019)
Gas displacement	7.213 scf/kWh	(IPCC, 2019)

This table lists parameters such as electricity tariffs, solar PV system costs/kWp over time, panel degradation rates, loan interest rates, VAT rates, specific yield, O&M costs, emission factors, and discount rates.

3.5.2 Parameterization

The ABM requires comprehensive parameter specifications across multiple dimensions to accurately represent household decision-making processes, environmental conditions, and policy contexts. The parameterization methodology encompasses three primary categories: empirical data-driven initialization, calculated dynamic variables, and behavioral parameter calibration.

3.5.2.1 Agent Attributes and Environmental Parameters

Static household agent attributes, including family size, dwelling characteristics, and initial environmental awareness levels, were directly

initialized from the processed empirical dataset encompassing 158 households, as detailed in Table 3.2. The simulation environment was defined through core economic and technical parameters, including electricity tariff structures, initial solar PV system costs, degradation rates, interest rates, and emission factors, established from the data sources previously identified and systematically presented in Table 3.4.

3.5.2.2 Dynamic Variable Computation

The model incorporates comprehensively calculated features that evolve throughout the simulation process, reflecting agent actions and environmental changes. Table 3.4 systematically categorizes these dynamic variables across economic parameters, financial incentives, energy and environmental metrics, financial performance indicators, social factors, and adoption status tracking. These calculated features, including solar PV system costs per household, payback periods, rates of return, and annual savings, were dynamically computed within the simulation framework, incorporating both established parameters and agent behavioral responses.

Table 3.4: Key Calculated Features and Dynamic Agent Variables

Category	**Calculated Feature**	**Description**	**Source**
Economic Parameters	cost-per-wp ($)	Unit cost per watt-peak of solar PV system	(Alabbasi et al., 2022; Haji et al., 2021)
	PV-system-cost ($)	Total capital cost of solar PV system	(Alabbasi et al., 2022; Haji et al., 2021)

	pv-maintenance-cost ($)	Annual maintenance expenditure	(Alabbasi et al., 2022; Haji et al., 2021)
	upfront-cost ($)	Initial capital outlay for household	(Alabbasi et al., 2022; Haji et al., 2021)
	vat-subsidy ($)	VAT reduction (5% of PV-system-cost and every 5 years , increase 1%)	Proposed
	loan-financed-amount ($)	Principal loan amount for solar PV system	Proposed
Financial Incentives	total-interest ($)	Cumulative interest (7% of the loan amount)	Proposed
	monthly-loan-repayment ($)	Monthly loan installment is equal to or less than the monthly electricity bill	Proposed
	annual-loan-repayment ($)	Aggregated yearly loan repayment	Proposed
	annual-bill-after-solar ($)	Post-adoption annual electricity cost	Proposed
	excess-energy-credits (kWh)	Net excess generation based on the applied net metering policy	(EWA, 2017)
Energy and Environmental Metrics	annual-grid-savings ($)	Monetary value of grid energy offset	Proposed
	gas_saved (SCF)	Natural gas is conserved due to solar PV generation	(Haji et al., 2021)

	co2_avoided (tons)	Carbon dioxide emissions mitigated	(Alabbasi et al., 2022; Haji et al., 2021)
	payback-period (years)	Time to recoup initial investment	(Haji et al., 2021)
Financial Performance Indicators	rate-of-return (%)	Annual return on investment percentage	(Alabbasi et al., 2022; Haji et al., 2021)
	annual-savings-after-solar ($)	Net annual financial benefit post-adoption	Proposed
Socio Factors	neighbor-awareness	Household knowledge of solar PV technology influenced by social network	Palmer et al., 2015; Rai & Robinson, 2015
	Social capital	Measure of household connections	(Coleman, 1988)
	Social influence	Agent's dynamic propensity for social influence, updated by network and scenario rules	Palmer et al., 2015 ; Rai & Robinson, 2015
Adoption status	Adopted-solar?	Boolean indicator of solar PV system adoption	(Zhang et al., 2016)

3.5.2.3 Behavioral Parameter Specification

Critical behavioral parameters governing agent decision making and social interactions represent essential, yet often unobservable, elements of the model structure. These parameters encompass the utility function component

weights (w_inc, w_pay, w_soc, w_env), individual adoption thresholds, logistic adoption probability function steepness (k), and parameters defining social influence propagation and awareness diffusion within network structures.

The establishment of behavioral parameter values employs a dual methodological approach.

1) Literature-Based Derivation: Parameter ranges and functional forms are derived from established theoretical frameworks, including the Diffusion of Innovation theory, Behavioral Economics principles, and Social Capital theory, supplemented by empirical findings from the previous agent-based modeling studies reviewed in Chapter 2.
2) Systematic Model Calibration: Behavioral parameters were systematically adjusted within theoretically plausible ranges to ensure model replication of established macro-level patterns and benchmarks, including baseline adoption rates consistent with Rogers' diffusion stages and characteristic S-shaped adoption curves under standard conditions. This calibration process, detailed in Section 3.7, provides essential anchoring for the behavioral dynamics of the model.

3.5.2.4 Parameter Integration and Validation

All model parameters were methodically established through empirical data integration, established literature standards, or scenario-specific assumptions tailored to policy contexts. The parameter specification encompasses both quantitative and qualitative behavioral factors, including decision thresholds, social influence metrics, and household demographic characteristics. This comprehensive parameterization approach ensures an accurate representation

of real-world dynamics and policy contexts relevant to the Bahraini case study. The complete parameter documentation, including units, default values, and descriptions, is provided in Appendix A to ensure the transparency and reproducibility of the simulation experiments..

3.6. Model Implementation Details

This section outlines the specific technical details regarding the implementation and execution of the ABM, as described previously.

3.6.1 Software Used

The ABM developed for this thesis was implemented using the NetLogo multi-agent programmable modeling environment (version 6.4) (Wilensky, 1999). As detailed in Section 3.2.2, NetLogo was chosen for its suitability in modeling complex systems, its capabilities in representing heterogeneous agents and interactions, its integrated tools for simulation experiments (such as BehaviorSpace for parameter sweeps and sensitivity analysis), and its widespread use in academic research (Vuthi et al., 2022; Wilensky & Rand, 2015). Figure 3.3 illustrates the main interface of the developed model, displaying the agent visualization canvas, user-configurable scenario controls, and several real-time output monitors and plots used during model development and exploratory analysis.

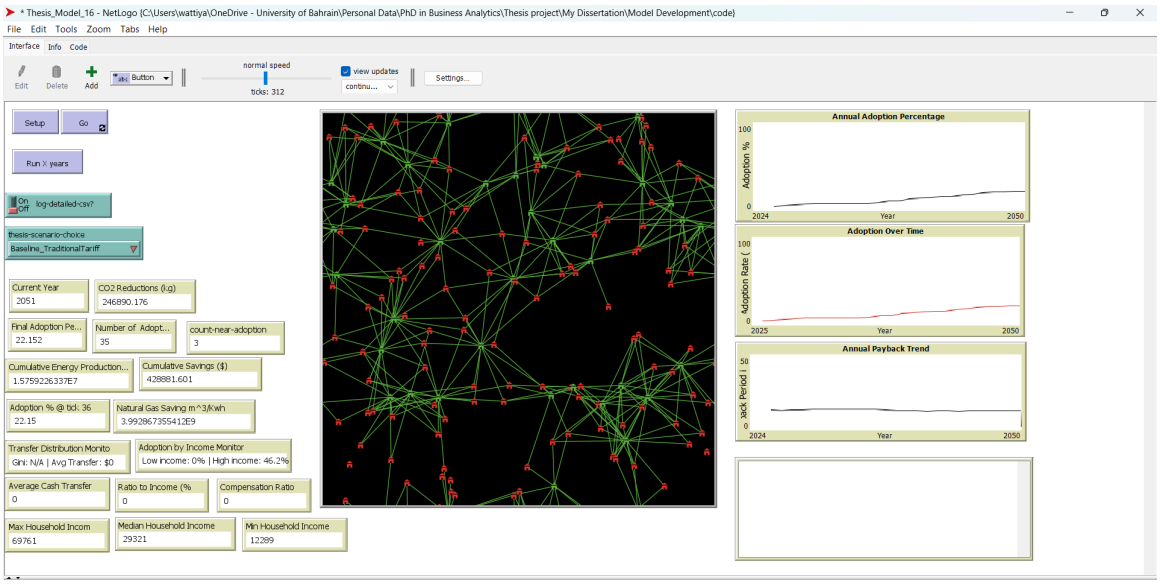


Figure 3.3: NetLogo Interface of the Residential Solar PV Adoption Model, showcasing agent visualization, scenario controls, and real-time output monitors and plots.

3.6.2 Simulation Setup

1) Time Horizon and Steps: The model simulates the period from 2025 to 2050, progressing in annual increments, which serve as the primary decision-making intervals for agents concerning solar PV adoption, social network updates, and, where applicable, the calculation and distribution of CTs, typically commencing in 2026 according to reform scenarios. Internal calculations related to solar PV energy generation, household electricity consumption, billing, and environmental impact accumulation were conducted based on the monthly patterns and aggregated annually within each simulation step.
2) Number of Runs per Scenario: To account for the inherent stochasticity in agent behaviors (e.g., probabilistic adoption decisions) and interactions (e.g., network link changes), each policy scenario described in Section 3.4 was simulated multiple times using different random number generator seeds. Consistent with the approach used in the foundational analyses, 50

simulation runs were conducted for each scenario. This number of repetitions was determined to provide adequate precision for estimating key output metrics (such as mean adoption rates and their variability), allow for statistically valid comparisons between policy outcomes by satisfying the Central Limit Theorem requirements for parametric tests, ensure methodological consistency across scenarios, and align with recommendations for managing moderate stochasticity often observed in socially influenced adoption models (J.-S. Lee et al., 2015; Lorscheid et al., 2012). The results presented in Chapter 4 are typically averages calculated across 50 runs, often accompanied by standard deviations or confidence intervals to indicate variability.

3) Random Seed Management: Unique random seeds were used for each of the 50 runs within a given scenario to explore the range of possible outcomes owing to stochastic events. To ensure a fair comparison between scenarios, the same set of initial random seeds is typically used across all policy scenarios. This practice helps isolate the impact of the policy change itself, reducing the possibility that the observed differences are solely due to different random initializations. NetLogo's built-in capabilities for managing experiments and random seeds through its BehaviorSpace tool were used for this purpose.
4) Data Export, Processing, and Data-Driven Analysis: The ABM, particularly when simulating multiple policy scenarios—eight distinct scenarios in this thesis—each with numerous stochastic replications (50 runs per scenario over a 25-year period), generates a substantial volume of high-dimensional output data. This includes time-series data for each of the 158 household agents across various dynamic attributes (e.g., adoption status, financial calculations, awareness levels) as well as aggregate

system-level metrics (e.g., overall adoption rates, installed capacity, fiscal impacts, environmental benefits) for each individual run. All output data from the ABM simulations, encompassing detailed results from the BehaviorSpace experiments for all scenarios, model calibration runs, and sensitivity analyses, were systematically exported from NetLogo in a structured comma-separated value (CSV) format. Given the considerable scale and complexity of this dataset, a data-driven analysis approach was employed for its processing and interpretation. This involved utilizing the Python programming language (Version 3.13.2), along with its extensive data science and analytics libraries (e.g., Pandas for data wrangling and manipulation, NumPy for numerical computation, Matplotlib and Seaborn for advanced visualization, and SciPy/Statsmodels for statistical testing and analysis). This robust analytical pipeline enabled the efficient handling and aggregation of large datasets, application of sophisticated statistical techniques to discern patterns and significant differences, and generation of customized visualizations to clearly communicate the multifaceted impacts of the simulated policies (as detailed in Section 3.8). This emphasis on rigorous, data-driven analysis of simulation outputs is central to deriving credible and actionable insights for policy design, and aligns with the core principles of Business Analytics.

These implementation details ensure that the simulations are conducted systematically, accounting for stochastic effects, and that the resultant data are processed and analyzed robustly to compare the different policy scenarios designed to influence residential solar PV adoption in Bahrain.

3.7. Model Calibration and Validation

Ensuring the credibility and robustness of an ABM is paramount to generating reliable insights and supporting policy recommendations. Calibration involves tuning model parameters so that the simulation reproduces known real-world patterns or benchmarks, whereas validation involves building confidence that the model is a sufficiently accurate representation of the system under study for the intended purpose (Grimm & Railsback, 2012). This section details the calibration strategy and validation techniques employed for the ABM developed in this study.

3.7.1 Calibration Strategy

In the absence of comprehensive longitudinal data on historical residential solar PV adoption, specifically among Bahraini nationals in the subsidized market, a conventional time-series fitting approach to calibration is deemed impractical. Consequently, a theory-driven calibration strategy was employed, emphasizing the replication of established macro-level diffusion patterns, as delineated by Everett Rogers' (2003) Diffusion of Innovation (DOI) theory, a widely recognized framework for understanding technology adoption dynamics.

1) Target Patterns: The primary objective of the calibration was to align the model's baseline (Traditional Tariff) adoption trajectory under the relevant baseline scenario (typically the baseline simulation) with key milestones of the DOI S-curve. Drawing from Rogers' adopter categories and empirical observations in analogous contexts, the model was calibrated to achieve: an early adoption rate consistent with the "innovator" and potentially the early part of the "early adopter" phase

within the initial years (e.g., targeting approximately 2.5% to 6% adoption by 2027). This served as a critical early benchmark for the diffusion process. Additionally, a longer-term adoption level approximating the onset of the "early majority" phase by the end of the simulation period under baseline (Traditional Tariff) conditions (e.g., around 20-22% adoption by 2050) was targeted.

2) Parameter Tuned: Calibration focused on adjusting key behavioral and social interaction parameters identified through sensitivity analysis as having a significant influence on adoption dynamics. These primarily include the household-specific adoption threshold, the logistic steepness parameter (k) governing adoption probability, parameters defining social utility and influence (k_soc, mid_soc), utility function weights, coefficients related to neighbor awareness propagation, and the impact of observing savings.
3) Tuning Process: The parameter space of the agent-based model was explored using NetLogo's BehaviorSpace tool. The initial parameter ranges were derived from existing ABM literature. Iterative exploration, which can incorporate multi-parameter techniques such as Latin Hypercube Sampling in promising regions, aims to identify parameter combinations that optimally reproduce predefined target patterns.

Extensive parameter sweeps were conducted using BehaviorSpace encompassing 21,870 unique parameter combinations, each subjected to five simulation runs. Table 3.5 details the parameters and their tested values, which were selected from empirically plausible ranges. The model accuracy for each combination was quantified by comparing the

simulated adoption rates against the target values for 2027 and 2050, utilizing the following metrics:

2027_accuracy=|2027adoption−2.5|

2050_accuracy=|2050adoption−22|

Combined accuracy=2027_accuracy+2050_accuracy

Table 3.5: Model Parameters Explored in BehaviorSpace

Parameter Symbol/Name	**Description**	**Explored Values in Sweep**
adoption_threshold	Adoption propensity threshold	0.65, 0.68, 0.70, 0.72
adoption-logistic-k (logistic-k)	Adoption logistic curve steepness	5.5, 6.0, 6.5
neighbor-adoption-awareness-coeff	Neighbor adoption awareness coefficient	0.01, 0.15
mid_soc	Social influence function midpoint	0.34, 0.35, 0.37
u_soc (calibrated as k_soc)	Social utility/influence scaling parameter	10, 12, 14
w_pay	Utility weight: payback/financial	0.40, 0.42, 0.45
w_soc	Utility weight: social influence	0.1, 0.107, 0.15
savings-awareness-factor	Savings awareness factor	1.0 × 10-4, 2.0 × 10-4, 3.0 × 10-4

1) Calibration Outcome: This iterative process yielded a final set of calibrated parameters (adoption threshold = 0.68, logistic-k = 6.5, k_soc = 12, mid_soc = 0.35, neighbor-awareness coefficient = 0.01,

utility weights w_inc=0.15, w_pay=0.45, w_soc=0.15, w_env=0.25). Under the relevant baseline (Traditional Tariff) scenario, the calibrated model successfully reproduces the target diffusion milestones. For instance, simulations yielded mean adoption rates statistically consistent with the target innovator/early adopter share by 2027 (achieving rates of 2.53% ± 0.20% or 4.43% ± 0.38% across stochastic replicates, fitting within the targeted 2.5-6% band) and approximated the early majority onset target by 2050 (22.9% ± 1.46%). The coefficients of variation remained low, indicating convergence.

3.7.2 Validation Techniques

The model's credibility and reliability were established through a comprehensive validation framework encompassing multiple methodological approaches, consistent with the established ABM standards (Grimm and Railsback, 2012; Thiele et al., 2014). This multifaceted validation strategy integrates empirical benchmarking, expert evaluation, technical verification, theoretical alignment, and robustness assessment to ensure model fidelity and analytical integrity.

3.7.2.1 Input Data Validation and Sample Representativeness

The empirical foundation of the ABM rests on a dataset of 158 owner-occupied households. This data, sourced from industry collaborators in Bahrain, provided detailed electricity consumption profiles and dwelling characteristics. To address potential sampling bias and ensure the model's generalizability, the representativeness of this sample was rigorously assessed. The income distribution assigned to the 158 agents was calibrated and validated against national benchmarks from Bahrain's Social Insurance

Organization (SIO, 2024). This process confirmed that the model's agent population reflects the national distribution across socioeconomic strata, lending credibility to the simulation's economic and equity-related outcomes.

3.7.2.2 Empirical Benchmarking and External Validation

The baseline adoption performance under traditional tariff conditions without policy interventions is systematically compared with the available empirical data. The simulated adoption rate of 23.73% was benchmarked against Alsabbagh's (2019) survey findings, indicating that 33.3% stated a willingness to install solar PV systems without subsidies. The observed differential between simulated and survey-based adoption rates aligns with the documented overestimation bias inherent in stated-preference methodologies, thereby supporting the model's external plausibility and realistic representation of intention-action gaps in technology adoption decisions.

3.7.2.3 Expert Assessment and Domain Validation

The model architecture, decision-rule formulations, and output magnitudes were rigorously evaluated by domain specialists including Bahraini energy policy analysts, solar PV industry practitioners, and agent-based modeling methodological experts. Through structured consultation processes, expert consensus confirmed that the model accurately represents the local market dynamics, regulatory environments, and household decision-making processes characteristic of the Bahraini context.

3.7.2.4 Technical Verification and Implementation Validation

Comprehensive code verification procedures were implemented to ensure accurate translation of the conceptual design into computational implementation. Unit testing protocols were applied to individual NetLogo

procedures, boundary condition verification was conducted for critical financial variables, including payback period constraints, and systematic stepwise debugging was performed on multi-attribute utility calculations and network formation algorithms. This technical validation process confirmed that the computational implementation accurately reflected the conceptual model specifications.

3.7.2.5 Theoretical Alignment and Conceptual Validation

The model's structural foundations and agent behavioral representations were systematically cross-referenced with established theoretical frameworks, including Rogers' diffusion of innovation theory, behavioral economics principles, and social capital theoretical constructs. This conceptual validation process confirmed theoretical consistency and ensured that model assumptions and behavioral rules align with the established academic understanding of technology adoption processes.

3.7.2.6 Pattern Validation and Robustness Assessment

Model robustness was evaluated through extensive sensitivity analysis and pattern validation across all eight policy scenarios examined. The characteristic S-shaped adoption trajectory was consistently reproduced across parameter variations, and scenario performance rankings remained invariant under comprehensive parameter perturbations, as detailed in Section 4.4.4 and Appendix B (Figures B.1–B.9). These validation outcomes demonstrate that the model's core analytical insights represent robust emergent properties rather than artifacts of specific parametric assumptions, thereby establishing confidence in its predictive capacity and policy-relevant conclusions.

3.8. Data Analysis Methods

Following the execution of the ABM simulations for each policy scenario detailed in Section 3.4, spanning the period from 2025 to 2050 and conducted over multiple iterations, as specified in Section 3.6, a systematic methodology was employed to analyze the resulting data. The primary objective of this analysis was to quantify the effects of various policy interventions, compare scenario outcomes, assess distributional impacts, evaluate fiscal and environmental consequences, and investigate the underlying dynamics, thereby addressing the central research questions of this thesis. This section delineates the data collected from the ABM outputs and the processes by which they are analyzed and reported in accordance with the "Observation" component of the ODD protocol (Grimm et al., 2006, 2010). The analysis involved the collection of specific output metrics, application of appropriate statistical techniques, and utilization of various visualization methods.

3.8.1 Output Metrics Collected

A comprehensive array of output metrics was documented at each time step or aggregated annually across multiple simulation runs for each scenario. These metrics were selected to capture the key dimensions of the system's behavior, household-level impacts, and policy effectiveness.

1) Adoption and Diffusion Metrics
    a) Cumulative Adoption Rate (%): The percentage of 158 household agents that adopted solar PV systems by a given year in the simulation.

b) Total Installed solar PV Capacity (kWp): The sum of the capacities of all solar PV systems installed by household agents in a given year.

2) Household Economic Metrics
    a) Payback Period (PBP, years): Calculated for each adopting household, often considering discounted cash flows, with distributions (mean, median, and interquartile range [IQR]) reported across adopters per scenario.
    b) Rate of Return (RoR, %): Calculated for adopted solar PV systems to indicate the profitability of the household investment.
    c) Annual Household Savings: The net initial capital outlay faced by adopters after considering the impact of any direct financial incentives such as VAT reduction or the structure of innovative loan schemes.
3) Distributional Equity Metrics (primarily for subsidy reforms and CT scenarios)
    a) Adoption Rate by Income Group (%): Solar PV adoption rates disaggregated by household income quintiles or other relevant socioeconomic groupings to assess the equity of adoption patterns.
    b) Gini Coefficient: Calculated on the distribution of cash transfer amounts across recipient households (for CT scenarios S_1, S_2, S_3) to measure the inequality of the transfer distribution.
    c) Compensation-to-Subsidy Ratio (CR): The ratio of the cash transfer amount received by a household to its estimated electricity subsidy loss under reform scenarios, indicating the adequacy of the compensation.

d) Transfer-to-Income Ratio (T2I): The Ratio of the cash transfer amount received to a household's annual income, indicating the relative financial significance of the transfer to that household.

4) Fiscal Metrics:
    a) Annual/Cumulative Subsidy Savings: The total cost to the government for financial incentives (e.g., foregone VAT) or cash transfers disbursed (in CT scenarios).
    b) Annual/Cumulative Net Fiscal Balance ($): The difference between subsidy savings and cost of incentives/transfers, indicating the overall fiscal impact on the government.
5) Environmental Metrics:
    a) Cumulative CO_2 Emissions Avoided (tons): Calculated based on the amount of grid electricity displaced by solar PV generation using appropriate emission factors for Bahrain's power sector.
    b) Cumulative Natural Gas Savings (SCF): Calculated based on the estimated reduction in natural gas consumption for electricity generation owing to solar PV adoption.
6) Social Metrics (exploratory)
    a) Correlation coefficients between modeled social factors (e.g., individual social capital scores, measures of social influence from network neighbors, average neighbor awareness levels) and solar PV adoption status or timing.
    b) Correlation between household environmental awareness scores and adoption status and timing.

3.8.2 Statistical Analysis

Statistical methods were employed to summarize the simulation outputs, quantify uncertainty, and test for significant differences between the policy scenarios.

1) Descriptive Statistics: For all key output metrics, standard descriptive statistics—including means, medians, standard deviations (SD), interquartile ranges (IQR), minimums, and maximums—were calculated across the 50 simulation runs for each scenario. These were typically reported for specific time points (e.g., the final year, 2050) or as averages over the relevant periods. This provides measures of the central tendency of outcomes and quantifies the variability or uncertainty arising from the stochastic elements of the model. Confidence intervals (CIs) were computed to estimate the precision of the mean outcomes.
2) Correlation Analysis: To explore the strength and direction of linear relationships between different variables within the simulation output, Pearson correlation coefficients (or Spearman rank correlation for non-normally distributed data) were calculated. For example, it was used to assess the association between modeled social factors (such as social influence or awareness) or psychological factors (environmental awareness) and the likelihood or timing of solar PV adoption under various policy conditions.

3.9. Sensitivity Analysis Methodology

To assess the robustness of the model's findings and understand the influence of key uncertain parameters, a systematic sensitivity analysis (SA) was

conducted. This approach aligns with best practices in ABM, which recommends examining how model outcomes vary in response to changes in input parameters and assumptions (Grimm and Railsback, 2012; Thiele et al., 2014). SA primarily employs a one-factor-at-a-time (OFAT) methodology. This technique involves systematically varying one parameter across a plausible range while maintaining all other parameters at their calibrated baseline (Traditional Tariff) values and observing their effects on key output metrics. The OFAT approach is frequently utilized because of its simplicity in implementation and ease of interpreting results, facilitating the identification of parameters to which the model is most sensitive (Broeke et al., 2016; Ligmann-Zielinska et al., 2020).

1) Parameter Varied: Based on the initial model exploration, literature review, and calibration process (Section 3.7), key parameters deemed to have significant uncertainty or potential influence on adoption dynamics were selected for SA. These included:
    a) Behavioral Parameters: Adoption Threshold, Adoption-Logistic-K (logistic steepness parameter k).
    b) Economic parameters: Annual decrement (solar PV cost decline rate).
    c) Social Influence Parameters: *w_soc* (weight of social utility), *mid_soc* (midpoint of social utility function), *k_soc* (steepness of social utility function), neighbor-adoption-awareness-coeff.
    d) Preference Weights: *w_pay* (weight for payback in utility) and *w_env_calculated* (weight for environmental motivation).
2) Variation Ranges: Each parameter was perturbed to a set of discrete values bracketing its baseline (Traditional Tariff), generally spanning

±20%. All other inputs were held constant at their calibrated default values.

3) Output Metrics Tracked: The impact of the parameter variations was assessed using these output metrics.
    a) Mean and 95% CI: We computed the sample mean and half-width of the 95% confidence interval for the adoption rate for each parameter setting.
    b) Sensitivity "Swing": For each parameter, the difference between the maximum and minimum mean adoption rates across all scenarios was calculated.
    c) Visualization: Appendix B (Figures B.1–B.9) presents error-bar plots of mean adoption versus parameter value, with dashed vertical lines indicating the baseline (Traditional Tariff) settings.
4) Execution: For each parameter variation within each relevant policy scenario (S_0, S_1, S_2, S_3), the model was simulated multiple times (typically 5) using unique random seeds to account for stochasticity. The mean values of the output metrics across these runs were then used for sensitivity assessment.

The primary objective of this SA was to ascertain whether the fundamental conclusions drawn from the main simulation results, particularly regarding the relative effectiveness and ranking of different policy scenarios, remained consistent despite the reasonable variations in these influential parameters. The findings of the sensitivity analysis contribute to understanding the model's structural assumptions and the confidence that can be placed in its policy insights. Detailed results of the sensitivity analysis are presented and discussed in Chapter 4 (Section 4.4.4).

Having detailed the development, empirical grounding, calibration, and validation of the Agent-Based Model, the subsequent chapter presents and analyzes the empirical findings generated from simulating various policy scenarios. Chapter 4 demonstrates the model's application in exploring the research questions related to solar PV adoption, household impacts, and fiscal implications.

Chapter 4: Results and Discussion

This chapter presents and analyzes the empirical findings from the Agent-Based Model (ABM) simulations of residential solar PV adoption in Bahrain's subsidized electricity market, which is detailed in Chapter 3. The analysis examines two distinct policy paradigms: financial incentives within the existing subsidy framework, and comprehensive electricity subsidy reform coupled with compensatory cash transfers.

These findings emerge from extensive model simulations (2025-2050) that capture the complex interplay between household decisions, policy interventions, and system-level outcomes. Through a systematic evaluation of multiple scenarios, the analysis reveals crucial insights into adoption patterns, distributional equity, and fiscal implications across different policy approaches.

This chapter is divided into three major analytical sections. Section 4.2 examines the effectiveness of traditional financial incentives, including VAT reduction and innovative loan schemes, in the current subsidized electricity market. Section 4.3 analyzes more fundamental reform scenarios, evaluating how subsidy removal, coupled with different cash transfer mechanisms, affects adoption patterns and household welfare. Section 4.4 synthesizes these findings to draw broader conclusions regarding policy effectiveness and implementation strategies.

Throughout the analysis, particular attention is paid to key performance metrics: Solar PV adoption rates across income quintiles, household financial impacts, distributional equity outcomes, and fiscal implications for the government. This multifaceted evaluation enables a comprehensive

assessment of how different policy approaches balance the competing objectives of accelerating solar PV adoption, ensuring social equity and maintaining fiscal sustainability.

The findings presented herein provide empirically grounded insights for policymakers seeking to optimize residential solar PV adoption while ensuring equitable outcomes in subsidized energy markets. These results form the foundation of specific policy recommendations, as detailed in the subsequent section.

4.1. Overview of Simulation Outcomes

The simulation outcomes presented herein were derived from the ABM detailed in Chapter 3, encompassing a 25-year period from 2025 to 2050. To ensure robustness and to account for the inherent stochasticity in agent interactions and decision-making processes, each policy scenario underwent 50 simulation runs with varying random seeds. This number of repetitions was chosen because it provides adequate precision for estimating key output metrics, allows for statistically valid comparisons between policy outcomes by satisfying the Central Limit Theorem requirements, ensures methodological consistency, and aligns with common practices in similar socially influenced adoption models**.** These findings typically reflect the average outcomes from these iterations, often supplemented by measures of variability, to provide a comprehensive understanding of the potential range of impacts. This methodological rigor is essential for generating reliable policy insights from complex adaptive systems simulations.

The core analysis was bifurcated into two primary sets of policy investigations, each benchmarked against a relevant baseline and featuring

specific intervention scenarios. The selection of these scenarios was based on the literature review in Chapter 2, which highlighted common financial barriers to solar PV adoption and key considerations for equitable and effective energy policy reform.

First, Financial Incentive Scenarios (within the current subsidized electricity market) evaluate policies designed to enhance the financial attractiveness of residential solar PV adoption, without altering Bahrain's existing electricity subsidy structure. This approach addresses barriers such as high upfront costs and access to finance, which are frequently cited as critical impediments to solar PV adoption (Fauzi et al., 2023; Wang et al., 2023). The established reference point is the baseline (Traditional Tariff), which assumes a continuation of the current subsidized electricity traditional tariffs and no additional PV-specific incentives beyond the existing net metering framework. The interventions explored included the following:

1) A VAT Reduction Scenario is aimed at lowering the initial investment cost of the solar PV systems.

2) An Innovative Loan Scenario is designed to provide accessible and affordable financing options to minimize immediate financial burdens on households.

3) A Combined Scenario that integrates both the VAT reduction and innovative loan mechanism is used to assess potential synergistic effects.

Second, the Subsidy Reform and Cash Transfer (CT) scenarios investigate the multifaceted impacts of eliminating existing electricity subsidies for Bahraini nationals and implementing various compensatory CT mechanisms. This set

of scenarios addresses the fundamental issue of price distortions in subsidized energy markets (Alabbasi, 2021) and explores mechanisms to mitigate adverse welfare effects on households, a crucial aspect of successful policy reform (Granado et al., 2012). The reference for this investigation is the Subsidy Removal Baseline (S_0) with a new tariff, which represents a scenario in which subsidies are removed without any form of financial compensation to consumers. The CT intervention scenarios designed to reflect different approaches to equity and administrative feasibility are as follows:

1) A Universal Cash Transfer Scenario (S_1), providing a uniform payment to all eligible households.
2) An Income-Targeted Cash Transfer Scenario (S_2) directs financial support primarily to low-income households.
3) A Tiered Household-Size Cash Transfer Scenario (S_3), a novel approach that calibrates compensation based on household size and the estimated impact of subsidy removal.

The subsequent sections systematically present and discuss the quantitative outcomes for each scenario across a range of performance metrics. This detailed analysis will be followed by a comparative discussion and synthesis of the findings, directly addressing the research questions outlined earlier. It is important to note that all figures and tables illustrating the results in this chapter are direct outputs of these ABM simulations.

4.2. Impact of Financial Incentives (within Subsidized Market)

This section presents and discusses the simulation results for the first set of policy investigations, focusing on the impact of specific financial incentives designed to promote residential solar PV adoption within Bahrain's subsidized electricity market. The scenarios analyzed include the baseline (Traditional Tariff), VAT Reduction scenario, Innovative Loan scenario, and combined (VAT + Loan) scenario, as detailed in Section 3.4.2.

4.2.1 Adoption Rates and Diffusion Dynamics under Financial Incentive Scenarios

The ABM simulations revealed marked differences in the projected trajectories of solar PV adoption across the four financial incentive policy scenarios from 2025 to 2050, as illustrated in Figure 4.1.

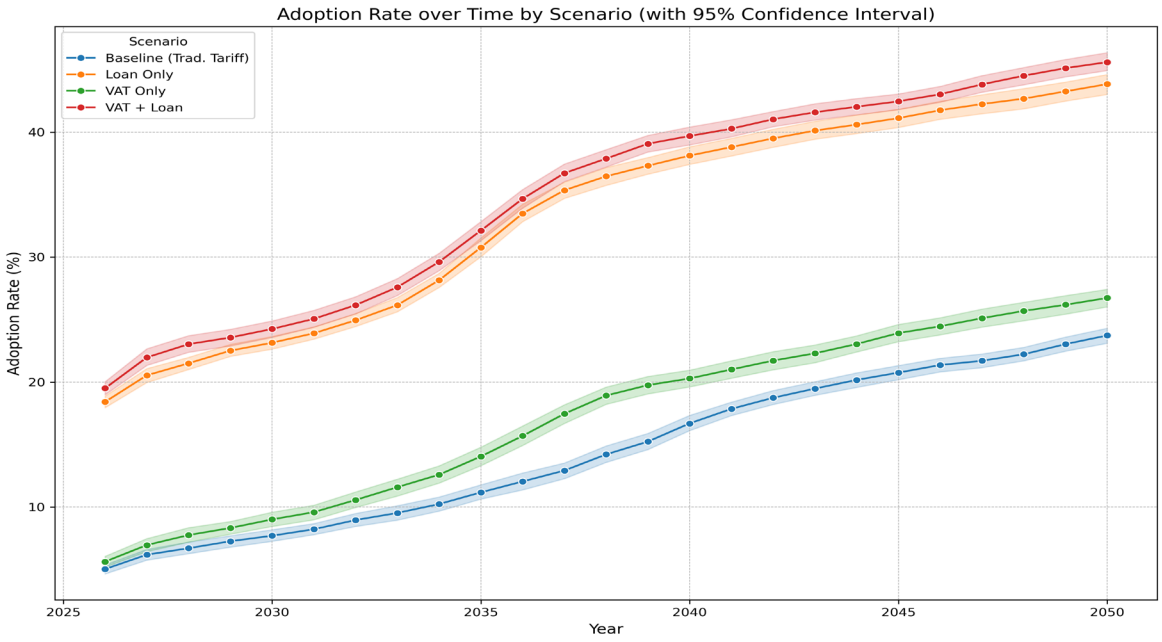


Figure 4.1: Adoption rate over time by scenario, showing mean and 95% confidence interval across runs.

Under the Baseline (Traditional Tariff) scenario, which includes no additional financial incentives beyond existing net metering, the model forecasts a modest rate of adoption. The simulation projects an initial slow uptake by "innovators," achieving approximately 2.53-6% adoption by 2027, consistent with the early stages of Rogers' (2003) diffusion of innovation theory. By 2050, this scenario is projected to result in an estimated 23.73% of households adopting solar PV systems (see Table 4.1). This relatively slow trajectory underscores the challenges identified in the Bahraini context, where highly subsidized electricity tariffs and high capital costs diminish the inherent financial appeal and relative advantage of solar PV systems (Rogers, 2003). As demonstrated by EzzEldin et al. (2022), the subsidized tariff of 3 fils results in an extended payback period of 83.5 years, compared to just 9.6 years with the actual cost-reflective tariff. This significant disparity in payback periods illustrates how artificially low electricity prices fundamentally alter the economic attractiveness of solar PV investments in Bahrain (Alabbasi, 2021; Alnaser, 2015).

Table 4.1: Summary Metrics for 2050 (Mean ± SD across 50 runs)

Scenario	Adoption Rate %	Total Max Adopter Capacity kWp
Baseline (Trad. Tariff)	23.73 (±2.26)	1,306.50
Loan Only	43.85 (±2.79)	1,692.50
VAT Only	26.73 (±2.60)	1,497.00
VAT + Loan	45.61 (±2.65)	1,778.00

The introduction of an Innovative Loan structured such that repayments are intended to be less than or equal to pre-solar PV electricity bills is projected to significantly increase the mean adoption rate to approximately 43.85% by 2050 (Table 4.1). This substantial increase suggests that alleviating financing

constraints and reducing perceived financial risk, concepts central to behavioral economics (Kahneman & Tversky, 1979), can unlock considerable latent demand for solar PV systems. This aligns with the literature that emphasizes financial incentives, such as loans, as crucial for promoting adoption (Juliusson, 2024; Tetteh, 2021). Similarly, the VAT Reduction scenario, which lowers the upfront cost of solar PV systems, results in a mean adoption rate of approximately 26.73% by 2050 (Table 4.1). While this policy enhances the initial affordability, it directly addresses the critical concern noted by Alnaser (2015) and EzzEldin et al. (2022), its impact on overall adoption appears less pronounced in this model than the loan scenario, although it still offers a notable improvement over the Baseline (Traditional Tariff). This is consistent with the finding that high upfront costs are a major barrier (Fauzi et al., 2023; Wang et al., 2023).

The most pronounced impact is observed under the Combined Scenario, where both innovative loans and VAT reductions are implemented simultaneously. This integrated strategy results in the highest mean adoption rate, with approximately 45.61% of households adopting solar PV systems by 2050 (see Table 4.1). This finding indicates a strong complementary effect, wherein addressing multiple financial barriers concurrently—upfront costs and financing affordability—leads to greater adoption than addressing them individually. This supports the notion that multifaceted approaches to overcoming barriers to adoption are more effective (Ahmed et al., 2022).

Across all scenarios, the diffusion curves in Figure 4.1 exhibit the characteristic S-shape, consistent with Rogers' (2003) theory. This pattern, characterized by an initial slow uptake by innovators and early adopters, followed by accelerated growth as the technology becomes more mainstream

and peer effects take hold (Sigrin et al., 2015), reflects the technology's increasing economic viability and growing influence of social awareness. Financial incentive scenarios effectively act as catalysts, accelerating movement along this S-curve by enhancing the perceived relative advantage of PV.

4.2.2 Financial Viability for Households under Incentive Scenarios

The financial attractiveness of investing in residential solar PV systems varies significantly across the simulated incentive scenarios, providing crucial insights into the observed adoption patterns. Key metrics, including the effective upfront cost for adopters, mean payback period (PBP), and mean rate of return (RoR), are summarized in Table 4.2.

Table 4.2: Average Financial Metrics for Adopted Systems by Financial Incentive Scenario

Scenario	Effective Cost ($)	Payback Period (PBP) (years)	Rate of Return (RoR) (%)
Baseline (Trad. Tariff)	8,818.20	12.99	8.01
Loan Only	3,190.27	6.15	237.35
VAT Only	8,489.54	12.79	8.32
VAT + Loan	3,010.55	6.21	253.21

These findings underscore the critical importance of financial mechanisms in promoting solar PV markets, particularly in regions such as Bahrain, where subsidized energy prices diminish the inherent relative advantage of solar PV

adoption (Rogers, 2003; Tongsopit et al., 2016). The baseline average payback period of approximately 12.99 years aligns with the research by Alnaser (2015), who showed that Bahraini residential electricity tariffs are heavily subsidized at $0.008/kWh for consumption under 3000 kWh, compared to the actual cost of $0.074/kWh. This significant price distortion, combined with extended payback periods of up to 83.5 years under subsidized tariffs (EzzEldin et al., 2022), creates fundamental economic barriers to solar PV adoption in Bahrain. As demonstrated in the Bahraini context, these artificially low electricity prices actively discourage investment in cleaner energy alternatives, making conventional energy sources appear deceptively more economically attractive (Alabbasi, 2021; Solaymani, 2021).

In contrast, the "VAT Only" scenario, while improving adoption over the baseline, exhibits a less pronounced shift in PBP (12.79 years) and RoR (8.32%) than the loan scenarios. This suggests that while reducing the initial capital cost is advantageous, addressing the ongoing affordability and cash flow implications through mechanisms such as innovative loans has a more profound impact on the perceived financial viability of the average adopter in this model. This aligns with the research by Haji et al. (2017), who emphasized the need for supportive financial structures in Bahrain's solar PV market, and is further supported by findings from Alnaser et al. (2023), showing that ongoing operational considerations, including maintenance costs and system performance, significantly influence adoption decisions. The extended payback periods under current market conditions particularly affect adoption rates, as demonstrated by EzzEldin et al. (2022), who found that subsidized tariffs result in payback periods over eight times longer than the cost-reflective rates.

The notable reductions in payback periods observed under the "Loan Only" (6.15 years) and "VAT + Loan" (6.21 years) scenarios are particularly significant, positioning solar PV investments within a range often deemed acceptable by households. This directly addresses the financial risk perceptions and temporal discounting effects highlighted in Behavioral Economics (Al-Sharafi et al., 2023; Vasseur & Kemp, 2015). When investments can be recouped more swiftly, their perceived risk diminishes and the upfront cost becomes less of a psychological barrier. This aligns with the findings of Wang et al. (2023), who identified the payback period as a critical economic factor.

The exceptionally high rates of return under these loan-inclusive scenarios highlight a compelling private financial case that can be constructed for solar PV when appropriate support mechanisms are implemented. These mechanisms effectively enhance perceived benefits and mitigate perceived losses (Kahneman & Tversky, 1979), thereby altering the decision frame for potential adopters.

Furthermore, achieving higher adoption volumes, as demonstrated in the incentive scenarios, could catalyze learning-by-doing cost reductions in the local solar PV market over time. This effect, quantified for other regions (van Benthem et al., 2008), would further enhance financial viability and the technology's relative advantage in the long term.

4.2.3 Installed Capacity Growth under Incentive Scenarios

The various financial incentive scenarios not only influence the rate at which households adopt solar PV systems, but also affect the total cumulative installed solar PV capacity and the characteristics of the systems selected by

adopters. As evidenced in Table 4.1 (see above), financial incentives are crucial in expediting adoption and enhancing total installed capacity. The cumulative installed capacities experience a significant increase with financial support, reaching 1778.00 kWp under the "VAT + Loan" (Combined) scenario, a 36% increase over the Baseline's 1306.50 kWp. This indicates that policies aimed at reducing financial barriers can facilitate substantial growth in the residential solar PV sector, aligning with the research by Haji et al. (2017), who emphasized the importance of supportive financial mechanisms for solar PV deployment in Bahrain. The significance of addressing financial barriers is further reinforced by EzzEldin et al. (2022), who demonstrate that the current market conditions in Bahrain result in prohibitively long payback periods that discourage investment. This is particularly relevant, given that Alnaser (2015) found substantial disparities between subsidized and actual electricity costs in Bahrain, which significantly impacts the economic feasibility of solar PV installations.

Figure 4.2 illustrates that financial incentives also affect the solar PV system capacities selected by adopters. Under the Baseline (Traditional Tariff), system capacities are concentrated at lower to moderate values (peaking around 10-15 kWp), reflecting affordability constraints. The "VAT Only" scenario shows a slight increase in mid-range capacities, while the "Loan Only" scenario shifts the distribution towards larger capacities (10-20 kWp). The "Combined (VAT + Loan)" scenario demonstrates the most significant impact, with adopters opting for larger systems (peaking around 15-20 kWp). This synergy, resulting from addressing multiple financial barriers, enhances adoption and promotes investment in more substantial solar PV installations. Such policy-induced shifts towards larger systems improve relative advantage

and reduce complexity in optimizing the system size (Rogers, 2003). When financially feasible, larger systems enable households to maximize their self-generation, resulting in greater savings.

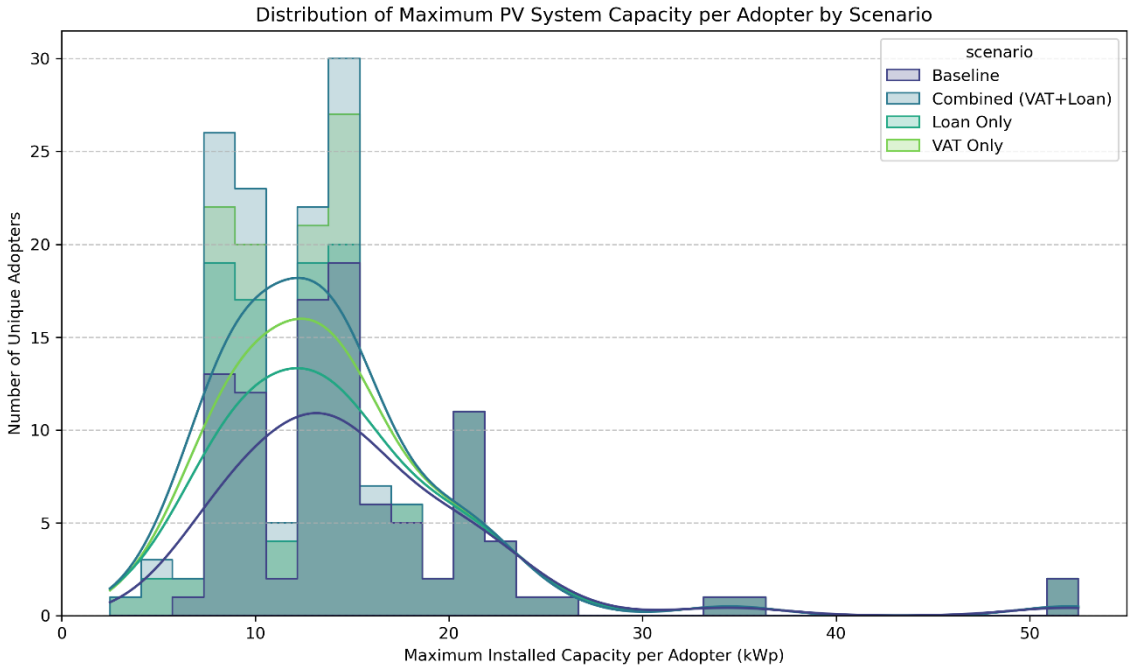


Figure 4.2: Distribution of maximum solar PV system capacities per adopter by traditional policy scenario.

The S-shaped diffusion curve for overall market penetration aligns with the diffusion of innovation theory (Rogers, 2003) and empirical solar PV adoption research (Bollinger & Gillingham, 2012; Rai & Robinson, 2015; Sigrin et al., 2015). Financial incentives act as catalysts, accelerating the progression along the S-curve and promoting deeper market penetration by encouraging larger individual system capacities.

4.2.4 Role of Social Capital and Network Effects and Environmental Awareness under Incentive Scenarios

ABM incorporates explicit mechanisms to examine how non-economic factors moderate the effects of financial incentives on solar PV adoption. This

analysis examined social interactions and environmental awareness as complementary drivers within the broader technology diffusion framework established in Chapter 2.

4.2.4.1 Social Factor Correlations Across Incentive Scenarios

Table 4.3 presents the correlation coefficients between key social variables (social capital, social influence, and neighbor awareness) and solar PV adoption status by 2050 across financial incentive scenarios. In the baseline scenario, social factors demonstrated minimal influence, with social capital showing a weak correlation ($r = 0.020$), negligible social influence ($r = 0.000$), and modest neighbor awareness effects ($r = 0.120$). This limited social impact reflects the economically unfavorable environment created by Bahrain's subsidized electricity tariffs, where even strong social networks cannot overcome fundamental economic barriers (Alabbasi, 2021; SEU, 2017).

However, the introduction of financial incentives substantially alters the effectiveness of the social factors. The VAT Reduction scenario exhibits the strongest social correlations (social capital: $r = 0.130$; social influence: $r = 0.140$; neighbor awareness: $r = 0.110$), while the Innovative Loan scenario shows moderate correlations across all social variables ($r = 0.070$-0.090). Interestingly, the Combined scenario maintains consistent moderate correlations ($r = 0.090$-0.100), suggesting that straightforward incentives, such as VAT reduction, may facilitate social discourse more effectively than complex financial instruments. These patterns align with established research demonstrating that peer effects and social interactions become significant facilitators once economic attractiveness is enhanced (Bollinger & Gillingham, 2012; Rai & Robinson, 2015).

Table 4.3: Correlation of Social Factors with Solar PV Adoption Status (2050) by Financial Incentive Scenario

Scenario	Social capital	Social influence	Avg neighbor awareness
Baseline (Trad. Tariff)	0.020	0.000	0.120
Loan Only	0.080	0.090	0.070
VAT Only	0.130	0.140	0.110
VAT and Loan	0.090	0.100	0.090

4.2.4.2 Environmental Awareness Paradox

Contrary to conventional expectations, environmental awareness exhibited statistically significant negative correlations with overall adoption across all scenarios (see Table 4.4). In the Baseline scenario, this correlation reaches $r = -0.086$ ($p = 0.043$), while the incentive scenarios maintain similar negative relationships ($r = -0.075$ to -0.100, all $p < 0.05$). This counterintuitive finding suggests that, as financial incentives enable broader market participation, environmental awareness becomes less critical as a distinguishing adoption driver for the majority of households.

Nevertheless, early adopters consistently demonstrate higher environmental awareness levels than late adopters across all scenarios, supporting Rogers' (2003) characterization of innovators as value-driven rather than purely economically motivated. For instance, in the Loan scenario, early adopters averaged 0.997 awareness, compared to 0.991 for late adopters. This pattern indicates that, while environmental concern may characterize initial market

entrants, economic utility assumes primacy for mass market adoption once financial barriers are addressed.

Table 4.4: Environmental Awareness Impact Analysis Results

Scenario	Correlation	P value	Early Adopter Awareness	Late Adopter Awareness
Baseline (Trad. Tariff)	-0.086	0.043	0.992	0.987
VAT Only	-0.099	0.000	0.989	0.977
Loan Only	-0.100	0.018	0.997	0.991
Combined	-0.075	0.005	0.979	0.962

4.2.4.3 Policy Implications and Theoretical Integration

The analysis revealed that social capital effects and solar PV system observability facilitate diffusion most effectively when financial incentives establish economic viability. In contexts with substantial market distortions, such as Bahrain's subsidized electricity environment, economic incentives appear essential for initiating adoption momentum before social effects can significantly amplify the diffusion processes. Furthermore, the persistent negative correlation between environmental awareness and mass adoption suggests that, while concern may distinguish early adopters, economic rationality drives broader market penetration once solar PV becomes financially accessible.

These findings contribute to understanding the attitude-behavior gap in renewable energy adoption, indicating that financial incentives primarily bridge this gap through economic appeal rather than reinforcing environmental attitudes. Consequently, policies leveraging social networks or

environmental messaging prove most effective when implemented alongside robust financial support, which clearly addresses the economic proposition of solar PV systems within Bahrain's unique market context.

4.2.5 Environmental Impact under Incentive Scenarios

The modeled financial incentives accelerate residential solar PV adoption, which in turn generates tangible environmental benefits. For Bahrain's energy sector, which is heavily reliant on natural gas, these co-benefits include the displacement of fossil fuel consumption and the mitigation of associated CO_2 emissions. Table 4.5 quantifies these cumulative environmental outcomes for each incentive scenario over the 2025-2050 simulation period.

Table 4.5: Cumulative Environmental Impact Metrics (2025-2050) by Financial Incentive Scenario

Scenario	**CO2 Avoided (tons)**	**Natural Gas Savings (SCF) million**
Baseline (Trad. Tariff)	6,941	112,252,635
Loan Only	14,180	229,323,503
VAT Only	8,327	134,675,719
VAT + Loan	15,269	246,933,224

Under the Baseline (Traditional Tariff) scenario, characterized by limited solar PV adoption (as discussed in Section 4.2.1), the model projects approximately 6,941 tons of CO_2 emissions avoided and about 112.25 million standard cubic feet (SCF) of natural gas conserved over the simulation period. The introduction of financial incentives significantly enhances the environmental outcomes. The Innovative Loan scenario is projected to result in the avoidance

of approximately 14,180 tons of CO_2 and the conservation of 229.32 million SCF of natural gas. The VAT Reduction scenario achieves more modest, though still improved, environmental savings, with approximately 8,327 tons of CO_2 avoided and 134.68 million SCF of natural gas conserved. The Combined Policy (VAT + Loan) scenario, which yielded the highest solar PV adoption rate, correspondingly delivered the most substantial environmental benefits: approximately 15,269 tons of CO_2 avoided and over 246.93 million SCF of natural gas conserved by 2050.

The results presented in Table 4.5 clearly demonstrate a direct and positive correlation: policies that effectively mitigate financial barriers to solar PV adoption, thereby enhancing economic viability for households and accelerating uptake, concurrently and significantly amplifying the associated environmental co-benefits. Specifically, the "VAT + Loan" (Combined) scenario led to more than a doubling of both CO_2 avoidance (a 120% increase) and natural gas savings (a 120% increase) compared with the baseline (Traditional Tariff) scenario. This stark contrast underscores the considerable environmental leverage that effective, multifaceted incentive programs can exert in transitioning towards cleaner energy.

It is also noteworthy that the "Loan Only" scenario results in greater environmental benefits than the "VAT Only" scenario. This directly mirrors the adoption rates discussed in Section 4.2.1, where the loan scheme was found to be more effective in driving solar PV penetration than the VAT reduction alone. This suggests that financial incentives that improve long-term financial cash flow and reduce effective upfront burdens through accessible financing are more potent not only in stimulating adoption volumes but also, as a direct consequence, in delivering greater emission reductions and

resource conservation. These findings are consistent with the literature reviewed in Chapter 2, which emphasizes the potential of renewable energy sources in Bahrain to contribute significantly to national environmental goals and reduce dependence on fossil fuels, despite the challenges posed by existing energy subsidy structures (Alabbasi et al., 2022; Al-Sarihi & Mansouri, 2022). Furthermore, the results reinforce the argument that proactive and well-designed policy interventions are necessary to unlock and maximize the environmental gains achievable from residential solar PV deployment, especially in markets such as Bahrain, where the underlying economics are distorted by subsidies (Alsabbagh, 2019; Boudekhdekh, 2022). The scale of improvement demonstrated by the incentive scenarios over the baseline effectively quantified the environmental opportunity cost associated with policy inaction or the implementation of suboptimal policy designs.

4.2.6 Fiscal Implications of Financial Incentives

While financial incentives are implemented with the primary goal of promoting the adoption of residential solar PV systems, they inevitably entail fiscal consequences for governing authorities. This subsection examines the fiscal dimensions associated with the VAT reduction incentives. The analysis compares the simulated annual and cumulative grid savings, which accrue to the government from the decreased consumption of subsidized conventional electricity by solar PV adopters, against the corresponding cumulative VAT subsidies, the latter representing revenue foregone by the government. These fiscal dynamics are depicted in Figure 4.3, and the key cumulative fiscal metrics are summarized in Table 4.6.

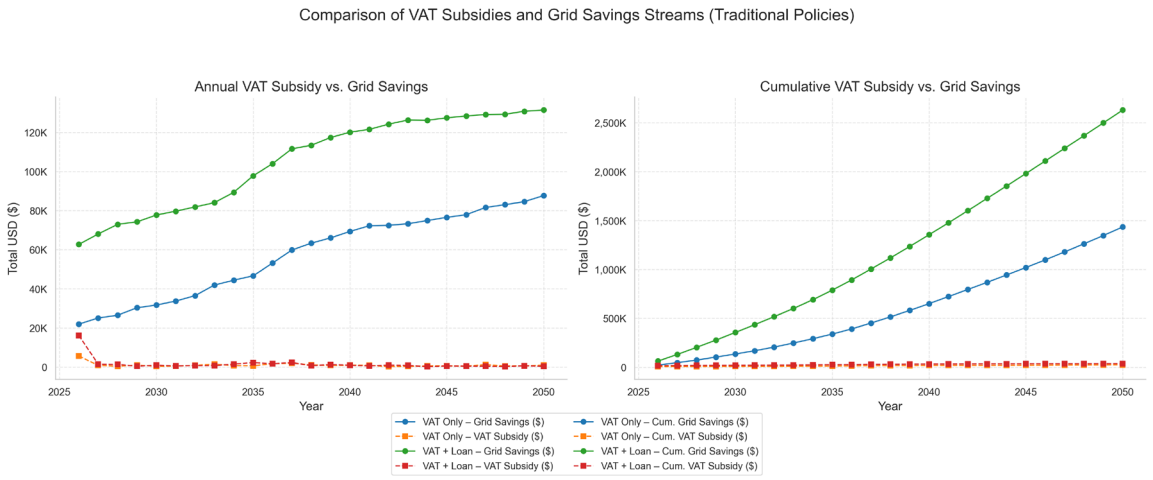


Figure 4.3: Annual and Cumulative Comparison of VAT Subsidies and Grid Savings

Table 4.6: Cumulative Fiscal Metrics for VAT Incentive Scenarios (2025-2050)

Scenario	**Cumulative VAT Subsidy ($)**	**Cumulative Grid Savings ($)**
VAT Only	24,623.00	1.43 million
VAT and Loan	37,507.00	2.63 million

Under the VAT Reduction scenario (termed "VAT Only"), the total cumulative VAT subsidy, which amounts to approximately $24,623 for the modeled sample of 158 households over the simulation period, is projected to yield substantial cumulative grid savings from the government's perspective. These savings, resulting from a reduced need to subsidize conventional electricity for PV-adopting households, amounted to approximately $1.43 million by 2050. In the Combined Policy scenario ("VAT and Loan"), where the VAT reduction is complemented by the innovative loan mechanism, a slightly higher cumulative VAT subsidy of approximately $37,507 is associated with even more significant cumulative grid savings, projected to reach around $2.63 million by 2050.

From a public finance perspective, the outcomes presented in Figure 4.3, and Table 4.6, suggest a compelling return on investment for the VAT subsidy component, particularly within the context of Bahrain's heavily subsidized electricity sector (Alabbasi, 2021). The data clearly indicate that the foregone VAT revenue is significantly outweighed by the long-term savings accrued from reduced expenditure on electricity subsidies for households that adopt solar PV systems. This finding robustly supports the argument frequently made in the energy policy literature concerning subsidized economies (Al-Saidi, 2020; Solaymani, 2021) that targeted subsidies for renewable energy adoption can be fiscally prudent, especially when they lead to a net reduction in overall government subsidy burdens. The significance of this fiscal impact is underscored by research showing that these subsidies divert substantial public funds that could otherwise support essential public services, such as healthcare, education, or critical infrastructure development.

The left panel of Figure 4.3, which shows the annual VAT subsidy versus grid savings, illustrates that while the VAT subsidy represents an upfront or early period cost to the government, the grid savings are an accumulating annual benefit that grows as more solar PV systems come online and continue to generate electricity over their operational lifespan. The right panel of Figure 4.3, depicting cumulative values, vividly demonstrates how these annual savings rapidly surpass the initial subsidy costs, leading to a net positive fiscal outcome for the government in the long term.

The enhanced grid savings observed under the "VAT and Loan" (Combined Policy) scenario further suggest that policy interventions that achieve higher adoption rates can yield proportionally greater net fiscal benefits to the government over time. This holds true even if the direct cost of one component

of the incentive package, such as VAT relief, is slightly higher because of the more widespread uptake, as the resulting increase in the displacement of subsidized electricity more than compensates for this initial outlay. It is important to acknowledge that the innovative loan component, if structured primarily through private financial institutions (potentially with government underwriting or interest rate support, the details of which are not fully elaborated in this fiscal analysis focused on VAT), would have its own distinct set of fiscal implications. However, its evident role in significantly boosting adoption (as discussed in Section 4.2.1) indirectly contributes to the overall grid savings achieved, and thus enhances the positive fiscal picture when combined with VAT relief. The analysis presented here effectively demonstrates that the cost of the VAT incentive can be viewed as a sound investment when considering the direct reduction in ongoing electricity subsidy payments by the government.

4.2.7 Overall Discussion of Financial Incentive Scenarios

The simulation results for financial incentive scenarios yield several critical insights. A primary finding is the effectiveness of both upfront cost reduction (VAT Reduction) and financing facilitation (innovative loans), which individually resulted in significant adoption increases compared to the baseline (Traditional Tariff). Both policies nearly doubled the projected adoption rate by 2050 in the case of loans and substantially increased it for VAT only (Table 4.1). This underscores the sensitivity of adoption to initial investment barriers and affordable financing, as highlighted by Alsabbagh (2019) and the literature on adoption barriers (Fauzi et al., 2023; Juliusson, 2024).

The Combined Policy (VAT + Loan) was the most effective, achieving the highest adoption rate (45.61% by 2050, Table 4.1), best financial metrics for adopters (Table 4.2), largest installed capacity (Table 4.1), and the greatest environmental benefits (Table 4.5). This indicates a strong synergistic effect of addressing multiple financial barriers concurrently, aligning with Rogers' (2003) concepts of perceived attractiveness and compatibility.

The findings also show a significant interaction between financial incentives and social influences. As discussed in Section 4.2.4, social capital and network effects appear to be enhanced when robust financial incentives make solar PV adoption economically rational, suggesting that financial attractiveness is a prerequisite for social diffusion processes (Sigrin et al., 2015) to gain momentum. This agrees with studies emphasizing social influence (Bollinger & Gillingham, 2012; Reeves et al., 2022) and the importance of perceived benefits (Schulte et al., 2022).

Fiscally, targeted incentives like VAT reduction can be cost-effective, with foregone tax revenue substantially offset by long-term savings from reduced electricity subsidies (Section 4.2.6). This aligns with literature suggesting fiscally responsible renewable energy promotion (Al-Sarihi & Mansouri, 2022).

Despite these positive impacts, even the most aggressive incentive package (Combined Policy) resulted in just under 46% adoption by 2050. This suggests that, in a market with heavily subsidized conventional electricity (Alnaser, 2015; Sanfilippo et al., 2024), where residential tariffs are as low as $0.008/kWh compared to actual costs of $0.074/kWh, financial incentives for solar PV may face an adoption ceiling. This market distortion is particularly significant given that installing a solar PV system under current subsidized

tariffs results in a payback period of 83.5 years, compared to just 9.6 years with cost-reflective tariffs (EzzEldin et al., 2022). Achieving higher solar PV penetration might require more fundamental reforms to address the subsidy structure itself, a theme explored in Section 4.3. This aligns with the findings of Alabbasi (2021) and SEU (2017), who noted that Bahrain's subsidized energy prices fundamentally alter conventional adoption drivers, creating market dynamics that deviate significantly from those observed in unsubsidized environments.

4.3. Impact of Subsidy Reform and Cash Transfers

This section examines the reform of Bahrain's residential electricity subsidies, analyzing the impacts of subsidy removal both independently and when combined with compensatory CT mechanisms. These CTs aim to mitigate the socioeconomic effects of increased energy prices while facilitating the transition towards sustainable energy practices. This analysis addresses the challenges of subsidy reform, including political complexities, social acceptance, and the protection of vulnerable populations, as examined in Chapter 2's literature review (Al-Saidi, 2020; Boersma & Griffiths, 2016; Solaymani, 2021). The study simulates several scenarios: complete subsidy removal without compensation (S_0 Subsidy Removal Baseline), and three CT schemes - Universal Dividend (S_1) providing uniform payments, Income-Targeted Transfer (S_2) directing support to lower-income households, and Tiered Household-Size Transfer (S_3) based on household size and reform impact. These scenarios are detailed in Section 3.4.3

4.3.1 Adoption Rates and Diffusion Dynamics under Subsidy Reform Scenarios

The chosen electricity subsidy reform pathway significantly influences both the temporal trajectory and final market penetration of residential solar PV adoption over the simulation period. Figure 4.4 shows the cumulative solar PV uptake patterns across different subsidy reform scenarios from 2025 to 2050. Table 4.7 summarizes the final solar PV adoption rates and the total installed capacities for each scenario.

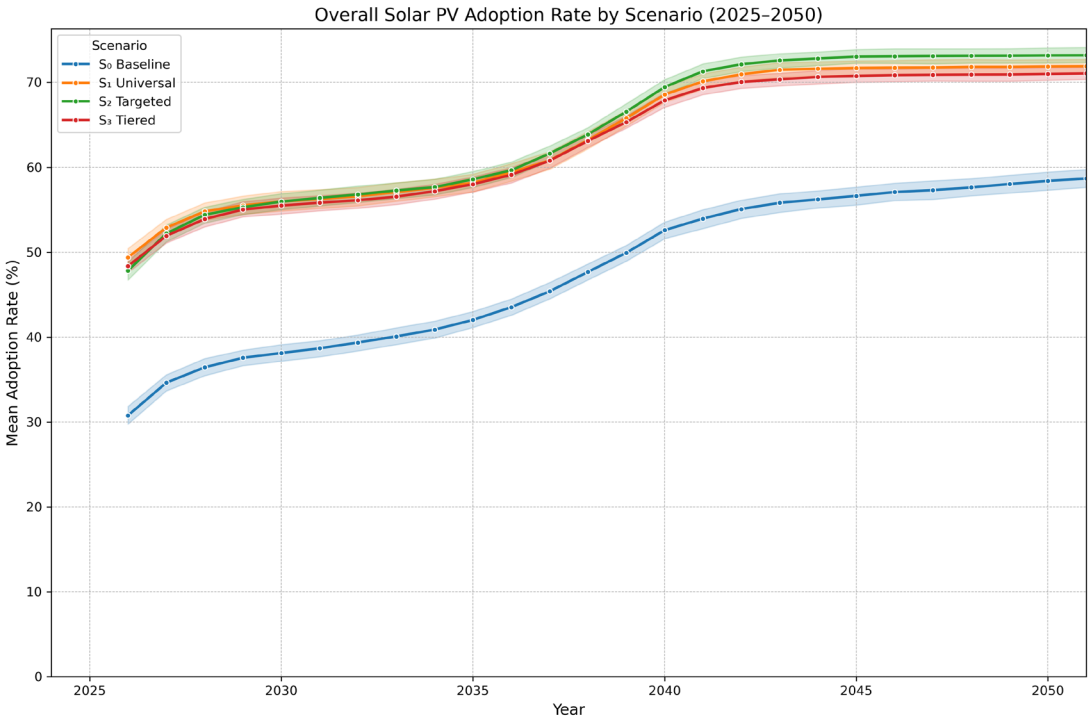


Figure 4.4: Overall Solar PV Adoption Rate by Subsidy Reform Scenarios with 95% confidence interval across runs

Table 4.7: Final Solar PV Adoption Rate (%) and Installed Capacity (kWp) by 2050 under Subsidy Reform Scenarios (Mean ± SD across 50 runs)

Scenario	Adoption Rate %	Total Max. Capacity (kWp)
S_0 Baseline	58.39 (±3.78)	2,024
S_1 Universal	71.87 (±3.13)	2,134
S_2 Targeted	73.18 (±3.12)	2,090
S_3 Tiered	70.99 (±2.73)	2,105

When residential electricity subsidies are removed without compensatory measures (S_0 Subsidy Removal Baseline), the Agent-Based Model projects a significant increase in solar PV adoption compared with the baseline scenario (which resulted in a 23.73% adoption rate). Under S_0, the final solar PV adoption rate is expected to reach 58.39% by 2050 (Table 4.7). This increase is driven by the shift in solar PV systems' "relative advantage' (Rogers, 2003) when households face higher cost-reflective electricity prices. However, the diffusion rate under S_0 only surpasses 50% market penetration around 2040 (Figure 4.4), suggesting that significant adoption barriers persist when the reform impacts remain unmitigated. The substantial upfront capital cost for solar PV installation—a major barrier in Bahrain (Alsabbagh, 2019; EzzEldin et al., 2022)—and potential "bill shock" from higher tariffs represent significant hurdles for households. This aligns with the prospect theory of Behavioral Economics (Kahneman & Tversky, 1979), where large upfront costs are perceived as significant "losses," creating psychological disincentives despite positive long-term savings. The absence of

compensatory measures in S_0 may thus amplify risk aversion among potential adopters.

In contrast to the S_0 scenario, implementing compensatory cash transfers along with subsidy removal significantly enhances solar PV technology diffusion in Bahrain's residential sector. All three cash transfer (CT) scenarios—S_1 (Universal), S_2 (Targeted), and S_3 (Tiered)—facilitate higher solar PV adoption compared to the S_0 baseline without compensation. The Universal Cash Transfer (S_1) achieves a 71.87% adoption rate by 2050, while the income-targeted scenario (S_2) reaches the highest rate of 73.18%. The Tiered Household-Size scenario (S_3) attains 70.99% adoption by 2050. This 12-15 percentage point increase across the CT scenarios versus the baseline demonstrates the effectiveness of financial mitigation strategies in overcoming subsidy removal barriers. The S-shaped diffusion curves under the CT scenarios show a steeper acceleration, indicating faster solar PV adoption mainstreaming.

While the final solar PV adoption percentages under various CT schemes converged to similar levels (71-73%), the patterns of initial uptake and timing showed important variations, as illustrated in Figure 4.4. The Tiered (S_3) and Targeted (S_2) CT designs demonstrate steeper initial adoption rates during early post-reform years (2026-2030). The rapid uptake of the Tiered scheme stems from its benefit calculation methodology, which scales transfers with household electricity demand and family size, addressing the financial concerns of households benefiting from larger solar PV systems. The Targeted scheme's strong early performance indicates that focused financial support for lower-income groups effectively enables their participation when capital constraints might otherwise exclude them. The Universal scheme (S_1), while

achieving high final adoption, shows a less aggressive initial slope compared to S_2 and S_3 schemes before converging to similar adoption levels, suggesting that targeted approaches may better catalyze early adoption in specific segments.

The higher adoption rates across all CT scenarios demonstrate that providing direct cash compensation is essential to unlocking Bahrain's residential solar PV potential. These transfers not only mitigate the welfare impact of increased electricity bills (addressing "loss aversion" as per Kahneman & Tversky, 1979) but also positively influence households' investment decisions regarding solar PV adoption. By improving affordability, reducing perceived financial complexity, and lowering investment risk, cash transfers enhance households' "perceived behavioral control" and adoption intention - key constructs from the Theory of Planned Behavior (Ajzen, 1991). Cash transfers effectively transform solar PV technology from a perceived risky investment to an attractive option for a larger segment of Bahrain's population. This finding supports the conclusions of the literature reviewed in Chapter 2, which emphasizes that financial incentives and support mechanisms are crucial for driving technology adoption and overcoming cost barriers (Juliusson, 2024; Tetteh, 2021).

4.3.2 Household Economic Impacts under Subsidy Reform Scenarios

Subsidy reform and CT scenarios generate distinct economic outcomes for households, particularly regarding solar PV system investment viability and the resulting energy cost savings. Key metrics for assessing financial attractiveness include the discounted payback period (PBP) and average rate

of return (RoR) over the system's operational lifetime. These financial indicators are presented in Table 4.8.

Table 4.8: Average Payback Period (Years) for Adopters by 2050 under Subsidy Reform Scenarios

Scenario	Average Payback Period (PBP)(Years)	Average Rate of Return (RoR) (%)
S_0 Baseline	3.38	27.77
S_1 Universal	1.58	64.94
S_2 Targeted	1.75	69.92
S_3 Tiered	1.81	61.39

Under the Subsidy Removal Baseline (S_0) scenario, where subsidies are eliminated without direct compensation to households, the model calculates an average PBP of 3.38 years for solar PV system adoption, with an average RoR of 27.77% (Table 4.8). This represents a significant improvement compared to the subsidized scenarios (the baseline scenario showed a PBP of 12.99 years, as per Table 4.2). The shorter PBP under S_0 results from the increased value of self-generated electricity when grid electricity prices reflect the true generation and distribution costs. This dramatic improvement in payback period aligns with findings from EzzEldin et al. (2022), who demonstrated that moving from subsidized to cost-reflective tariffs in Bahrain could reduce solar PV system payback periods from 83.5 years to just 9.6 years. The significance of this shift is further supported by Alnaser (2015), who highlights the substantial disparity between subsidized residential rates ($0.008/kWh) and actual electricity costs ($0.074/kWh) in Bahrain. However, a three-year PBP may still be considered too long by households with budget

constraints or higher discount rates, particularly given the socioeconomic attributes of the target population (Tetteh, 2021).

The introduction of any CT scenario dramatically enhanced the financial metrics for PV-adopting households. Universal CT (S_1) resulted in a 1.58-year average PBP with a 64.94% RoR. Targeted CT (S_2) achieved a 1.75-year PBP and the highest RoR of 69.92%. The Tiered CT (S_3) yielded a 1.81-year PBP and 61.39% RoR (Table 4.8). Payback periods under two years are considered highly attractive for household energy investments (Zhang et al., 2016). This indicates that CTs make solar PV systems more financially appealing post-subsidy reform, transforming them into rapid recoupment investments with altered risk profiles.

Shortened PBPs (often below the two-year psychological threshold for household investment decisions, as noted by Rai et al. (2016)) address key behavioral economic barriers. These include temporal discounting (where future savings are undervalued compared to immediate costs, as noted by Rai and Sigrin (2013)) and perceived investment risk, which disadvantage technologies requiring high upfront costs such as solar PV systems. Swift investment recovery reduces financial risk (Al-Sharafi et al., 2023; Vasseur & Kemp, 2015) and minimizes capital outlay barriers for adopters, aligning with the behavioral economics frameworks discussed in Chapter 2. The high Rates of Return of 61-70% under CT implementation scenarios emphasize the strong financial rationale for solar PV adoption when compensatory support mechanisms accompany subsidy reforms. These RoRs exceed typical low-risk household investment returns, making solar PV financially attractive.

4.3.3 Installed Capacity Growth under Subsidy Reform Scenarios

The enhanced solar PV adoption rates documented in Section 4.3.1 translate into measurable variations in the cumulative installed capacity across subsidy reform scenarios. The total solar PV deployment represents both household adoption frequency and the scale of residential renewable energy investment in Bahrain's distinctive market environment (Alabbasi, 2021). Table 4.7 presents the aggregate installed solar PV capacity in kilowatt-peak (kWp) by 2050 for each subsidy scenario across the 158 modeled households.

The Subsidy Removal Baseline (S_0) scenario generates projected installed capacity of 2,024 kWp by 2050, substantially exceeding the maximum capacity achieved under financial incentive scenarios within the subsidized market framework. Furthermore, this outcome aligns with findings from EzzEldin et al. (2022), who showed that cost-reflective tariffs in Bahrain could dramatically improve solar PV system economics. In comparison, the most effective subsidized market intervention, the "VAT + Loan" scenario detailed in Section 4.2, achieved 1,778 kWp (Table 4.1). Consequently, this performance differential demonstrates that electricity price increases through subsidy elimination stimulate solar PV deployment independent of direct financial support mechanisms, thereby corroborating recent empirical evidence from Bahrain's reform experience (Alabbasi, 2021). Moreover, the enhanced economic advantage of solar PV systems in unsubsidized markets simultaneously drives both adoption frequency and installation scale, thus establishing a direct causal relationship between tariff reform and renewable energy deployment capacity.

However, the integration of compensatory CTs with subsidy reform produces additional capacity improvements, indicating the synergistic effects of addressing both market price signals and household affordability constraints. This approach aligns with the recommendations of Haji et al. (2017), who proposed combining Feed-in Tariffs with government subsidies for capital costs in Bahrain. The Universal Cash Transfer (S_1) scenario achieves the highest aggregate installed capacity at 2,134 kWp by 2050, representing a 5.4% enhancement over baseline subsidy removal conditions. The Tiered Household-Size Transfer (S_3) generates substantial capacity of 2,105 kWp, constituting a 4.0% improvement over S_0. Income-Targeted Transfer (S_2) produces 2,090 kWp, despite achieving the highest adoption rate, representing a 3.3% increase over the baseline.

While the final installed capacity differences among cash transfer mechanisms remain modest (2,090-2,134 kWp), all scenarios significantly exceed the no-compensation baseline (2,024 kWp). This aligns with the findings from recent reform efforts in Bahrain, which demonstrated the potential for significant savings through carefully structured policy changes (Alabbasi, 2021). The effectiveness of these approaches is particularly relevant, given Bahrain's historical context of having among the highest energy subsidies globally (Al-Saidi, 2020). Given comparable capacity outcomes, cash transfer mechanism selection should prioritize adoption velocity, distributional equity, fiscal sustainability, and administrative feasibility considerations, particularly within Bahrain's socioeconomic context.

The primary finding confirms the effectiveness of cash transfer in accelerating solar PV capacity growth within reformed electricity market structures while

addressing the specific challenges of Bahrain's transition from a heavily subsidized energy market (Sanfilippo et al., 2024).

4.3.4 Distributional Equity Implications of Subsidy Reform and CT Scenarios

A critical dimension in evaluating electricity subsidy reforms and CT policies is their impact on distributional equity. Energy transitions can disproportionately affect vulnerable populations, which is central to energy policy literature (Groot & Oostveen, 2019; Zarepour & Wagner, 2022). The ABM simulations showed that equity effects varied by CT design, as measured through Gini coefficients, solar PV adoption patterns by income, and compensation profiles.

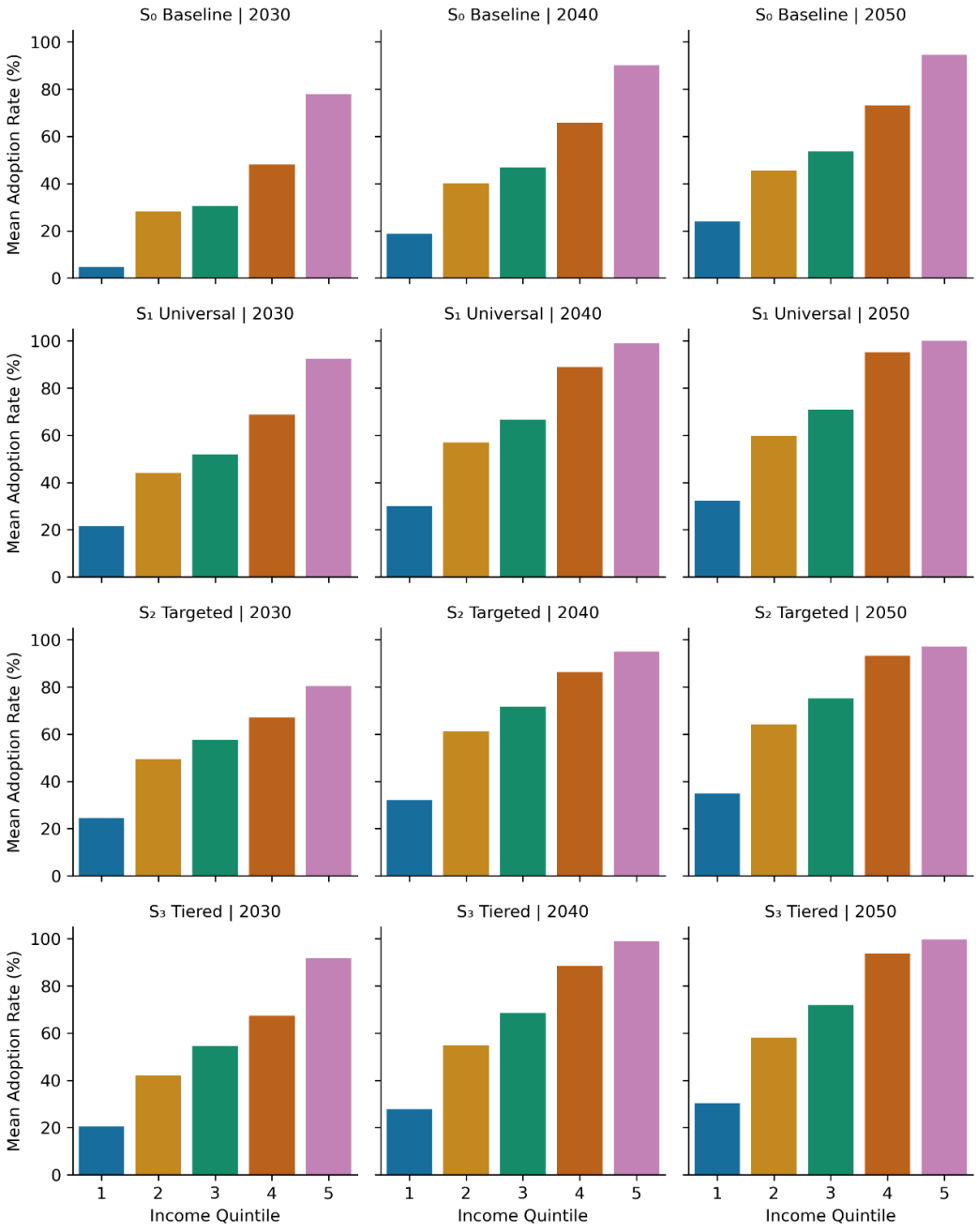


Figure 4.5: Solar PV Adoption Rate by Income Quintile, Scenario, and Year

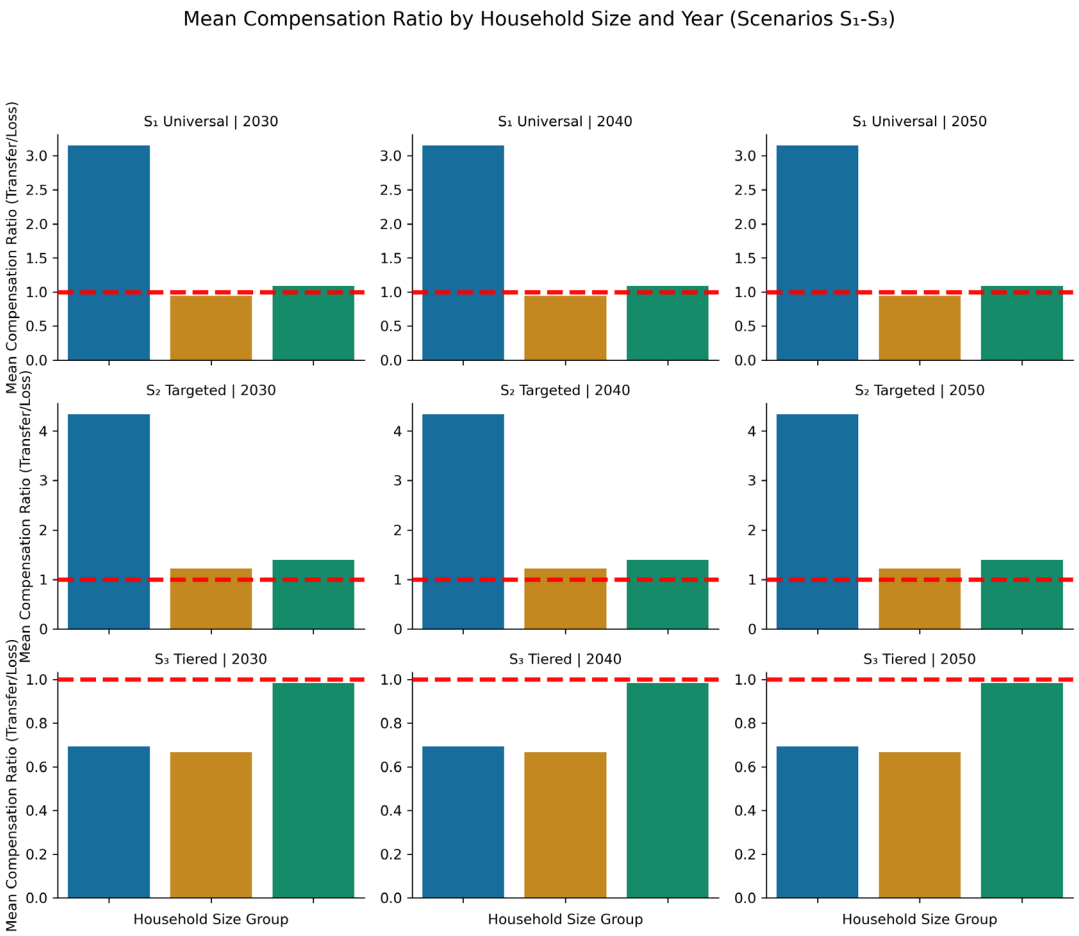


Figure 4.6: Mean Compensation Ratio by Household Size Group, Scenario, and Year

Table 4.9: Average Equity Metrics for Cash Transfer Scenarios

Scenario	**Gini (Cash Transfers)**	**Avg. Comp. Ratio (Transfer/Loss)**	**Avg. Transfer/Income Ratio**
S₁ Universal	0.146	1.088	0.096
S₂ Targeted	0.309	1.407	0.128
S₃ Tiered	0.364	0.891	0.100

Simulations show that subsidy removal alone (S_0 Subsidy Removal Baseline) significantly exacerbates energy inequality. Solar PV adoption becomes skewed towards higher-income households, who can better absorb increased tariffs and upfront solar PV costs (Figure 4.5). This leads to a regressive outcome, where benefits accrue to the affluent, while lower-income groups, who are unable to invest in PV, face higher energy burdens, potentially worsening energy poverty. This aligns with concerns about uncompensated reforms imposing a "loss" (Kahneman & Tversky, 1979) on vulnerable populations.

Appropriately structured CT mechanisms substantially enhance distributional equity and promote inclusive participation in energy transition, thereby addressing the fundamental component of Research Question 3 (RQ3). However, the specific design configuration of these transfer systems proves to be paramount in determining equity outcomes.

The analysis of the CT compensation schemes reveals critical trade-offs in policy design, particularly when operating under a fixed budget that funds only 85.6% of the aggregate subsidy loss. The choice of distribution mechanism, rather than the budget size itself, proves to be the primary driver of the observed differences in equity and efficiency.

While the Universal CT approach (S_1) offers administrative simplicity and achieves a low Gini coefficient for transfers (0.146, Table 4.9), suggesting an equitable distribution of the transfers themselves, it produces a highly skewed distribution of compensation effectiveness. This is because the universal transfer amount is decoupled from the magnitude of an individual household's subsidy loss. Consequently, households with minimal losses receive the same standard transfer as those with high losses, creating extreme individual

compensation ratios that result in a high *mean* compensation ratio of ~3.15 for smaller households (Figure 4.6). This statistical artifact masks the reality that the overall policy is underfunded. While it appears to over-compensate one group, this is at the expense of others who are barely made whole, and it does little to accelerate adoption among lower-income quintiles (Figure 4.5). The modest transfer-to-income (T2I) ratio of 0.096 (Table 4.9) further limits its effectiveness as a broad income support tool.

In contrast, the Income-Targeted scheme (S_2) demonstrates superior effectiveness in channeling resources toward economically disadvantaged households, significantly enhancing their adoption rates (Figure 4.5) and providing the highest relative income support (T2I ratio of 0.128, Table 4.9). However, this policy design exacerbates the distributional distortions seen in S_1. By also decoupling the transfer from the loss, it produces an even more extreme mean compensation ratio of ~4.34 for small households, while the mean ratios for all other groups also exceed 1.0 (Figure 4.6). This result, seemingly impossible under a budget deficit, highlights the potent effect of statistical outliers and reveals a key policy flaw. The fiscal inefficiency of S_2 arises not from an excessive budget, but from a severe misallocation of funds, where transfers are not proportional to need (i.e., the loss incurred). While the policy effectively boosts adoption, its administrative complexity and the hidden inequities created by its distributional mechanism may limit its practical feasibility (Hanna & Olken, 2018).

Most critically, the innovative Tiered CT (S_3) presents a fundamentally different design philosophy. In this scenario, the transfer amount is directly coupled to the household's specific subsidy-loss. As a result, the compensation ratios transparently reflect the underlying budget deficit, with all household

groups showing an average compensation below 1.0 (Figure 4.6). Its average Compensation Ratio of 0.891 (Table 4.9) is an honest reflection of the policy's fiscal constraints. This approach better addresses household loss aversion (Kahneman & Tversky, 1979) by aligning compensation with the experienced loss. Furthermore, its administrative burden may be lower than strict income targeting, as consumption patterns are often easier to verify (Mostafavi-Dehzooei et al., 2020). The high Gini coefficient (0.364, Table 4.9) in this context does not necessarily signal a flaw, but rather reflects an intentionally uneven distribution of transfers designed to match an uneven distribution of losses. While this design is more distributionally efficient, its systematic under-compensation, made plain to all recipients, could undermine the social and political acceptance of the reform.

In conclusion, this analysis demonstrates that all CT designs involve significant trade-offs, which are magnified under a constrained budget. The core choice is between decoupled transfers (Universal and Targeted), which are simple to communicate but create inefficient and potentially inequitable distributional outcomes, and coupled transfers (Tiered), which are more efficient and transparent in allocating limited funds but may be perceived as universally inadequate. This study underscores the critical importance of interrogating not just the headline metrics but the underlying mechanisms of policy design, revealing that the method of distribution is as important as the amount distributed in achieving equitable and effective energy subsidy reforms.

4.3.5 Fiscal Performance Analysis of Subsidy Reform and CT Scenarios

The implementation of electricity subsidy reform presents governments with a critical fiscal trade-off; savings from eliminating costly subsidies must be weighed against new fiscal commitments for compensatory CT programs to mitigate social impacts. This balancing act is central to the reform's political economy, as highlighted in Chapter 2, which emphasizes fiscal sustainability for policy viability (Alabbasi, 2021; Al-Saidi, 2020; Granado et al., 2012). To examine these fiscal dynamics, this subsection analyzes the projected fiscal impact under each simulated reform scenario. Figure 4.7 illustrates the annual fiscal components by scenario, while Figure 4.8 depicts the cumulative net fiscal impacts from 2025 to 2050, providing a comprehensive view of each policy pathway's financial implications.

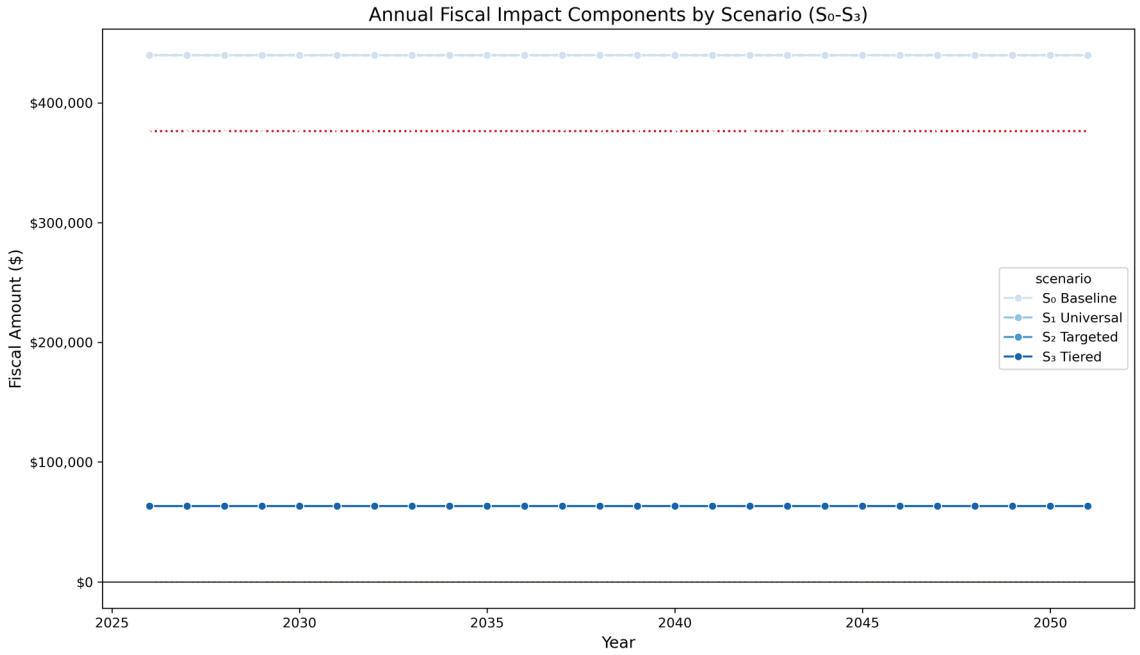


Figure 4.7: Annual Fiscal Impact Components by Subsidy Reform Scenario

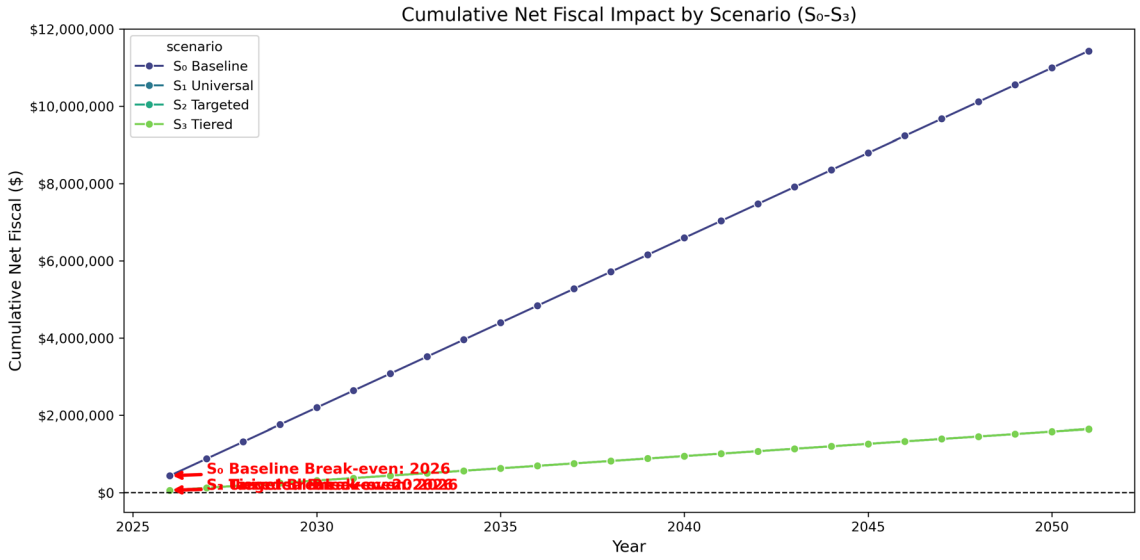


Figure 4.8: Cumulative Net Fiscal Impact by Subsidy Reform Scenario (2025-2050)

The simulation results show that removing residential electricity subsidies generates significant annual government savings, which are projected to reach approximately $440,000 by 2026 for the modeled sample of 158 households. Under the S_0 Subsidy Removal Baseline scenario, the government maintained a positive net fiscal position throughout the simulation. While these savings may moderate over time due to changing consumption patterns and increased residential solar PV adoption, the overall fiscal outlook for S_0 remains positive from the governmental revenue perspective.

When CT scenarios (S_1, S_2, and S_3) are introduced, expenditures from these compensatory programs partially offset gross savings from subsidy elimination. However, the simulations show that these CT expenditures remain below the S_0 baseline fiscal position, ensuring that all three cash transfer scenarios maintain positive annual net fiscal impacts throughout the simulation horizon. The stability of CT expenditure trajectories suggests that potential reductions in CT payouts might be counterbalanced by factors such

as population growth or inflation, which could increase aggregate transfer costs.

The cumulative fiscal analysis in Figure 4.8 shows the S_0 Subsidy Removal Baseline scenario generates the highest net fiscal savings, reaching $11.4 million by 2050 for the modeled sample of 158 households. However, this fiscal performance must be contextualized. As detailed in Sections 4.3.1 and 4.3.4, this S_0 outcome is achieved at the cost of suppressed solar PV adoption rates and adverse distributional equity outcomes, particularly burdening lower-income households.

All three CT scenarios (S_1, S_2, and S_3) are projected to achieve positive cumulative fiscal balances by 2050, demonstrating their long-term viability, even when 85% of the avoided subsidy expenditure is recycled to households as cash transfers. This challenges the assumption that compensatory mechanisms undermine the fiscal objectives of subsidy reform, suggesting that social protection and fiscal prudence are compatible.

A notable aspect is how quickly the fiscal break-even point, when cumulative subsidy savings equal cumulative cash transfer costs, is reached. This milestone will occur by 2026 across all three CT scenarios (Universal, Targeted, and Tiered), as shown in Figure 4.8. This quick return to fiscal neutrality enhances the political feasibility of reforms by minimizing the transitional period of fiscal pressure. By 2050, all three CT designs converged to a similar net fiscal saving of approximately $1.6 million for the modeled sample of 158 households. This convergence indicates that policymakers can focus on optimizing CT design based on adoption acceleration, equity enhancement, and administrative efficiency without concerns about divergent long-term fiscal impacts, provided the funding mechanism remains consistent.

It is important to note that these fiscal projections represent outcomes for the modeled sample of 158 owner-occupied households and would require appropriate scaling to estimate the national-level fiscal impacts for Bahrain's entire residential sector. The relative patterns and policy rankings observed in the sample results provide valuable insights for policy design, while the absolute fiscal magnitudes should be adjusted based on the total number of eligible households nationwide.

The comprehensive fiscal analysis presented in this section leads to a definitive and policy-relevant conclusion: Compensatory cash transfers, when thoughtfully designed and appropriately funded (e.g., through the redirection of a significant portion of subsidy savings), can unequivocally uphold fiscal sustainability in conjunction with comprehensive electricity subsidy reform. The simulations clearly demonstrate that all modeled CT scenarios yield positive cumulative fiscal balances of approximately $1.6 million by 2050 for the sample (Figure 4.8), directly challenging the often-held presumption that social protection measures inherently undermine or compromise core budgetary objectives during complex reform processes.

The fiscal break-even point projected for 2026 across all CT scenarios represents a key advantage for implementation. This swift return to fiscal neutrality shows that well-structured transfer mechanisms with dedicated funding from the reform can quickly achieve self-sustainability. This bolsters political will and public confidence by minimizing transition costs and addressing concerns about long-term budgetary implications.

The convergence of fiscal outcomes across S_1, S_2, and S_3 scenarios by 2050, under the 85% subsidy saving recycling parameter, is significant. Despite differences in distributional characteristics and impacts on adoption equity (as

detailed in Section 4.3.4), these CT designs produce comparable fiscal impacts in the long term. This gives policymakers flexibility. Once subsidy savings recycling is established, CT design selection can focus on achieving specific objectives related to energy transition speed, social equity, administrative feasibility, and public acceptability without undue concern about fiscal burden.

These ABM simulation findings support the consensus within the international subsidy reform literature that well-structured compensatory mechanisms can reconcile fiscal prudence with social protection goals (Granado et al., 2012; Inchauste & Victor, 2017). Rather than facing a trade-off between fiscal consolidation and social welfare, this analysis validates that carefully calibrated transfer programs can advance multiple objectives, while balancing fiscal constraints with equity considerations in the national energy transition policy.

4.3.6 Environmental Impact under Subsidy Reform and CT Scenarios

The adoption of residential solar PV systems, owing to effective electricity subsidy reforms with compensatory CT schemes, provides substantial environmental co-benefits for Bahrain. These advantages come from reduced reliance on fossil fuel-based (mainly natural gas) electricity generation, leading to the avoidance of greenhouse gas emissions, especially carbon dioxide (CO_2), which is a key contributor to climate change. This economic restructuring aligns with environmental outcomes, a fundamental aspect of sustainable development, and climate change mitigation strategies (Belhadj et al., 2022; Solaymani, 2021). The environmental benefits, measured CO_2

emissions avoided, and natural gas saved over the 25-year simulation (2025 to 2050) for modeled households are shown in Table 4.10.

Table 4.10: Total Cumulative Environmental Benefits by 2050 under Subsidy Reform Scenarios

Scenario	**Total CO2 Avoided (Metric Tons)**	**Total Gas Saved (SCF)**
S_0 Baseline	21,038	340,235,852
S_1 Universal	27,029	437,123,025
S_2 Targeted	27,160	439,244,563
S_3 Tiered	26,806	433,525,355

Under the S_0 Subsidy Removal Baseline scenario—modeling electricity subsidy elimination without compensatory measures—the Agent-Based Model projects a reduction of 21,038 metric tonnes of CO_2 emissions and conservation of 340.24 million standard cubic feet (SCF) of natural gas over the simulation period. This environmental baseline is particularly significant for Bahrain, where the projected costs associated with global warming are considered a strong impetus for pursuing energy subsidy reforms (Boudekhdekh, 2022). Higher grid electricity costs render solar PV adoption more economically rational, yielding environmental benefits without additional reform-linked incentives.

The simulation results demonstrate that implementing compensatory cash transfer scenarios significantly enhances positive environmental outcomes by simultaneously addressing technology adoption economics and social equity dimensions of subsidy reforms.

Specifically, the Universal Cash Transfer (S_1) scenario, through its per-capita distribution mechanism, avoided 27,029 tonnes of CO_2 emissions while saving 437.12 million SCF of natural gas over the simulation period. Furthermore, the Targeted CT (S_2) scenario achieved the highest solar PV adoption rate and consequently generated the greatest environmental benefits, avoiding 27,160 tonnes of CO_2 emissions and simultaneously conserving 439.24 million SCF of natural gas. Meanwhile, the Tiered CT (S_3) scenario, by tailoring compensation to household characteristics, avoided 26,806 tonnes of CO_2 emissions and saved 433.53 million SCF of natural gas during the simulation period.

The environmental outcomes in Table 4.10 demonstrate substantial positive externalities from policies that correct market price distortions through subsidy removal, while enabling clean energy technology adoption by addressing household affordability concerns through compensation mechanisms.

When comparing environmental performance of CT scenarios (S_1, S_2, and S_3) against the subsidy-removal baseline (S_0), significant improvements are evident across all CT designs. The Targeted CT (S_2) scenario, which achieved the highest solar PV adoption rate (Table 4.7), delivered the largest environmental benefits. The 27,160 tonnes of CO_2 emissions avoided and 439.24 million SCF of natural gas saved under S_2 represent a 29.1% increase compared to S_0 baseline (21,038 tonnes CO_2, 340.24 million SCF gas saved). The Universal CT (S_1) and Tiered CT (S_3) scenarios show environmental gains of 28.5% and 27.4% respectively over S_0, with corresponding increases in natural gas savings. This aligns with Bahrain's commitment to reduce reliance

on subsidized fossil fuels, although Bahrain's capacity to fulfill these commitments requires careful consideration(Alnaser et al., 2023; SEU, 2017).

The 12-15 percentage point increase in solar PV adoption rates achieved by CT scenarios above S_0 baseline translates proportionally into larger environmental gains for Bahrain. These findings are particularly relevant, given that Bahrain aims to reduce greenhouse gas emissions by 392,000 tons of CO2 per year through renewable energy integration(Alnaser et al., 2023).

These positive findings reinforce the interconnectedness of economic, social, and environmental policy objectives in the sustainable development paradigm. For Bahrain, specifically, as noted by Alabbasi (2021), this transition requires careful balancing of environmental goals with social considerations. The environmental benefits derived from reforming subsidies are particularly relevant, given that Bahrain's electricity sector has historically been maintained at low prices for both social and economic reasons, with the domestic sector receiving highly subsidized electricity (55-80%).

The results demonstrate the potential for significant environmental improvements through policy reform, particularly noteworthy given Bahrain's position as one of the GCC countries with historically among the highest global energy subsidies (Al-Saidi, 2020). This confirms that socially inclusive policies often drive accelerated environmental progress and ecological sustainability while addressing Bahrain's specific challenges in transitioning from a heavily subsidized energy market to a more sustainable model.

4.3.7 Overall Discussion of Subsidy Reform and Cash Transfer Scenarios

The simulation results from the ABM, analyzing the elimination of residential electricity subsidies and implementation of compensatory CT mechanisms, provide compelling evidence for a carefully managed policy approach to energy sector reform in Bahrain. The findings reveal the relationships among economic efficiency, social equity, household behavior, and fiscal sustainability, providing a foundation for policy recommendations on residential solar PV adoption during subsidy reform.

A critical finding is that removing electricity subsidies without compensatory measures (Scenario S_0) presents significant drawbacks. While uncompensated reform enhances the economic attractiveness of residential solar PV systems by increasing grid electricity costs, it impedes overall solar PV adoption compared with scenarios with compensation mechanisms. The S_0 scenario raises substantial equity concerns, as simulations show solar PV adoption becomes skewed towards higher-income households who can better absorb increased electricity tariffs and solar PV system costs (as shown in Figure 4.5). This outcome highlights the regressive potential of uncompensated subsidy reform and emphasizes the necessity of pairing subsidy removal with robust compensatory measures to protect vulnerable households and promote equitable participation in the renewable energy transition, addressing Research Question 2 (RQ2).

In contrast to S_0, compensatory cash transfers (in Scenarios S_1, S_2, and S_3) act as effective catalysts for change. These CT mechanisms boost residential solar PV adoption to 71-73% by 2050 (Table 4.7), up from 58% under subsidy removal alone (S_0). CTs enhance the financial attractiveness of solar PV

investment, reducing the average payback periods to under two years across all CT scenarios (Table 4.8). This has transformed solar PV into a financially viable proposition for a broader segment of the Bahraini population. Thus, CTs function not only as welfare cushions but also as active policy instruments that facilitate clean energy technology adoption by addressing affordability constraints amplified by subsidy reform, aligning with Research Question 3 (RQ3).

While CTs demonstrate a positive impact, the specific CT scheme design is crucial for balancing elevated adoption levels with equitable distributional outcomes.

First, universal dividends (S_1) enhance overall adoption rates and offer administrative simplicity but provide less targeted relief mechanisms. Consequently, uniform transfers may undercompensate larger households experiencing high energy consumption, while simultaneously overcompensating smaller, lower-consuming households. Therefore, these schemes may inadequately stimulate solar PV adoption among the lowest-income groups (Figure 4.5, Figure 4.6).

By contrast, income-targeted schemes (S_2) directly benefit vulnerable households, thereby promoting their solar PV transition and achieving the highest adoption rate (Table 4.7). While this addresses vertical equity principles, it requires a complex means-testing infrastructure and administrative processes (Hanna & Olken, 2018).

Most significantly, the Tiered Household-Size Transfer (S_3) emerges as a promising alternative, achieving near-maximal aggregate solar PV adoption (71%, Table 4.7) while simultaneously delivering superior adoption equity

across income quintiles by 2050 (Figure 4.5). By linking transfers to observable proxies such as household size and pre-reform electricity consumption, this approach provides more equitable compensation (Figure 4.6). This approach balances renewable energy adoption, distributional fairness, and fiscal responsibility while offering greater administrative simplicity than income-targeting methodologies (Clements et al., 2013; World Bank, 2022).

Building on these comparative findings, all modeled CT scenarios (S_1, S_2, and S_3) were fiscally viable and sustainable, contingent on recycling 85% of the gross fiscal savings from eliminated electricity subsidies to fund cash transfers. With the confirmation of fiscal viability, the CT design selection should focus on solar PV adoption targets, energy transition speed, and social equity objectives. This policy approach, integrating subsidy reform with compensatory cash transfers, advances Bahrain's renewable energy goals, while protecting vulnerable households.

4.4. Comparative Discussion and Synthesis

This chapter details the simulated impacts of two key policy intervention sets aimed at promoting residential solar PV adoption in Bahrain. Section 4.2 analyzed financial incentives—VAT reduction and a loan scheme, both separately and combined—within Bahrain's subsidized electricity market. Section 4.3 examined a more fundamental approach: electricity subsidy reform, both alone and combined with compensatory CT mechanisms, to mitigate socio-economic impacts and enable energy transition.

This section presents a comparative discussion and synthesis of the findings. It aims to draw broader conclusions regarding the effectiveness of policy

paradigms in achieving solar PV adoption targets, the necessity of systemic subsidy reform for transformative change, the role of ABM as an analytical tool in energy policy design, the behavioral factors influencing household decision-making, and the robustness of the simulation results presented in this chapter. By integrating these analytical elements, this section provides a comprehensive understanding of the policy landscape and offers insights relevant to policymakers, researchers, and stakeholders in promoting sustainable energy transitions, particularly in regions similar to Bahrain.

4.4.1 Financial Incentives vs. Subsidy Reform with Compensation: A Comparative Perspective

A fundamental policy question confronting decision-makers in Bahrain and nations with extensively subsidized energy sectors is the optimal pathway for achieving renewable energy objectives: whether targeted financial incentives within existing subsidy frameworks can adequately drive solar PV adoption or whether comprehensive subsidy reform represents an essential prerequisite for transformative change. The simulation results presented in this thesis provide empirically grounded insights into this strategic policy dilemma, establishing a quantitative foundation for the comparative assessment of these alternative approaches.

The simulation analysis demonstrates that even the most comprehensive financial incentive package—the "Combined" scenario integrating VAT reduction with accessible loans—achieved only 45.61% residential adoption by 2050. This leaves approximately 55% of Bahraini households non-adopters, despite 25 years of sustained incentives. This performance ceiling reflects the inherent limitations when grid electricity prices are artificially suppressed through extensive subsidization. As documented in Bahrain's

energy policy literature, heavily subsidized residential electricity tariffs create substantial market distortions that fundamentally diminish the "relative advantage" (Rogers, 2003) of solar PV investment (Alabbasi, 2021; Alnaser et al., 2023; Alsabbagh, 2019; Haji et al., 2017). Consequently, artificially low grid electricity pricing functions as a persistent economic disincentive against self-generation, constraining the achievable outcomes through incentive mechanisms alone.

In marked contrast, scenarios with comprehensive electricity subsidy reform achieved significantly higher adoption rates of 71-73% by 2050 when coupled with compensatory cash transfers (S_1, S_2, S_3). Notably, even uncompensated subsidy removal (S_0) achieved 58.39% adoption, exceeding the optimal incentive packages within the subsidized frameworks. This performance differential results from the reformed tariff structures fundamentally enhancing solar PV financial attractiveness through cost-reflective pricing mechanisms, consistent with findings from Bahrain's renewable energy programs (Alnaser, 2023b; EzzEldin et al., 2022). Furthermore, the strategic integration of compensatory cash transfers demonstrates enhanced effectiveness through dual mechanisms: direct enhancement of household affordability and mitigation of loss aversion behavioral responses (Kahneman & Tversky, 1979) associated with increased electricity expenditure. This combination renders solar PV systems economically viable for substantially broader population segments, as evidenced by dramatically reduced average payback periods consistently falling below two years under CT scenarios.

Despite these promising adoption outcomes, subsidy reform without compensation generates significant distributional inequities, concentrating adoption among higher-income households better positioned to absorb

increased costs, as extensively analyzed in Section 4.3.4. This pattern aligns with empirical evidence indicating that high initial costs constitute significant adoption barriers, with investment willingness correlating strongly with household income level (Alnaser, 2023b; Alsabbagh, 2019; EzzEldin et al., 2022). Therefore, the strategic combination of subsidy reform with appropriately designed compensatory CTs emerges as the optimal approach in Bahrain's context. Such transfers are essential for ensuring distributional equity, protecting vulnerable households, and enhancing the social acceptability of reforms, particularly when affordable electricity represents a component of the historical social contract (Al-Sarihi & Mansouri, 2022). The modeled CT mechanisms effectively address affordability concerns arising from higher electricity prices, an inevitable consequence of transitioning from artificially low tariff regimes.

Given these comparative findings, achieving Bahrain's renewable energy targets to generate 20% of electricity from renewable sources by 2035 (GIF, 2023; NREAP, 2017; PMS, 2021) necessitates comprehensive strategies that incorporate systemic subsidy reforms. The critical challenge for policymakers involves designing reform packages that maximize solar PV adoption while ensuring equitable distributional impacts, maintaining fiscal sustainability, and preserving administrative feasibility, as explored through the cash transfer scenarios analysis presented in Section 4.3.

To further clarify the comparative trade-offs for policymakers, the following SWOT analysis synthesizes the key characteristics of the two primary policy paradigms evaluated in this research.

Table 4.11: SWOT Analysis of Competing Policy Paradigms for PV Adoption

Paradigm	Strengths	Weaknesses
A) Financial Incentives (within existing subsidy system)	• Politically Feasible: Avoids the challenges of subsidy reform. • Positive Fiscal Return: VAT reduction incentives can be more than offset by long-term savings on electricity subsidies. • Effective at Boosting Adoption: Can nearly double the adoption rate compared to the baseline (from ~24% to ~46%).	• Limited Impact (Adoption Ceiling): Cannot achieve mass adoption (>50%) due to the persistent market distortion of subsidized electricity. • Does Not Address Root Cause: Fails to correct the underlying inefficient price signals.
B) Subsidy Reform & Cash Transfers (CTs)	• Highly Effective: Achieves mass adoption rates of over 70%, unlocking Bahrain's full residential solar potential. • Corrects Market Fundamentals: Aligns electricity prices with true costs, creating a sustainable market for renewables. • Fiscally Sustainable: Can be designed to be budget-neutral or positive by recycling subsidy savings.	• Politically and Socially Challenging: Subsidy reform is often unpopular and requires significant political will and public buy-in. • Administratively Complex: Requires robust institutional capacity to manage the reform and accurately distribute cash transfers.

	Opportunities	Threats
A) Financial Incentives (within existing subsidy system)	• Can serve as a first phase to build market infrastructure (installers, supply chains) and public awareness before a full reform. • Leverages Bahrain's high solar potential and existing national energy goals (NREAP, NEEAP).	• Policy Instability: Changes to incentive programs can create market uncertainty. • Risk of Entrenching Subsidies: May be seen as a long-term solution, delaying necessary fundamental reforms.
B) Subsidy Reform & Cash Transfers (CTs)	• Unlocks Full Economic Potential: Creates a truly competitive market for solar and other energy efficiency technologies. • Aligns with Global Trends: Positions Bahrain as a leader in sustainable energy policy and fiscal reform in the GCC region.	• Public Resistance: Strong opposition from the public due to higher electricity bills could derail the reform process. • Implementation Failure: Poorly designed or communicated CTs could fail to protect vulnerable households, leading to social hardship and loss of trust.

4.4.2 The Role of Agent-Based Modeling in Complex Policy Design

The application of the ABM in this research has provided valuable insights into the complex energy transition challenges of Bahrain. While traditional modeling approaches often struggle to capture the nuanced dynamics of

subsidized energy markets (Karimi & Vaez-Zadeh, 2021), ABM's bottom-up perspective offers distinct advantages in analyzing policy interventions within Bahrain's unique market conditions.

The model's capacity to represent heterogeneous household characteristics proved particularly valuable in understanding adoption patterns across Bahrain's diverse socioeconomic landscape. By simulating distinct household agents with varying attributes, the model captures the complexity of Bahrain's residential sector, where responses to policy interventions are influenced by multiple interacting factors, including income levels, consumption patterns, and social networks. This granular representation enabled a detailed analysis of how different demographic segments might respond to various policy interventions, a critical consideration given Bahrain's historically subsidized electricity market structure.

The ABM framework effectively integrates multiple theoretical perspectives while enabling ex-ante policy evaluation through computational experimentation. This proved especially valuable when assessing politically sensitive reforms, such as subsidy restructuring, allowing for a detailed analysis of potential outcomes before implementation. The ability to simulate various scenarios while accounting for Bahrain's specific market conditions and social dynamics offers insights that would be difficult to obtain through conventional analytical methods.

The observed patterns of adoption across different income groups and policy scenarios reflect complex interactions between market conditions and social dynamics unique to Bahrain's context. These findings demonstrate ABM's utility in designing effective and equitable energy policies within the complex socio-technical system characteristics of Bahrain's residential energy sector,

particularly when evaluating the comparative effectiveness of different cash transfer designs and their equity implications.

4.4.3 Key Drivers of Solar PV Adoption in Bahrain's Market Context

The simulation results revealed three interconnected factors that drive solar PV adoption in Bahrain's residential sector. Economic considerations proved fundamental, particularly given Bahrain's heavily subsidized electricity rates (Alnaser, 2015). The model demonstrated that policies improving solar PV financial attractiveness through shortened payback periods or reduced upfront costs were essential for initiating adoption, especially given the current market conditions where subsidized tariffs result in extended payback periods (EzzEldin et al., 2022).

Social influence mechanisms emerged as significant accelerators once economic barriers were addressed. This aligns with recent findings in Bahrain, showing that community awareness and demonstration projects significantly influence adoption decisions (Albuflasa, 2018). The simulation revealed that peer effects and visible installations became particularly effective after policy interventions improved PV's economic viability.

Policy interventions, especially those combining subsidy reform with compensatory measures, proved most effective in Bahrain. This finding supports recent research on GCC energy transitions (Al-Saidi, 2020), suggesting that comprehensive policy approaches that address both economic and social factors are crucial for successful renewable energy adoption.

4.4.4 Sensitivity Analysis Discussion: Robustness of Findings and Parameter Uncertainty

To assess the robustness of the model's findings and understand the influence of key uncertain parameters, a comprehensive one-at-a-time (OAT) sensitivity analysis was conducted. This analysis served as an exploratory tool to test the model's behavior under different assumptions. The parameters were systematically varied around an initial baseline configuration to identify which variables had the most significant impact on adoption outcomes. The insights gained from this sensitivity analysis then informed the selection of the final calibrated parameter values, as detailed in Section 3.7.1, which were used to generate the definitive policy scenario results presented in this chapter. The remainder of this section discusses the findings of that sensitivity analysis.

The analysis revealed a clear parameter influence hierarchy, as summarized in Table 4.12, which ranks the tested parameters by their overall impact on adoption rates.

Table 4.12: Parameter Ranking by Adoption-Rate Influence and Precision

Parameter	**Baseline value**	**Max Δ Adoption (%)**	**Mean 95 % CI (%)**
Environmental weight (w_env_calculated)	0.27	6.84	0.82
Neighbor awareness (neighbor_adoption_awareness)	0.005	5.82	0.79
Logistic steepness (adoption_logistic_k)	5.5	5.44	0.75
Adoption threshold (adoption_threshold)	0.7	4.43	0.68

Payback weight (w_pay)	0.424	4.3	0.71
Social midpoint (mid_soc)	0.35	2.66	0.84
Social steepness (k_soc)	12	1.82	0.96
Cost-decline rate (yearly_decrement)	0.022	1.25	0.63
Social weight (w_soc)	0.107	1.09	0.88

Note: 'Max Δ Adoption (%)' represents the full range of adoption rate variation across all tested parameter values, while the discussion reports ± ranges from baseline values.

The results show that non-economic motivations and social dynamics are the most significant drivers of uncertainty in the model. Figure 4.9 illustrates the model's high sensitivity to the environmental weight (w_env_calculated). As the dominant parameter, variations in environmental preference were capable of altering final adoption rates by up to ±3.4 percentage points.

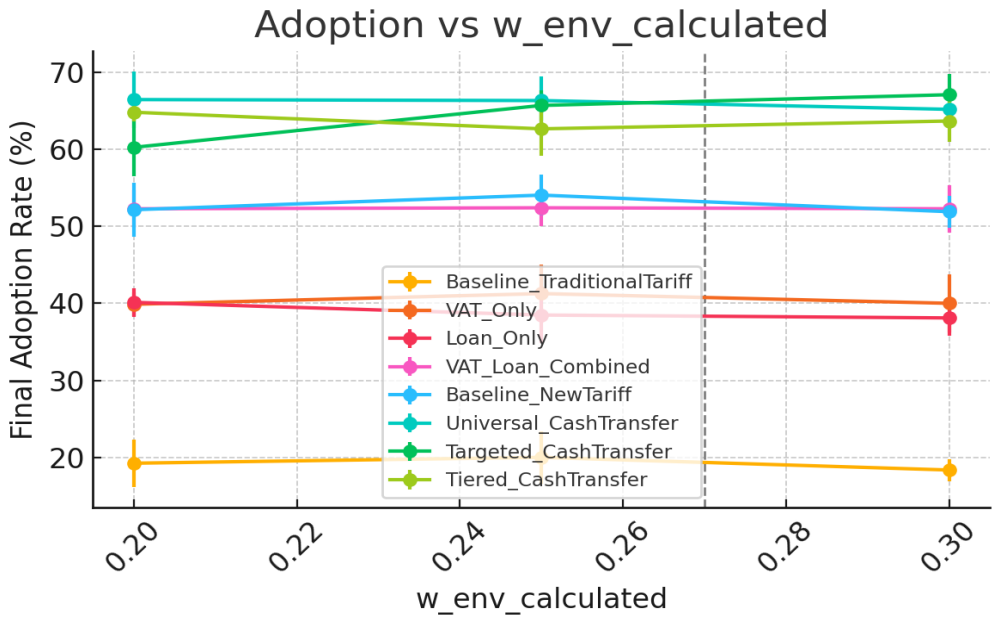


Figure 4.9: Sensitivity of Final Adoption Rate (%) to the Environmental Weight across eight policy scenarios

The next most influential parameters were social and behavioral factors. Figure 4.10 shows the impact of neighbor awareness, while Figure 4.11

displays the effect of the adoption logistic steepness. These visualizations, which plot the results for all eight scenarios, demonstrate the critical role of social learning and behavioral thresholds in household decision-making.

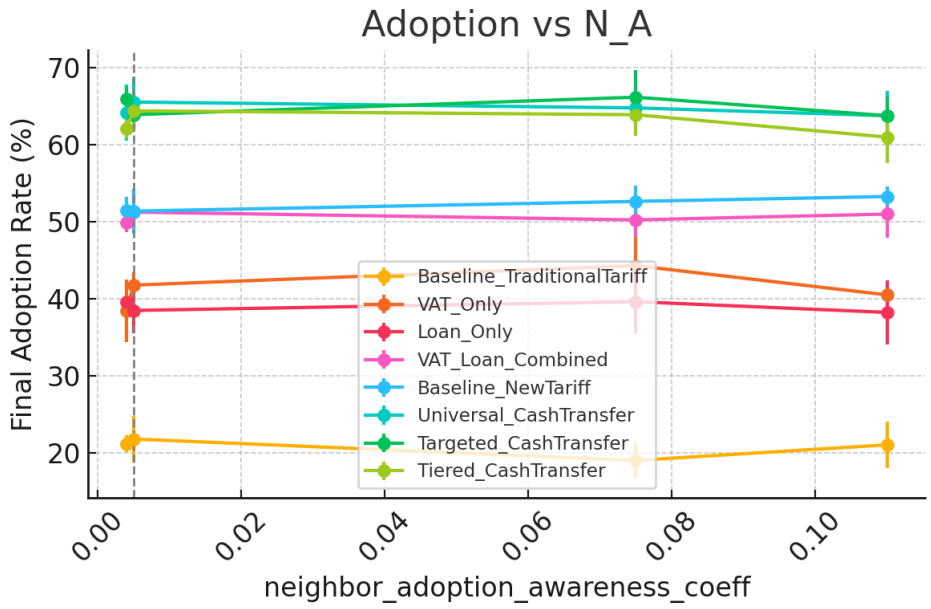


Figure 4.10: Sensitivity of Final Adoption Rate (%) to the Neighbor-Adoption Awareness Coefficient across eight policy scenarios

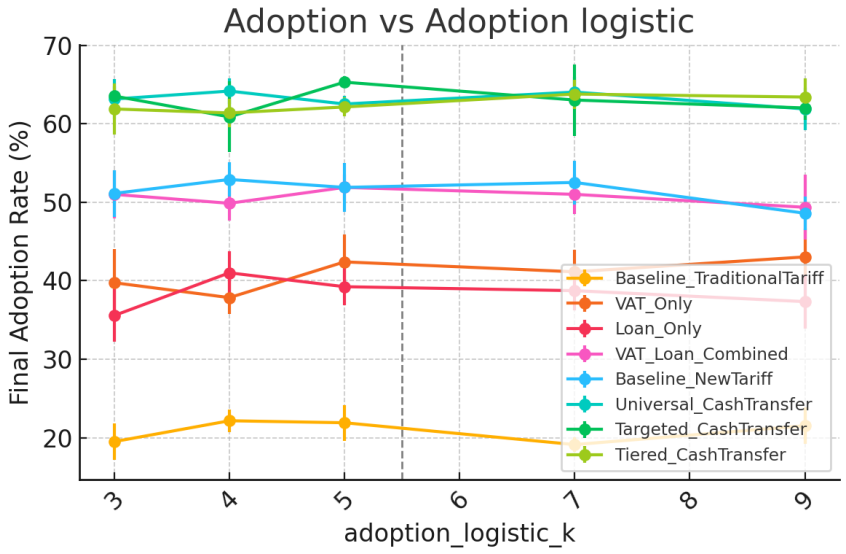


Figure 4.11: Sensitivity of Final Adoption Rate (%) to the Logistic Steepness across eight policy scenarios

The most important conclusion from this comprehensive analysis is the remarkable stability of the policy scenario rankings. As the visualizations here and in the complete set in Appendix B demonstrate, despite systematic parameter variations, the two distinct tiers of outcomes are preserved:

1. The four scenarios involving subsidy reform (S_0, S_1, S_2, S_3) consistently and significantly outperform the other four scenarios.
2. The four scenarios based on financial incentives within the current subsidy system (Baseline, VAT Only, Loan Only, VAT + Loan) consistently result in lower adoption rates.

This unwavering separation between the two policy paradigms provides powerful evidence for the thesis's central conclusion: achieving transformative, mass-market PV adoption in Bahrain necessitates a fundamental subsidy reform. The fact that this conclusion holds true even when key model assumptions are varied across a wide range of plausible values gives strong confidence in the robustness and reliability of the policy insights generated by this research.

4.5. Answering the Research Questions

This section addresses the research questions posed in Chapter 1. The answers are drawn from the comprehensive ABM simulation results and analyses presented in Sections 4.2-4.4.

RQ1: How effective are specific financial incentives (VAT reduction and innovative loans) in stimulating residential solar PV adoption within Bahrain's subsidized electricity market?

The ABM simulations demonstrate that targeted financial incentives can significantly enhance residential solar PV adoption rates in Bahrain's subsidized electricity market. The analysis compared three incentive approaches against the baseline (Traditional Tariff) scenario, achieving 23.73% adoption by 2050.

The VAT Reduction scenario showed modest effectiveness, with adoption increasing by 26.73% by 2050. While this measure reduced initial capital costs, its impact on key financial metrics remained limited, with the payback period improving marginally from 12.99 to 12.79 years and the rate of return from 8.01% to 8.32%. This modest improvement reflects the persistent challenge of high upfront costs in Bahrain's residential sector (EzzEldin et al., 2022).

In contrast, the Innovative Loan scenario demonstrated a substantially greater impact, achieving 43.85% adoption by 2050. By addressing financing affordability and cash flow concerns, this mechanism significantly improved solar PV financial viability, reducing the average payback period to 6.15 years and yielding a substantially higher rate of return. This supports evidence of financing barriers in Bahrain's renewable energy market (Albuflasa, 2018).

The Combined Approach (VAT + Loan) proved to be the most effective, reaching 45.61% adoption by 2050 with the most favorable financial metrics (payback period: 6.21 years). However, this comprehensive package could not overcome the fundamental market distortion created by Bahrain's electricity subsidies, suggesting an inherent ceiling for incentive-only policies within the existing subsidy structure.

Building on these findings, RQ2 examined the effects of more fundamental market reforms through subsidy removal.

RQ2: What are the effects of removing residential electricity subsidies on the solar PV adoption rates and household welfare in Bahrain?

The simulation of the uncompensated electricity subsidy removal (Scenario S_0) revealed significant impacts on both solar PV adoption and social equity in Bahrain's residential sector. Subsidy removal substantially enhanced the economic attractiveness of solar PV self-generation, resulting in a 58.39% adoption rate by 2050, more than doubling the 23.73% projected under the baseline scenario. The average payback period improved dramatically to 3.38 years, making solar PV investment financially attractive for many households.

However, the improved adoption rate has significant distributional consequences. In Bahrain's context, where electricity tariffs have historically been maintained at low levels (55-80% subsidized) for social and economic reasons (Albuflasa, 2018), uncompensated subsidy removal created marked inequities. High-income households with greater financial resilience could manage both increased electricity costs and solar PV investment, whereas lower-income households faced a double burden.

The analysis revealed a concerning pattern of regressive effects. Despite facing significantly higher electricity bills, low-income households were unable to invest in solar PV systems, thereby bearing the full impact of increased energy costs without accessing the offsetting benefits of self-generation. This corroborates previous findings in Bahrain, showing that high upfront costs and limited financing options affect vulnerable households (EzzEldin et al., 2022).

Therefore, while subsidy removal effectively stimulates solar PV adoption through market correction, its implementation without compensatory measures exacerbates energy poverty and social inequalities in Bahrain's residential sector. This finding is particularly relevant given Bahrain's historical experience with subsidy reforms, where previous attempts at price adjustments required careful consideration of social impact (Boersma & Griffiths, 2016).

Having established the effects of subsidy removal, RQ3 explored how compensatory mechanisms can address these equity concerns.

RQ3: How do different compensatory cash transfer designs (universal, targeted, and tiered) influence the speed, level, and equity of solar PV adoption following subsidy removal?

The simulation results demonstrate that compensatory CTs significantly accelerate solar PV adoption following subsidy removal in Bahrain's residential sector. All three CT designs—Universal (S_1), Income-Targeted (S_2), and Tiered (S_3)—achieved substantially higher final adoption rates (ranging from 71-73% by 2050) compared to the uncompensated subsidy removal scenario (S_0: 58.39%). This acceleration is evidenced by steeper adoption curves and dramatically reduced average payback periods, which fall between 1.58-1.81 years across the CT scenarios.

Each CT design, however, demonstrated distinct distributional outcomes. Universal CT (S_1), while administratively simple, showed limited effectiveness in promoting equitable adoption across income groups. Under this policy, lower-income quintiles continued to lag behind higher-income

households, reinforcing previous evidence on income-based adoption barriers in Bahrain's residential sector (EzzEldin et al., 2022).

Conversely, the Income-Targeted CT (S_2) proved most effective at stimulating adoption among lower-income households. It achieved the highest overall adoption rate (73.18%) and provided the strongest pro-poor benefits, as indicated by the highest transfer-to-income ratios. This targeted approach directly addresses known financing constraints within Bahrain's renewable energy market (Albuflasa, 2018).

Most notably, the novel Tiered CT (S_3) achieved a robust overall adoption rate (70.99%) while producing the most balanced adoption distribution across income quintiles. The success of this design stems from its structure, which aligns the compensation mechanism more closely with the specific financial impact of the reform on households of different sizes and consumption patterns. This suggests that policy designs considering both capacity-to-pay and the magnitude of the loss can lead to more equitable and socially acceptable outcomes.

The equity impacts of the transfer distributions themselves were further quantified through their Gini coefficients: Universal (0.146), Targeted (0.309), and Tiered (0.364). These values reflect the differing philosophical approaches to vertical equity within each design, a significant finding given Bahrain's experience with targeted support systems in energy policy (Al-Saidi, 2020). While all CT policies successfully mitigated the negative impacts of subsidy removal, a deeper analysis of their compensation efficiency revealed significant structural differences, which are explored in the subsequent discussion.

Finally, RQ4 examined the broader fiscal and environmental implications of these approaches.

RQ4: What are the comparative fiscal implications and environmental co-benefits of the different policy pathways?

The analysis revealed distinct fiscal and environmental outcomes across policy approaches in Bahrain's residential energy sector. From a fiscal perspective, financial incentives within the subsidized market demonstrated positive long-term potential, despite the initial costs. The VAT + Loan scenario, which requires upfront government investment, generates substantial savings through reduced electricity subsidy expenditure for PV-adopting households.

Subsidy reform scenarios with cash transfers (S_1, S_2, S_3) demonstrated robust fiscal sustainability. When funded by recycling 85% of gross subsidy savings, all CT scenarios achieved fiscal break-even by 2026 and generated comparable net fiscal savings (approximately $1.6 million) by 2050. This rapid break-even point is particularly relevant in Bahrain's policy context, where fiscal sustainability remains a key consideration (Al-Saidi, 2020).

Regarding environmental benefits, these scales were scaled directly with the adoption rates. Within the subsidized market framework, the Combined VAT + Loan scenario achieved the highest environmental impact, avoiding 15,269 tons of CO_2 emissions and saving 246.93 million SCF of natural gas. These environmental gains are significant, given Bahrain's climate commitment and natural gas consumption patterns (EzzEldin et al., 2022).

The subsidy reform scenarios with CTs demonstrated superior environmental performance, with CO_2 reductions ranging from 26,800 to 27,160 tons and gas

savings between 433-439 million SCF. This represents a 27-29% improvement over the uncompensated subsidy removal (S_0). The enhanced environmental benefits stem from higher solar PV penetration rates (71-73%) compared to incentive-only approaches (46%).

In summary, although both policy approaches could potentially lead to positive fiscal outcomes, subsidy reform with well-designed cash transfers offers the most significant environmental benefits through higher adoption rates. While supporting Bahrain's dual objectives of fiscal sustainability and environmental protection, these model-derived insights should be viewed as indicative pathways. As with any simulation, the model represents a simplification of complex real-world dynamics, providing valuable insights for understanding these systems, rather than constituting definitive predictions.

The comprehensive analysis presented in this chapter provides significant insights into the different impacts of various policy pathways on residential solar PV adoption in Bahrain. These findings directly address the research questions posed, and highlight the key trade-offs between adoption effectiveness, social equity, and fiscal sustainability. Having addressed all research questions, Chapter 5 synthesizes these findings, discusses their broader academic and policy implications, offers specific recommendations, and concludes the thesis.

Chapter 5: Conclusion and Recommendations

5.1. Summary of Key Findings

As stated in the introduction, the primary aim of this research was to evaluate and compare the effectiveness of different policy strategies (financial incentives and subsidy reform with cash transfers) in accelerating residential solar PV adoption in Bahrain, assessing their economic, social equity, and fiscal implications. Through a comprehensive analysis of financial incentives and electricity subsidy reform mechanisms, this study developed an Agent-Based Model (ABM) to evaluate policy impacts on solar PV adoption, household economics, distributional equity, and fiscal outcomes. This research particularly focused on addressing Bahrain's unique market context, characterized by extensive electricity subsidies and ambitious renewable energy targets.

The main findings of this research are extensively detailed in Chapter 4, encompassing financial incentive effectiveness, electricity subsidy reform with compensatory cash transfers, behavioral and social dynamics, and implementation considerations for policy design. The principal outcomes are summarized as follows.

- VAT Reduction demonstrated limited effectiveness, increasing adoption rates from 23.73% to 26.73% by 2050, suggesting that addressing upfront capital costs in isolation is insufficient when fundamental market price distortions remain unaddressed.
- The Innovative Loan Mechanism achieved substantially higher adoption rates of 43.85% through enhanced financing accessibility and

the strategic alignment of loan repayment structures with existing household cash flow patterns.

- The combined VAT + Loan package demonstrated the highest performance among incentive-only approaches, reaching 45.61% adoption by 2050 with markedly improved financial metrics, including an average payback period of 6.21 years.
- The maximum achievable penetration rates plateaued at approximately 46%, revealing the fundamental limitations inherent in incentive-only approaches when implemented in heavily subsidized electricity markets.
- Uncompensated reform (S_0) enhanced solar PV adoption to 58.39%, but generated pronounced distributional inequities, concentrating adoption among higher-income household segments while imposing disproportionate energy cost burdens on vulnerable populations.
- All compensatory cash transfer (CT) scenarios substantially increased solar PV adoption to 71-73% by 2050, driven by a dramatic reduction in average payback periods to an economically attractive 1.58-1.81 years.
- The Income-Targeted CT (S_2) proved most effective at stimulating adoption among lower-income households, but its decoupled design (where transfers are independent of subsidy loss) resulted in significant distributional inefficiencies.
- The Tiered CT (S_3) achieved the most equitable adoption patterns across all income quintiles by utilizing a coupled design that linked

compensation directly to household loss, a more rational approach that also made the budget deficit transparent.

- The Universal CT (S_1) was the least effective in promoting equity and exhibited similar distributional inefficiencies to the targeted policy due to its decoupled design.
- All three CT scenarios ensure a positive net fiscal impact by capping total transfers at 85.6% of gross subsidy savings, confirming the fiscal viability of the compensation mechanism..
- Social network effects demonstrated varying degrees of influence across policy scenarios, with correlation coefficients ranging from 0.020 to 0.140, and effectiveness increased notably when fundamental financial barriers were systematically reduced through policy intervention.
- Environmental awareness exhibited complex relationships with adoption trajectories, demonstrating stronger predictive influence among early adopter segments (awareness levels 0.992-0.997) compared to later adoption phases (0.962-0.991).
- Peer effects and observability factors become more significant under improved economic conditions, indicating that social dynamics can amplify policy impacts once fundamental financial barriers are addressed.
- Policy timing and sequencing have emerged as critical factors, with simulation results suggesting that phased implementation could enhance both adoption rates and equity outcomes.

- The market structure implications reveal the need for coordinated reforms across electricity pricing, renewable energy policies, and social protection systems.
- Stakeholder impacts showed varying distributions across different policy designs, emphasizing the importance of a comprehensive impact assessment in policy selection.

5.2. Academic Contributions

This thesis contributes significantly to the academic discourse on energy policy, technology diffusion, and computational modeling through several key avenues:

1. Methodological and Contextual Innovation: This study demonstrates the robust application of Agent-Based Modeling to residential solar PV adoption within the under-researched context of heavily subsidized Gulf Cooperation Council (GCC) economies. This work extends both the geographical and socioeconomic scope of ABM applications in energy policy while generating quantitatively grounded, context-specific insights for Bahrain's energy transition. This provides a methodological template and empirical foundation for other GCC nations that face similar policy challenges.
2. Integrated Policy Analysis Framework: The study provides a comprehensive analytical framework that compares distinct policy paradigms—incentives within existing subsidy structures versus fundamental subsidy reform with compensatory mechanisms—using a unified modeling approach. This facilitates a direct comparison of the

multifaceted impacts across the adoption, equity, and fiscal dimensions within a single analytical framework.

3. Novel Policy Mechanism and Design Insights: This study introduces and evaluates an innovative Tiered Household-Size Cash Transfer (CT) mechanism, contributing critical insights into compensatory policy design for energy transitions. The novelty lies in its "coupled" design, which directly links a household's compensation to its specific subsidy loss. This approach is shown to achieve robust adoption rates while promoting superior distributional equity across income quintiles. Most importantly, it avoids the significant distributional inefficiencies and misleading statistical artifacts that arise from "decoupled" universal or targeted transfers. By demonstrating a more rational and transparent framework for allocating funds under a budget constraint, this research advances the understanding of how to design effective and equitable compensation policies for energy subsidy reform.
4. Theoretical Integration in Computational Modeling: The research enriches the ABM literature by explicitly incorporating and operationalizing concepts from the Diffusion of Innovation theory, Behavioral Economics, and Social Capital Theory within agent decision-making frameworks. This advances theoretical integration in computational energy policy modeling and demonstrates how multiple behavioral theories can be synthesized using agent-based approaches.

5.3. Policy Implications and Recommendations

The simulation findings provide quantitative evidence for optimal policy design within subsidized energy markets. This section presents evidence-

based recommendations for optimizing solar PV uptake, ensuring equitable participation, and maintaining fiscal sustainability, progressing from strategic priorities to implementation.

5.3.1 Strategic Policy Framework for Bahrain

Based on a comprehensive simulation analysis, three strategic priorities emerged for accelerating residential solar PV adoption in Bahrain. These recommendations were ranked according to their effectiveness in simultaneously achieving multiple policy objectives.

1. Primary Recommendation: Comprehensive Subsidy Reform with Carefully Designed Compensation

A comprehensive electricity subsidy reform, when coupled with a well-designed compensatory cash transfer (CT), represents the optimal policy pathway. This approach is projected to achieve high solar PV adoption rates of 71-73%, fundamentally outperforming incentive-only strategies that yield adoption ceilings of approximately 46%. This transformative level of adoption is essential for establishing the market fundamentals and achieving the scale of decarbonization required to meet the Kingdom of Bahrain's ambitious long-term Net Zero 2060 commitment.

The success of such a reform is critically dependent on the design of the concurrent CT mechanism. As demonstrated by the uncompensated scenario (S_0), subsidy removal without compensation can generate significant distributional inequities. While all tested CT designs improve equity relative to S_0, their effectiveness varies. Crucially, a positive net fiscal impact is achieved in all CT scenarios by capping total transfers at 85.6% of the gross

subsidy savings, ensuring the policy is fiscally favorable for the government budget within 1-2 years of implementation.

2. Secondary Strategy: Integrated Financial Incentive Implementation

In policy contexts where a complete subsidy removal is not immediately feasible, the deployment of an integrated financial incentive package is the next best alternative. The model shows that a combination of policies addressing both upfront costs (VAT reduction) and financing affordability (innovative loan mechanisms) yields the best outcomes among incentive-only options. The innovative loan component is particularly effective, offering cash-flow-neutral repayment structures aligned with household electricity savings, which reduces perceived financial risk and encourages investment.

3. Recommended Cash Transfer Design: Tiered (Coupled) Mechanism

Among the tested compensation policies, the novel Tiered Household-Size CT (S_3) emerges as the recommended design. Its superiority lies in its ability to promote equitable adoption across all income quintiles while maintaining distributional rationality and administrative feasibility.

- Mechanism: Its "coupled" design, which aligns compensation directly with a household's estimated subsidy loss, proves to be the most efficient and transparent method for distributing limited funds. This approach avoids the significant statistical distortions and inefficient allocation of resources inherent in the "decoupled" designs of the other scenarios.
- Comparison: While income-targeted schemes (S_2) are effective at boosting adoption for the lowest-income groups, they create severe distributional imbalances and require costly administrative infrastructure. Universal transfers (S_1) are simple to administer but are

poorly targeted and inefficient. The Tiered CT (S_3) offers the most robust balance, making it a more viable and equitable blueprint for real-world policy reform.

It is crucial to note that these strategic recommendations align directly with the Kingdom of Bahrain's established national objectives and fiscal realities. The National Renewable Energy Action Plan (NREAP) sets clear targets for renewable energy integration—aiming for 5% of total generation by 2025 and 20% by 2035 — which serve as critical milestones toward the Kingdom's ultimate commitment to achieving Net Zero carbon emissions by 2060. The simulation results indicate these goals are difficult to achieve through incentives alone but become viable through the recommended subsidy reform pathway.

Furthermore, the core recommendation to correct price signals through subsidy reform strongly supports the foundational goals of the National Energy Efficiency Action Plan (NEEAP), which seeks to reduce national electricity consumption. By addressing the market distortions caused by artificially low tariffs, the proposed policies create a powerful incentive for the efficient energy use that the NEEAP promotes.

From a fiscal perspective, the recommended pathways are designed to be self-sustaining, with the cost of cash transfers funded by subsidy savings. This approach is consistent with Bahrain's broader need for fiscal consolidation and the prudent management of state resources, a common challenge across GCC economies. Therefore, the policy framework proposed in this thesis should not be seen as a new or alternative agenda, but rather as an evidence-based implementation strategy designed to help the Kingdom of Bahrain achieve its existing, stated energy and economic goals.

5.3.2 Regional Applicability and Methodological Contributions

These findings extend beyond Bahrain to inform policies across GCC nations and comparable subsidized energy markets. The demonstrated necessity of coupling subsidy reform with equitable compensation provides universal guidance for ensuring social and political sustainability of energy transition policies.

This study reconceptualizes cash transfers as active catalysts for renewable energy adoption rather than passive welfare protection, opening innovative policy design opportunities for aligning social protection with environmental objectives. The ABM framework provides a replicable analytical template for the ex-ante assessment of complex energy policy packages, enabling evidence-based design that accounts for heterogeneous population responses and emergent system dynamics.

5.3.3 Implementation Framework and Complementary Measures

A phased strategy manages transition complexity while building institutional capacity. The recommended sequence involves initially introducing targeted financial incentives to develop the market infrastructure, followed by progressive subsidy reform with corresponding compensation mechanisms. This aligns with the Diffusion of Innovation principles regarding the introduction of manageable change and market preparation.

Success, however, requires more than just financial engineering; it necessitates addressing critical non-financial barriers. The simulation findings on the importance of social influence and information diffusion in adoption

decisions point to a clear opportunity for policymakers to actively leverage social networks as a low-cost, high-impact policy tool. A proactive strategy to harness social capital should be a core complementary measure. This can be achieved through:

- Empowering 'Solar Ambassadors': Create official programs that identify and support early adopters, empowering them to share their positive experiences with their neighbors and community groups. This turns satisfied customers into credible, grassroots advocates for solar PV technology.
- Facilitating Community-Based Initiatives: Support the formation of community solar projects or group-purchasing schemes. These initiatives not only reduce costs through bulk buying but also strengthen social norms around solar PV adoption and build collective momentum.
- Localized Information and Trust Building: Move beyond generic national campaigns and instead deliver targeted information through trusted local community leaders and channels. This approach capitalizes on existing social capital to build trust and disseminate information more effectively.

Alongside these social strategies, success also depends on streamlining administrative processes for permitting and grid connection and implementing comprehensive quality assurance frameworks for solar PV equipment and installation services.

Implementation must incorporate adaptive management principles with context-sensitive calibration rather than uncritical adoption of international models. Regular monitoring and evaluation mechanisms enable data-driven

refinements as markets evolve, creating responsive policy ecosystems capable of addressing emerging challenges, while maintaining alignment with sustainable energy transition objectives.

This comprehensive framework addresses both economic incentives and broader socio-technical systems, recognizing that an effective energy transition policy must account for the complex interplay of factors influencing household adoption decisions within Bahrain's distinctive subsidized energy market context.

5.3.4 Implementation Challenges and Political Feasibility

While the agent-based model demonstrates the clear superiority of subsidy reform coupled with compensatory CTs, the successful real-world implementation of such a policy hinges on navigating significant administrative and political challenges. A discussion of these practical constraints is essential for grounding the model's recommendations.

5.3.4.1 Administrative Feasibility

The three CT designs tested (Universal, Targeted, and Tiered) present a trade-off between targeting accuracy and administrative complexity.

- Universal CT (S1): This approach offers the lowest administrative burden, as it requires minimal data beyond basic household registration for distributing payments. This makes it quick to implement but, as the simulations show, it is the least efficient at directing funds where they are most needed.
- Income-Targeted CT (S2): This design, while effective at stimulating adoption in low-income quintiles, represents the highest administrative

challenge. It would necessitate the creation and maintenance of a robust, verifiable national household income database, a complex and costly undertaking that many countries struggle with. The risk of exclusion errors (failing to reach eligible low-income households, particularly in the informal sector) and inclusion errors (providing benefits to non-eligible households) is high.

- Tiered Household-Size CT (S3): The novel Tiered CT offers a pragmatic middle ground. By linking compensation to more easily verifiable data—such as household size and historical electricity consumption data from utility records—it reduces the administrative burden compared to strict income targeting while still achieving a high degree of distributional equity. This "coupled" design represents a more administratively feasible pathway for a data-driven compensation scheme.

5.3.4.2 Political Feasibility and Stakeholder Management

Subsidy reform is inherently politically sensitive. In the Bahraini context, where subsidized electricity is often viewed as part of the social contract, any reform would likely face resistance from various stakeholders. A successful transition would require a carefully managed political strategy, including:

- Clear Communication: A transparent public information campaign is essential to explain the rationale for the reform, the long-term unsustainability of the current subsidy model, and the tangible benefits of the new compensation program. This helps build public trust and preempts misinformation.

- Phased Implementation: A gradual, phased-in approach to tariff adjustments, communicated well in advance, would allow households and the market to adapt, reducing the risk of "bill shock" and widespread public backlash. This aligns with international best practices for successful subsidy reform.
- Stakeholder Engagement: Proactive engagement with key groups, including parliament, business leaders, and civil society, is crucial to building a coalition of support. Highlighting the fiscal benefits (redirecting savings to other public services) and the economic opportunities in the growing renewable energy sector can help secure buy-in from different constituencies.

To summarize the proposed implementation pathway, the following table presents a phased strategic framework separating the recommended policy actions into short, mid, and long-term horizons.

Table 5.1: Phased Policy Implementation Framework for Residential Solar PV Adoption in Bahrain

Timeframe	Policy Action	Rationale and Key Objectives
Short-Term (0-2 Years)	Launch Integrated Financial Incentives & Awareness Campaigns: • Implement the combined VAT reduction and innovative loan package. • Launch targeted information campaigns focusing on the economic	Build Market Infrastructure: • Stimulate initial demand to grow the local installer base and supply chains. • Enhance Public Awareness: Address documented knowledge gaps and build consumer confidence in the technology. • Leverage Social Networks: Use early adopters as 'solar ambassadors' to accelerate peer-to-peer diffusion.

	and environmental benefits of solar PV.	
Mid-Term (2-5 Years)	Introduce Phased Subsidy Reform with Tiered Cash Transfers: • Begin a gradual, pre-announced phase-in of cost-reflective electricity tariffs. • Simultaneously roll out the Tiered Cash Transfer (S3) mechanism to compensate households.	• Correct Market Distortions: Allow the true economic benefits of solar PV to become apparent as electricity prices normalize. • Ensure Social Equity: Protect households, particularly vulnerable ones, from the immediate financial impact of tariff reform. • Maintain Fiscal Viability: Fund the CT program directly from the savings generated by subsidy removal.
Long-Term (5+ Years)	Scale-Up, Monitor, and Adapt: • Fully implement the cost-reflective tariffs. • Continuously monitor the effectiveness of the Tiered CT and adjust parameters based on real-world data. • Integrate residential solar into broader national energy and grid management strategies.	• Achieve Mass Adoption: Drive PV adoption towards the 70%+ levels projected in the simulation. • Adaptive Management: Create a responsive policy ecosystem that can be refined as the market matures. • Sustainable Transition: Solidify the role of distributed residential solar as a core component of Bahrain's long-term, sustainable energy mix.

5.4. Limitations of the Research

While this study fulfills its primary objectives and provides valuable insights for policymakers, several important limitations should be acknowledged. These constraints span data availability, modeling approaches, and implementation considerations, each affecting different aspects of the analysis.

➢ Data and Parameter Constraints:

- Household income distribution relied on simplified assumptions due to limited detailed socioeconomic data for Bahrain, potentially affecting the prediction accuracy.
- Historical solar PV adoption patterns are scarce, necessitating calibration from international experiences that may not fully capture the unique local dynamics and cultural factors specific to Bahrain's context.

➢ Model Structure Constraints:

- A key methodological limitation is the model's use of a simplified random graph to represent the social network. This abstraction captures generalized peer effects but does not reflect the complex, non-random structures of real-world social ties. This simplification may introduce bias by potentially misrepresenting the true speed and pattern of technology diffusion across different community structures.
- A notable limitation of the model is the treatment of environmental awareness as a static agent attribute. In reality, public awareness and pro-environmental values are likely to evolve dynamically over the 25-year simulation period, influenced by factors such as national education

campaigns, media coverage, and the increasing visibility of renewable energy projects. By assuming a static value, the model may present a conservative forecast that understates a potential driver of adoption in the later years of the simulation. The significance of this assumption is underscored by the sensitivity analysis conducted for this thesis (see Section 4.4.4), which found that the environmental weight parameter (w_env_calculated) was the most influential factor on adoption rates. This highlights the importance of this variable and confirms that its dynamic nature is a key area for future model refinement.

- The model excludes commercial and industrial sectors, potentially missing important adoption interactions.
- Technical constraints, including grid integration limits and storage requirements, were simplified to maintain the computational tractability.

➢ Policy Implementation Considerations:

- The administrative costs and feasibility of different cash transfer mechanisms have not been fully quantified, particularly for complex-targeting schemes.
- The political and economic aspects of subsidy reform, including stakeholder resistance and institutional constraints, were not explicitly modeled.
- Design parameters drawn from international experience, whose applicability to Bahrain's unique context may vary.

➢ Methodological Constraints:

- The Agent-Based Model necessarily simplifies complex household decision-making processes to maintain computational feasibility while capturing essential behavioral dynamics.

Despite these limitations, this study provides valuable policy insights and contributes significantly to the understanding of residential solar PV adoption in subsidized markets. The sensitivity analysis (Section 4.4.4) demonstrated the robustness of the core findings across parameter variations, providing confidence in the main conclusions.

These limitations suggest specific directions for future research, underscoring that the ABM serves as a powerful tool for understanding complex dynamics and comparing policy alternatives under explicit assumptions rather than providing exact numerical forecasts. The findings offer a robust foundation for policy design, while acknowledging areas where additional research could enhance the understanding of renewable energy adoption in Bahrain and similar contexts.

5.5. Directions for Future Research

Building on this research's findings and limitations, several promising avenues emerge for advancing the understanding of solar PV adoption dynamics in subsidized energy markets, particularly within the GCC context. These directions address knowledge gaps through enhanced data collection, methodological improvements, and expanded policy analyses.

➢ Enhanced Data Collection and Analysis:

- Future research should prioritize comprehensive household surveys to gather empirical data on solar PV adoption preferences and decision-

making processes specific to Bahrain's sociocultural context. This would address the current reliance on simplified assumptions and international calibration data, enabling a more accurate representation of the local adoption dynamics.

➢ Model Development and Refinement:

- Future work can build directly on this by refining the model's social network dynamics to improve realism. This includes testing more realistic topologies, such as 'small-world' or 'community-cluster' networks, to better simulate how influence propagates through both close-knit groups and wider social circles. Furthermore, incorporating empirical data from surveys to map actual community and familial ties would allow for a more nuanced simulation of peer effects by differentiating the influence of strong social ties (e.g., family) from weak ones (e.g., acquaintances), thereby enhancing the model's precision.
- Future research could enhance the model's behavioral realism by incorporating a dynamic environmental awareness parameter. This could be implemented as a variable that evolves over time, perhaps linked to the overall adoption rate within the simulation to create a feedback loop (i.e., as more solar panels become visible, general awareness increases). Alternatively, it could be tied to external scenarios representing different intensities of national information campaigns. Modeling awareness dynamically would allow for a more nuanced exploration of how public attitudes might accelerate the energy transition in the long term.

- Expanding the model to include interactions between residential, commercial, and industrial solar PV adoption would capture the important cross-sector dynamics that are currently excluded from the analysis.
- Developing more detailed representations of grid integration challenges and storage requirements would enhance technical realism, while maintaining computational tractability.

➢ Policy Design and Implementation:

- Critical policy research gaps require attention to bridge simulation findings with practical implementation. Examining administrative costs and implementation requirements for different cash transfer mechanisms would provide essential feasibility assessments, particularly for complex targeting schemes that are promising but resource intensive.
- Studying the political economy of subsidy reform in greater detail, including stakeholder analysis and resistance factors, addresses the current limitation of excluding institutional constraints from the modeling framework.
- Exploring innovative financing mechanisms tailored to different household segments and income levels would expand the policy toolkit beyond the current focus on traditional incentives and cash transfer.

These research directions would significantly enhance the understanding of residential solar PV adoption in subsidized markets, while providing actionable insights for policy development. Expanding this analytical framework could facilitate more effective and equitable renewable energy

transitions in Bahrain and in similar GCC contexts, contributing to evidence-based policy design in energy-exporting economies.

5.6. Conclusion

The transition to sustainable energy systems represents a critical challenge for Bahrain's heavily subsidized electricity market, where conventional policy approaches face inherent limitations. This study addresses this challenge by developing a comprehensive ABM that integrates financial mechanisms, social dynamics, and household heterogeneity to evaluate policy effectiveness in promoting residential solar PV adoption.

The analysis revealed fundamental insights into renewable energy adoption within subsidized markets. Most significantly, the research demonstrates that financial incentives alone encounter adoption ceilings of approximately 46% owing to artificially low electricity prices that diminish investment incentives. In contrast, comprehensive subsidy reform coupled with well-designed compensatory mechanisms achieves superior adoption rates of 71-73% while offering pathways to address distributional equity through different compensation designs. This finding challenges conventional approaches that rely primarily on subsidies and tax incentives without addressing underlying market distortions.

Building on these core findings, this study introduces and evaluates a novel tiered CT mechanism. The innovation lies in its "coupled" design, which aligns transfer amounts with household-specific subsidy losses. This approach stands in stark contrast to traditional "decoupled" transfers (e.g., universal or flat-rate targeted grants), which our findings show can produce significant distributional inefficiencies and misleading compensation metrics. The tiered

design, therefore, represents a significant advance in creating a more rational and transparent framework for compensatory policy.

These findings provide actionable guidance for multiple stakeholder groups involved in Bahrain's energy transition. For policymakers, this research provides quantitative evidence supporting comprehensive reform strategies over incremental approaches, enabling evidence-based decisions that navigate the trade-offs between adoption acceleration and social equity. The analysis further demonstrates that a positive net fiscal impact is achievable through the strategic allocation of subsidy savings—specifically by capping transfers as a fraction of savings—addressing primary concerns regarding reform feasibility.

Private-sector stakeholders benefit from an enhanced understanding of market development dynamics and consumer adoption patterns under different policy scenarios. This research illuminates how policy design affects market penetration rates and customer segments, supporting strategic planning for renewable energy investments and service provision.

This study contributes to sustainable development objectives by demonstrating pathways for transitioning from subsidized conventional energy systems to market-based renewable alternatives. The methodological framework advances the understanding of complex policy interactions, whereas the empirical findings support Bahrain's national renewable energy targets through evidence-based implementation strategies.

This significance extends beyond Bahrain's borders, as the analytical framework and policy insights provide a valuable model for other GCC countries facing comparable challenges in subsidized electricity markets. The

research methodology provides a replicable template for conducting ex-ante policy assessments that account for heterogeneous population responses and emergent system dynamics, thereby addressing critical gaps in traditional aggregate modeling approaches.

By implementing the evidence-based recommendations developed through this research, Bahrain can achieve substantial progress towards its renewable energy goals. It can establish a regional model for an effective energy transition policy that carefully navigates the complex trade-offs between economic efficiency, social equity, and environmental sustainability. This integrated approach positions Bahrain to lead regional efforts in developing innovative policy solutions for sustainable energy transitions within resource-rich economies.

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Appendix A

Model Parameters and Their Units/Periods

Table A.1: Key monetary parameters, units, and how they are applied in the ABM model.

Parameter	**Example Value**	**Unit**	**Period**	**Description**
cost-per-wp	663.2	USD/Wp	One-time	Initial PV system cost per watt-peak (installed)
annual-income	Varies	USD/year	Per year	Household income
pv-system-cost	Varies	USD	One-time	Cost of installed PV system (per household)
final-upfront-cost	Varies	USD	One-time	Out-of-pocket cost after subsidies/loans (per household)
vat-savings	Varies	USD	One-time	VAT reduction benefit (if policy enabled)
loan-financed-amount	Varies	USD	One-time	Amount financed through loan
monthly-loan-repayment	Varies	USD/month	Per month	Monthly loan repayment
annual-loan-repayment	Varies	USD/year	Per year	Total annual loan repayment

monthly-cleaning-cost	3.32	USD/month	Per month	PV maintenance (cleaning) cost
total-pv-maintenance-cost	Varies	USD/year	Per year	Total annual maintenance cost (cleaning, inverter)
annual-bill-before-solar	Varies	USD/year	Per year	Electricity bill before solar adoption
annual-bill-after-solar	Varies	USD/year	Per year	Electricity bill after solar adoption
annual-savings	Varies	USD/year	Per year	Savings from PV adoption (bills + transfers)
cash-transfer	0–Varies	USD/year	Per year	Cash transfer received by household
subsidy-loss	0–Varies	USD/year	Per year	Loss from subsidy removal in new-tariff scenario
T_new	0.077	USD/kWh	Ongoing	Flat unsubsidized tariff (applied to consumption)

tier1-rate	0.008	USD/kWh	Ongoing	Subsidized tier 1 electricity rate
tier2-rate	0.024	USD/kWh	Ongoing	Subsidized tier 2 electricity rate
tier3-rate	0.042	USD/kWh	Ongoing	Subsidized tier 3 electricity rate
base-universal-amount	1000	USD/year	Per year	Universal transfer (per household, per year)
per-person-universal	300	USD/person/year	Per year	Universal transfer (per person, per year)
base-targeted-amount	400	USD/year	Per year	Targeted transfer (per household, per year)
per-person-targeted	150	USD/person/year	Per year	Targeted transfer (per person, per year)
fixed-amount	1000	USD/year	Per year	Fixed transfer in targeted policy
min-income-threshold	20000	USD/year	Per year	Min income for tiered transfer

max-income-threshold	60000	USD/year	Per year	Max income for tiered transfer
income-cutoff	30000	USD/year	Per year	Income cutoff for targeted transfer
household-size-factor	0.27	Unitless	-	Adjustment for extra transfer for households >4 members
transfer-term-years	25	Years	-	Duration for present value of transfer calculation

Note: "Per year" means the value is annual; "Per month" is monthly; "One-time" is only at installation.

Table A.2: Key non-monetary parameters, units, and how they are applied in the ABM model.

Parameter	**Example Value**	**Unit / Range**	**Period**	**Description**
start-year	2025	Year	One-time	Simulation start year
final-year	2050	Year	One-time	Simulation end year
current-month	1	1–12	Each cycle	Current simulation month

annual_yield_per_kwp	1685	kWh/kWp/year	Per year	PV panel yearly yield per kWp installed
panel-degradation-rate	0.005	Fraction/year	Per year	PV panel annual degradation rate
adoption_threshold	0.68	0–1	One-time or scenario	Default utility threshold for PV adoption decision
max-payback-period	20	Years	Scenario	Maximum payback period considered for adoption
min-payback-period	1	Years	Scenario	Minimum payback period considered
link-creation-radius	10	Model units	Scenario	Radius for creating social links
max-new-links-per-cycle	4	Number	Per cycle	Maximum new social links per cycle
savings-threshold	54	USD/year	Scenario	Minimum annual savings to influence neighbors (for links)
adoption-logistic-k	6.5	Slope	Scenario	Steepness of logistic adoption curve
w_inc	0.15	0–1	Scenario	Weight of income utility in adoption decision

w_pay	0.45	0–1	Scenario	Weight of payback utility in adoption decision
w_soc	0.15	0–1	Scenario	Weight of social utility in adoption decision
w_env_calculated	0.25	0–1	Scenario	Weight of environment utility in adoption decision
k_inc	12	Slope	Scenario	Slope for income utility logistic function
k_env	12	Slope	Scenario	Slope for environment utility logistic function
k_soc	12	Slope	Scenario	Slope for social utility logistic function
mid_env	0.45	0–1	Scenario	Midpoint for environment utility logistic function
mid_soc	0.35	0–1	Scenario	Midpoint for social utility logistic function
alpha_sc	0.6	0–1	Scenario	Weight of social capital in social utility

alpha_si	0.2	0–1	Scenario	Weight of social influence in social utility
alpha_ana	0.2	0–1	Scenario	Weight of neighbor awareness in social utility
neighbor-adoption-awareness-coeff	0.01	Fraction	Scenario	Coefficient for neighbor adoption impact on awareness
discount-rate	0.02	Fraction	Scenario	Discount rate for present value calculations
env-awareness	0–1	-	Per agent	Environmental awareness score of household
payback-period	1–20	Years	Per agent	Calculated PV system payback period
rate-of-return	Varies	%	Per agent	Internal rate of return for PV investment
adopted-solar?	true / false	Boolean	Per agent	Has the household adopted solar PV
awareness-level	0–0.5	-	Per agent	Household's awareness of solar benefits
risk-tolerance	0.05–0.9	-	Per agent	Household risk aversion

individual-threshold	0.45–0.95	-	Per agent	Household-specific adoption utility threshold
canInstall?	true / false	Boolean	Per agent	Can the household physically install PV
pv-capacity	e.g., 2.5	kWp	Per agent	Installed PV capacity for household
social-influence	0–1	-	Per agent	Social influence score (dynamic, from network)
social-capital	0–1	-	Per agent	Social capital score (dynamic, from network)
family-members	e.g., 2–10	Count	Per agent	Number of household members
income_quintile	1–5	-	Per agent	Income quintile of the household

Note: All variables are defined as in the ABM code. Scenario values may vary by simulation experiment.

Appendix B

Sensitivity Analysis Results

This section presents sensitivity analysis results, showing how key output metrics respond to variations in input parameters across scenarios S_0-S_3.

Table B.1: Sensitivity Analysis Summary (Scenarios S_0-S_3)

Parameter Varied	**Scenario**	**Variation Tested**	**Final Adoption Rate (%)**
Adoption Threshold	S_0 Baseline	0.600	52.660
Adoption Threshold	S_0 Baseline	0.650	52.780
Adoption Threshold	S_0 Baseline	0.700	53.160
Adoption Threshold	S_0 Baseline	0.750	52.660
Adoption Threshold	S_0 Baseline	0.800	54.180
Adoption Threshold	S_1 Universal	0.600	66.460
Adoption Threshold	S_1 Universal	0.650	64.560
Adoption Threshold	S_1 Universal	0.700	64.940
Adoption Threshold	S_1 Universal	0.750	66.200
Adoption Threshold	S_1 Universal	0.800	62.660
Adoption Threshold	S_2 Targeted	0.600	67.090
Adoption Threshold	S_2 Targeted	0.650	65.820
Adoption Threshold	S_2 Targeted	0.700	64.050
Adoption Threshold	S_2 Targeted	0.750	64.940
Adoption Threshold	S_2 Targeted	0.800	67.470
Adoption Threshold	S_3 Tiered	0.600	64.680
Adoption Threshold	S_3 Tiered	0.650	64.810
Adoption Threshold	S_3 Tiered	0.700	64.430
Adoption Threshold	S_3 Tiered	0.750	64.180

Adoption Threshold	S_3 Tiered	0.800	64.180
Adoption-Logistic-K	S_0 Baseline	3	49.870
Adoption-Logistic-K	S_0 Baseline	4	54.180
Adoption-Logistic-K	S_0 Baseline	5	52.530
Adoption-Logistic-K	S_0 Baseline	7	50.630
Adoption-Logistic-K	S_0 Baseline	9	53.540
Adoption-Logistic-K	S_1 Universal	3	62.530
Adoption-Logistic-K	S_1 Universal	4	63.670
Adoption-Logistic-K	S_1 Universal	5	64.300
Adoption-Logistic-K	S_1 Universal	7	64.050
Adoption-Logistic-K	S_1 Universal	9	64.810
Adoption-Logistic-K	S_2 Targeted	3	65.950
Adoption-Logistic-K	S_2 Targeted	4	65.950
Adoption-Logistic-K	S_2 Targeted	5	66.960
Adoption-Logistic-K	S_2 Targeted	7	63.160
Adoption-Logistic-K	S_2 Targeted	9	66.960
Adoption-Logistic-K	S_3 Tiered	3	64.680
Adoption-Logistic-K	S_3 Tiered	4	66.080
Adoption-Logistic-K	S_3 Tiered	5	63.920
Adoption-Logistic-K	S_3 Tiered	7	63.160
Adoption-Logistic-K	S_3 Tiered	9	63.800
K Soc	S_1 Universal	10	65.190
K Soc	S_1 Universal	12	63.160
K Soc	S_1 Universal	14	64.050
K Soc	S_1 Universal	16	65.440
K Soc	S_2 Targeted	10	65.820
K Soc	S_2 Targeted	12	65.190
K Soc	S_2 Targeted	14	65.320
K Soc	S_2 Targeted	16	66.200
K Soc	S_3 Tiered	10	63.290

K Soc	S_3 Tiered	12	64.430
K Soc	S_3 Tiered	14	65.570
K Soc	S_3 Tiered	16	63.800
Mid Soc	S_1 Universal	0.300	65.950
Mid Soc	S_1 Universal	0.350	61.650
Mid Soc	S_1 Universal	0.380	63.670
Mid Soc	S_1 Universal	0.400	62.660
Mid Soc	S_2 Targeted	0.300	64.560
Mid Soc	S_2 Targeted	0.350	64.940
Mid Soc	S_2 Targeted	0.380	67.090
Mid Soc	S_2 Targeted	0.400	64.810
Mid Soc	S_3 Tiered	0.300	64.810
Mid Soc	S_3 Tiered	0.350	64.560
Mid Soc	S_3 Tiered	0.380	64.680
Mid Soc	S_3 Tiered	0.400	64.430
Neighbor-Adoption-Awareness-Coeff	S_1 Universal	0.004	61.900
Neighbor-Adoption-Awareness-Coeff	S_1 Universal	0.005	65.190
Neighbor-Adoption-Awareness-Coeff	S_1 Universal	0.075	65.950
Neighbor-Adoption-Awareness-Coeff	S_1 Universal	0.110	65.060
Neighbor-Adoption-Awareness-Coeff	S_2 Targeted	0.004	65.570
Neighbor-Adoption-Awareness-Coeff	S_2 Targeted	0.005	65.320
Neighbor-Adoption-Awareness-Coeff	S_2 Targeted	0.075	66.710

Neighbor-Adoption-Awareness-Coeff	S_2 Targeted	0.110	63.540
Neighbor-Adoption-Awareness-Coeff	S_3 Tiered	0.004	64.940
Neighbor-Adoption-Awareness-Coeff	S_3 Tiered	0.005	65.700
Neighbor-Adoption-Awareness-Coeff	S_3 Tiered	0.075	62.780
Neighbor-Adoption-Awareness-Coeff	S_3 Tiered	0.110	65.440
W Env Calculated	S_1 Universal	0.200	65.700
W Env Calculated	S_1 Universal	0.250	63.040
W Env Calculated	S_1 Universal	0.300	64.680
W Env Calculated	S_2 Targeted	0.200	62.410
W Env Calculated	S_2 Targeted	0.250	65.190
W Env Calculated	S_2 Targeted	0.300	64.050
W Env Calculated	S_3 Tiered	0.200	64.940
W Env Calculated	S_3 Tiered	0.250	64.300
W Env Calculated	S_3 Tiered	0.300	65.060
W Pay	S_1 Universal	0.300	63.800
W Pay	S_1 Universal	0.350	63.040
W Pay	S_1 Universal	0.400	64.430
W Pay	S_1 Universal	0.420	65.570
W Pay	S_2 Targeted	0.300	66.080
W Pay	S_2 Targeted	0.350	65.190
W Pay	S_2 Targeted	0.400	62.780
W Pay	S_2 Targeted	0.420	65.570
W Pay	S_3 Tiered	0.300	65.320
W Pay	S_3 Tiered	0.350	64.430
W Pay	S_3 Tiered	0.400	62.910

W Pay	S_3 Tiered	0.420	63.800
W Soc	S_1 Universal	0.090	64.680
W Soc	S_1 Universal	0.100	63.540
W Soc	S_1 Universal	0.110	63.160
W Soc	S_1 Universal	0.120	62.660
W Soc	S_2 Targeted	0.090	65.060
W Soc	S_2 Targeted	0.100	65.570
W Soc	S_2 Targeted	0.110	64.560
W Soc	S_2 Targeted	0.120	63.800
W Soc	S_3 Tiered	0.090	66.460
W Soc	S_3 Tiered	0.100	63.290
W Soc	S_3 Tiered	0.110	63.160
W Soc	S_3 Tiered	0.120	65.820
Yearly Decrement	S_1 Universal	0.015	64.810
Yearly Decrement	S_1 Universal	0.022	62.780
Yearly Decrement	S_1 Universal	0.035	62.530
Yearly Decrement	S_2 Targeted	0.015	64.560
Yearly Decrement	S_2 Targeted	0.022	65.190
Yearly Decrement	S_2 Targeted	0.035	63.920
Yearly Decrement	S_3 Tiered	0.015	62.030
Yearly Decrement	S_3 Tiered	0.022	67.340
Yearly Decrement	S_3 Tiered	0.035	65.820

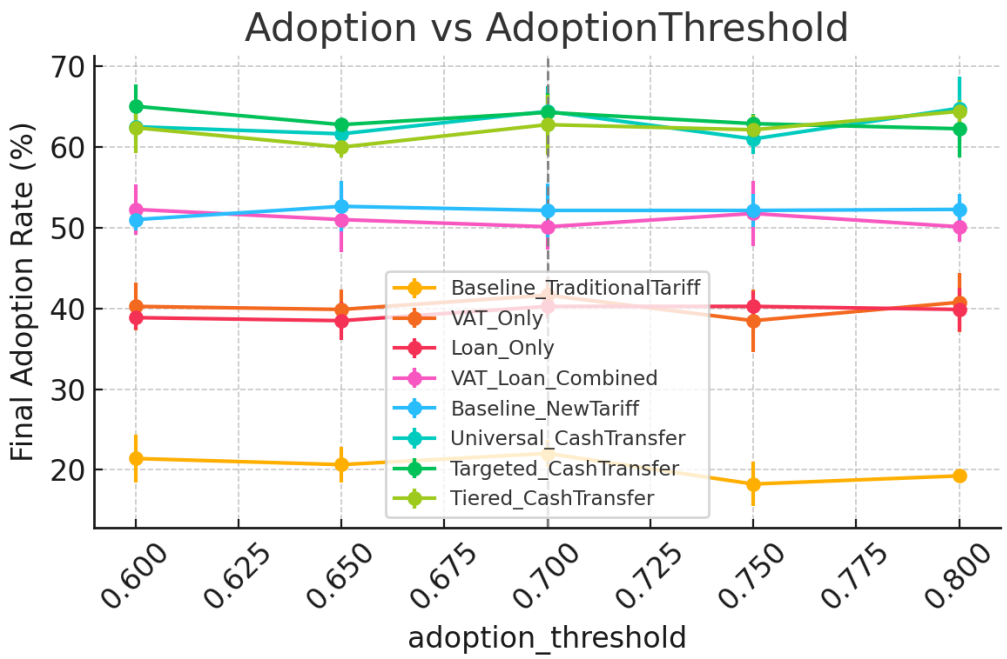


Figure B.1: Sensitivity of Final Adoption Rate (%) to the Adoption Threshold (adoption_threshold) across eight policy scenarios.

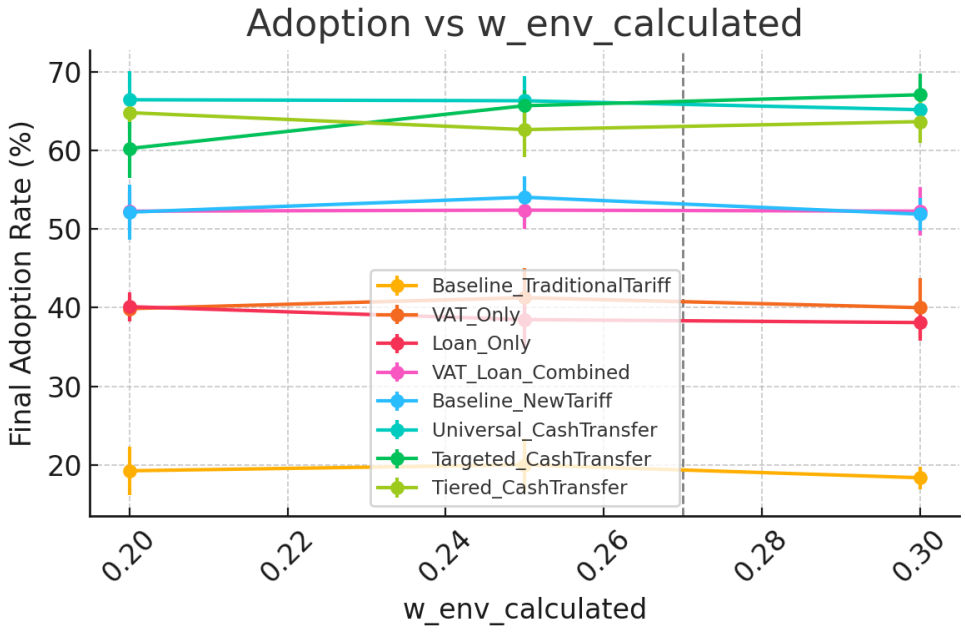


Figure B.2: Sensitivity of Final Adoption Rate (%) to the Environmental Weight (w_env_calculated) across eight policy scenarios

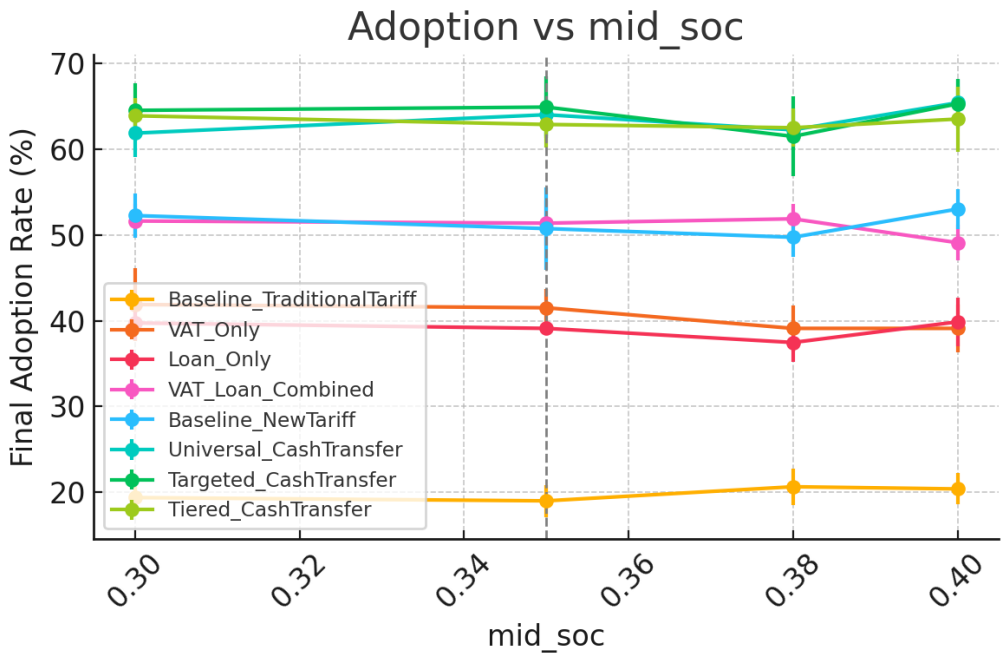


Figure B.3: Sensitivity of Final Adoption Rate (%) to the Social Midpoint (mid_soc) across eight policy scenarios

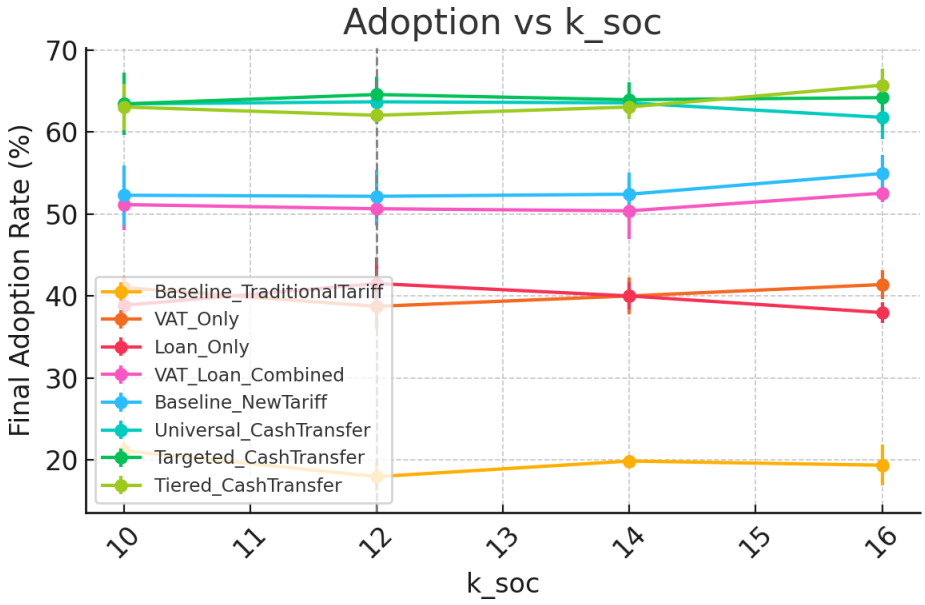


Figure B.4: Sensitivity of Final Adoption Rate (%) to the Social Steepness (k_soc) across eight policy scenarios

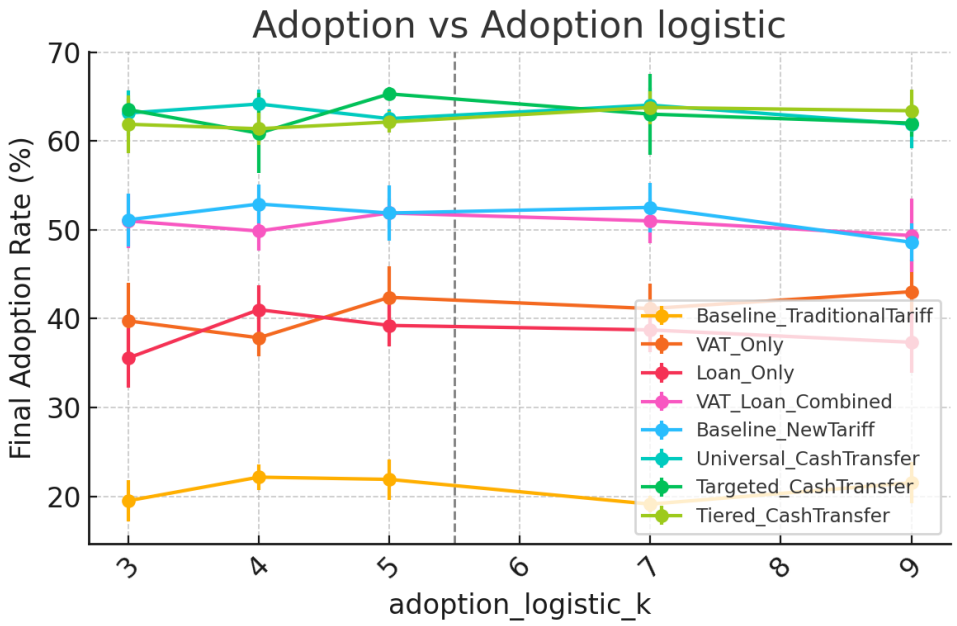


Figure B.5: Sensitivity of Final Adoption Rate (%) to the Logistic Steepness (adoption_logistic_k) across eight policy scenarios

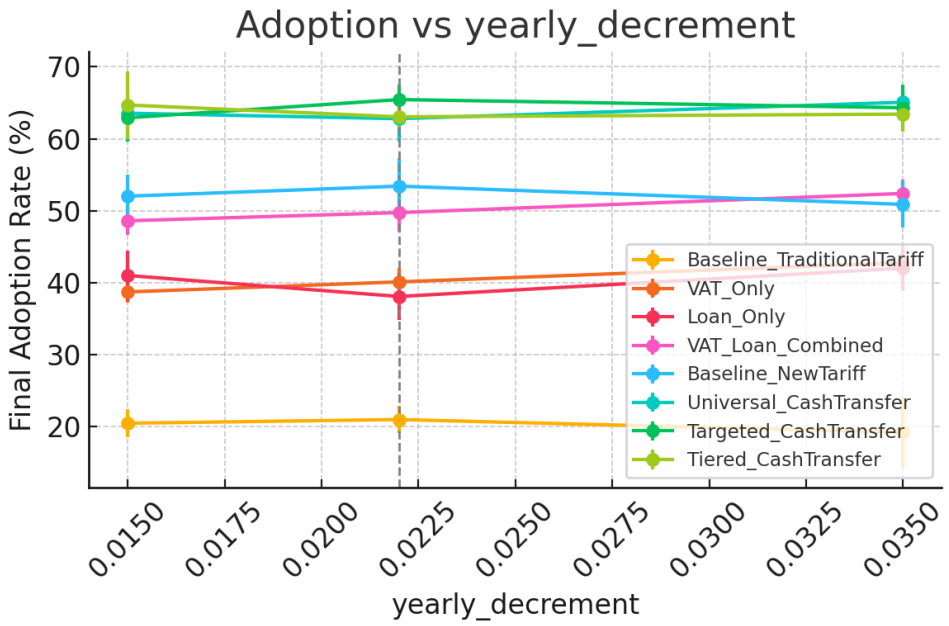


Figure B.6: Sensitivity of Final Adoption Rate (%) to the Annual Cost-Decline Rate (yearly_decrement) across eight policy scenarios

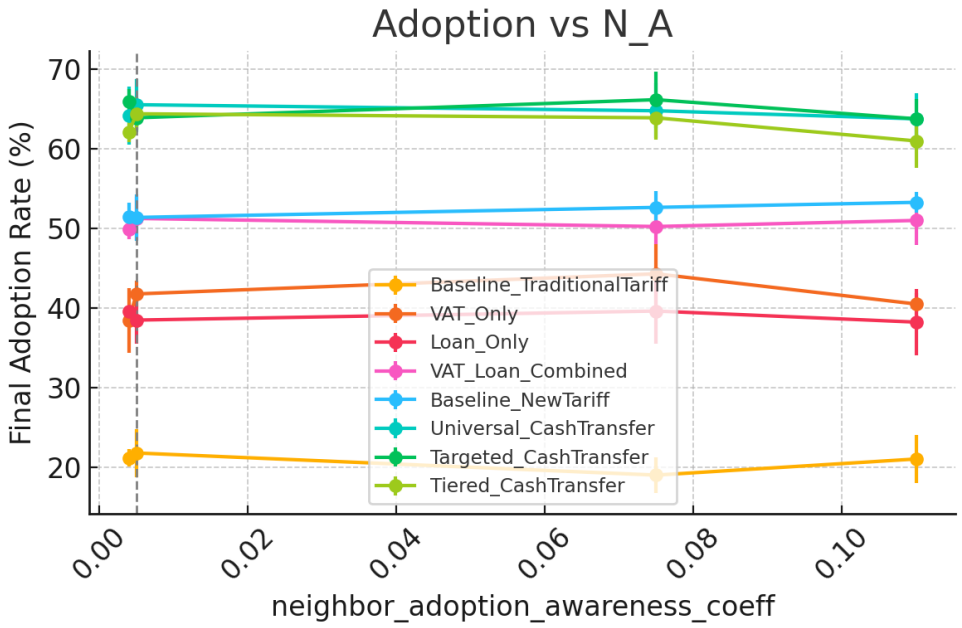


Figure B.7: Sensitivity of Final Adoption Rate (%) to the Neighbor-Adoption Awareness Coefficient (neighbor_adoption_awareness_coeff) across eight policy scenarios

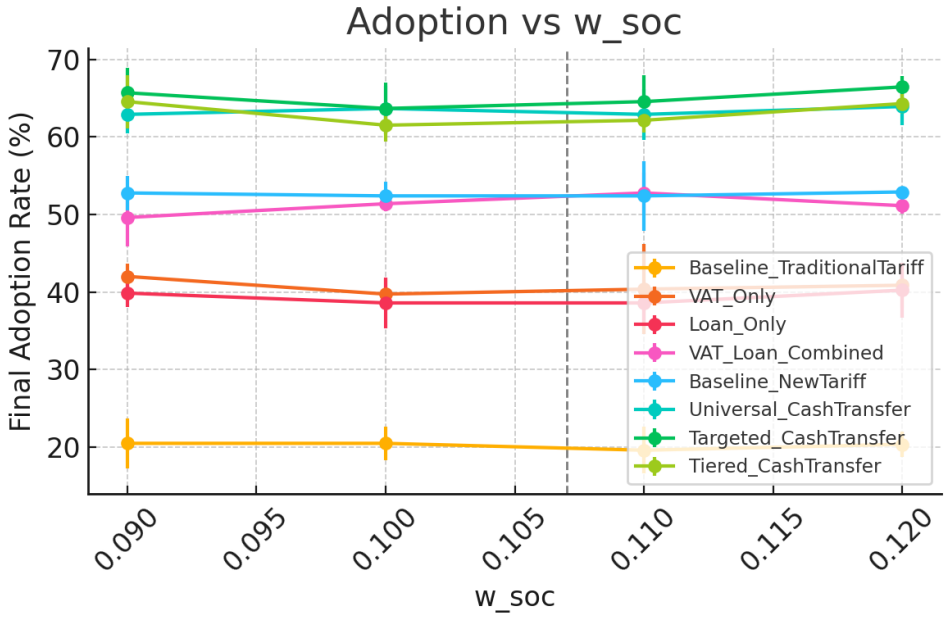


Figure B.8: Sensitivity of Final Adoption Rate (%) to the Weight on Social Preference (w_soc) across eight policy scenarios

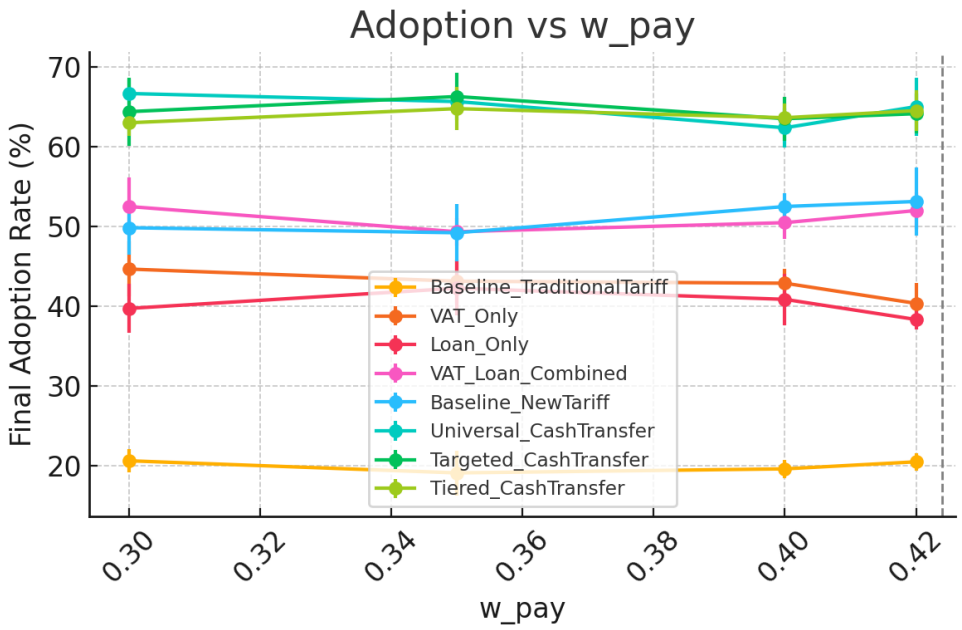


Figure B.9: Sensitivity of Final Adoption Rate (%) to the Weight on Payback (w_pay) across eight policy scenarios

ملخص الدراسة

يُعد تبني الألواح الكهروضوئية الشمسية السكنية أمراً حيوياً للانتقال نحو الطاقة المستدامة، لكنه يواجه عوائق كبيرة في أسواق الطاقة المدعومة مثل البحرين. تستقصي هذه أطروحة الدكتوراه مسارات السياسات لتحسين انتشار الألواح الكهروضوئية السكنية، وذلك من خلال تقييم: (١) الحوافز المالية (تخفيض ضريبة القيمة المضافة، القروض المبتكرة) ضمن نظام دعم الكهرباء الحالي، و(٢) إصلاح دعم الكهرباء مقترناً بآليات التحويلات النقدية التعويضية (الشاملة، المستهدفة، ونموذج متدرج مبتكر). تعالج هذه الدراسة التحدي الأساسي المتمثل في تحفيز تبني الألواح الكهروضوئية في أسواق الكهرباء ذات الدعم المرتفع.

تم استخدام نموذج محاكاة قائم على العوامل (ABM) مستند إلى بيانات تجريبية لمحاكاة قرارات التبني المتباينة للأسر البحرينية (٢٠٢٥–٢٠٥٠)، مع دمج العقلانية الاقتصادية، والعوامل السلوكية (نظرية انتشار الابتكار، الاقتصاد السلوكي)، وتأثيرات الشبكات الاجتماعية (نظرية رأس المال الاجتماعي). قيّم النموذج تأثيرات السياسات على انتشار الألواح الكهروضوئية، واقتصاديات الأسر، والعدالة التوزيعية، والتوازن المالي، والفوائد البيئية.

تكشف النتائج الرئيسية أنه بينما تعزز الحوافز المالية المجمعة بشكل كبير تبني الألواح الكهروضوئية ليصل الى (٤٥.٦١٪) مقارنة بمعدل التبني من دون أي حوافز مالية (٢٣.٧٣٪)، إلا أن سقفاً للتبني يستمر بسبب الدعم القائم. ثبُت أن إصلاح الدعم مقترناً بالتحويلات النقدية التعويضية أكثر فعالية لتحقيق تبنٍ أعلى (٧١–٧٣٪) وتحسين الجدوى المالية للألواح الكهروضوئية (فترات استرداد التكلفة ١.٥٨–١.٨١ سنة). ومع ذلك، يؤدي إلغاء الدعم وحده إلى تبنٍ غير عادل. حقق نموذج التحويلات النقدية المتدرج المبتكر بنسبة تبني (٧٠.٩٩٪) التوزيع الأكثر إنصافاً عبر شرائح الدخل الخُمسية والتعويض الفعال، مع ضمان الاستدامة المالية طويلة الأمد.

تساهم هذه الدراسة بتطبيق نموذج المحاكاة القائم على العوامل في تصميم سياسات الطاقة في سياق دول مجلس التعاون الخليجي ذات الدعم المرتفع، ومقارنة نماذج سياسات متباينة، وتقييم آلية مبتكرة للتحويلات النقدية. تؤكد على ضرورة اقتران إصلاح الدعم بتعويض عادل وفعال. يبرز نموذج التحويلات النقدية المتدرج كسياسة واعدة للبحرين، توازن بين تسريع التبني، والعدالة التوزيعية، والمسؤولية المالية. تقدم الدراسة رؤى مستندة إلى الأدلة للبحرين والدول المماثلة الساعية لتسريع انتقالات الطاقة المستدامة.

جامعة البحرين

كلية إدارة الأعمال

تحليل قائم على البيانات لتأثير سياسات الطاقة المتجددة على سوق الطاقة البحريني

أطروحة مقدمة كجزء من متطلبات الحصول على درجة دكتوراه الفلسفة في تحليلات الأعمال

إعداد

وائل محمد عطية محمد أبومسّلم

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د. عبدالله العباسي

مركز البحرين للدراسات الاستراتيجية والدولية والطاقة

مملكة البحرين

يونيو 2025