MASTER

Assessing the impact of natural gas alternatives and energy renovation options on the households of a neighbourhood

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ASSESSING THE IMPACT OF NATURAL GAS ALTERNATIVES AND ENERGY RENOVATION OPTIONS ON THE HOUSEHOLDS OF A NEIGHBOURHOOD

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Assessing the Impact of Natural Gas Alternatives and Energy Renovation Options on the Households of a Neighbourhood

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ABSTRACT

The government of the Netherlands is fighting climate change by focusing on CO_2 emission reduction. To achieve CO_2 reduction targets and to increase energy security, the Dutch government is promoting energy conservation in the residential sector by providing 'low-interest loans' for energy efficiency renovations and subsidies for adopting sustainable heating alternatives. Despite, low-interest loans and subsidies, the adoption of energy renovations and the sustainable heating alternative is low among Dutch households.

Further, due to increasing earthquakes in the Groningen gas, the Dutch government has decided to become natural gas-free by 2050. In line with the goals of the Dutch government, the Metropolitan Region of Amsterdam (MRA) is planning to become natural gas-free by 2035. Along the lines, of becoming free from natural gas, the MRA has plans to expand its district heating network (DHN). However, the MRA advises its local municipal governments to investigate the attractiveness of DHN in presence of other natural gas alternatives (NGA) to households, before implementing DHN (Amsterdam Metropolitan Area, 2016). However, assessing desirability at a neighbourhood level is dependent on the residents, because residents of each household have varying interests and preferences.

Considering the above-mentioned initiatives and their suggested developments, this study aims to create a strategy for understanding the implications of the energy transition at neighbourhood level from the perspective of 'homeowners'. The research focuses on the homeowner because owner-occupied houses account for 55.8% of the housing stock and the renovation rates are low among the housing stock. Thus, by investigating the impact of energy transition from a homeowner's perspective, it is possible to identify potential opportunities for a homeowner to move forward during the energy transition.

In order to assess the impact on homeowners, a techno-economic study is performed to assess the attractiveness of various energy renovation options and natural gas alternatives for households. For techno-economic assessment, building energy simulation models are created in IESVE using building information obtained from multiple data sources and the occupant behaviour information. Later the simulation models are subjected to changes imparted by renovation measures and then natural gas alternatives. Further, the outputs of energy simulation are combined with the information from grey literature for analysing the techno-economic impact.

A techno-economic analysis is insufficient for explaining the adoption of an NGA by the neighbourhood, because switching to an NGA requires significant infrastructural change; change in actors and their roles, change in governance, etc. Thus, the study is complemented with socio-technical scenarios, explaining the NGA adoption process. In the sociotechnical scenario study, various opportunities, barriers, key trends, activities, and actors their enable the adoption of each natural gas alternative is discussed. The sociotechnical scenario study uses Multilevel perspective for narrating the transition.

The results of the techno-economic assessment show that heat pump is a financially attractive natural-gas alternative. For district heating or green gas to become financially attractive, the households are required to renovate the building and achieve significant energy emission reductions. As a result of significant energy reductions, the households are able spend less on fuels. The reduced fuel expenditure leads to lower overall expenditure for both district heating and green gas.

Maximum CO_2 emission savings are achieved in order by 1. *district heating*, 2.gas boiler with *green gas* and 3. *air source heat pump running on electricity*. To further reduce CO_2 emissions, it required that older buildings (or poorly insulated) are renovated. Further, it important that poorly insulated buildings are renovated first, rather than directly switching to natural gas alternatives. This, option enables the household to save money on energy expenditures and also achieve high CO_2 emission savings. It is observed that delaying renovation (further towards 2035) is relatively undesirable for reducing CO_2 emissions, than delaying the adoption of natural gas alternatives (further towards 2035). Thus, it is suggested that poorly insulated buildings are renovated first, rather than directly adopting NGA.

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1 INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

1.1.1 Climate Change

The Earth has undergone massive changes in the last two hundred years, the global GDP has increased by 10700% (Roser, 2019). This change is primarily driven by the industrial revolution and technological advancements. However, during this period production methods depended heavily on fossil fuels and this dependence has resulted in global warming (Ritchie and Roser, 2019).

CO_2 is a direct product of fossil fuel combustion and a major contributor to global warming. It creates a greenhouse effect on a global scale by absorbing and emitting the thermal radiation coming from the sun (Ritchie and Roser, 2019). However, CO_2 levels in the atmosphere determine the habitability of various species of flora and fauna. If the earth is to become warmer by 5°C, then a large number of plant and animal species are expected to go extinct (Westman *et al.*, 1990).

Climate change from global warming has become a key issue to address for the governments and organizations around the world. In the Netherlands, climate change is likely to cause heatwaves, heavy rainfalls, droughts, and the spread of new diseases (Ligtvoet *et al.*, 2015). However, the severity of the consequences is dependent on the rate at which the CO_2 is released into the atmosphere. According to climate change experts, by reaching and sustaining 'net-zero global anthropogenic CO_2 emission', it is possible to halt global warming on the multi-decadal time scale (Allen *et al.*, 2018). Consequently, many governments and especially the Dutch government is actively trying to combat climate change.

1.1.2 Earthquakes in Groningen

The largest natural gas field of Europe is in the province of Groningen, was first discovered in 1959. The gas field accounts for 50% of natural gas production in the Netherlands (Roggenkamp and Hammer, 2004). Since the late 1990s, the province has started to experience gas-induced earthquakes and their frequency has only increased in recent times (DutchNews.nl, 2018a). It is predicted that in 2025, there would be at least one earthquake event per day which is less than or equal to magnitude-5 on the Richter scale (van Putten, van Putten and van Putten, 2016).In 2016, the Dutch minister of the Department of Economic Affairs has limited natural gas production in Groningen to 27 bn Sm^3/year. After an earthquake measuring 3.2 on the Richter scale in January 2018, the government has announced to bring down production to 12 bn Sm^3/year (DutchNews.nl, 2018b). Further, the national government plans to stop extracting gas altogether in Groningen by 2030 (DutchNews.nl, 2018a).

1.1.3 Energy Security

Energy security is also important for the government of the Netherlands, as the present economy is largely dependent on fossil fuels. Fossil fuels account for 92% of primary energy supply in 2016 (CBS Statline, 2019). Of which, the Netherlands has imported 53% of its fossil fuels from other countries and the remaining 47% is indigenous production. The government considers these imports as concern for energy security, because of the geopolitical conflicts like the ones happened in Ukraine and the Middle east (Ministry of Economic Affairs, 2016).

On the other hand, the government is facing another problem concerning the dwindling of natural gas resources, within the country. Though the natural gas obtained from its internal reserves account for 44% of primary energy supply, the reserves are dwindling. End of 2017, the natural gas reserves were only 45% of 1990's level (CBS StatLine, 2018). By continuing with the current trend for discovery and extraction, the gas reserves might last for another 16 years or until 2033 (CBS Statline, 2019). Thus, it becomes important for the government to secure energy supply even before 2050.

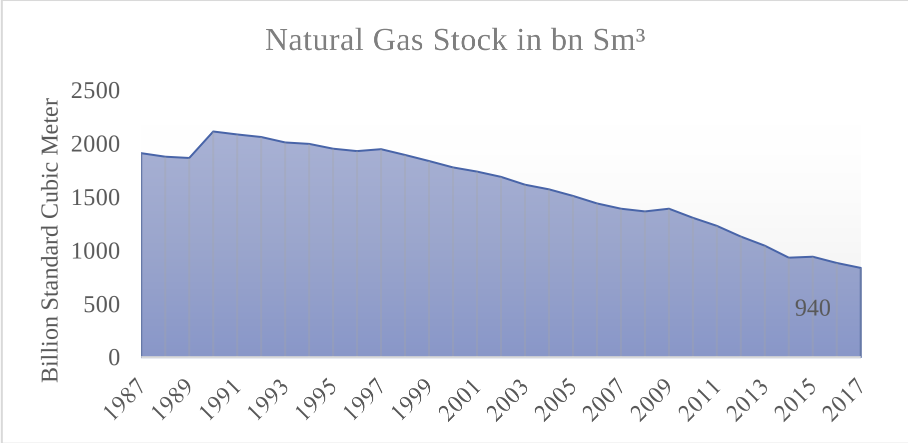

Figure 1 Natural Gas Reserves (CBS StatLine, 2018)

1.1.4 Energy Policy of the Built Environment

To prevent climate change, the government of Netherlands is undertaking many actions to reduce greenhouse gas emissions by 49% in 2030, and by 95% in 2050, compared to 1990 levels (Government of the Netherlands, 2019b). The sectors that are contributing to the greenhouse gas reductions are electricity, industry, built environment, traffic and transport, and agriculture. The focus of the study is built-environment because it consumes 30% of the total fossil fuels used in the Netherlands. Thus, reducing greenhouse gas emissions in this sector is important for securing long term sustainability of the Netherlands energy economy.

To achieve emission reductions and to increase energy security, the Dutch government is promoting energy conservation in the residential sector for reducing energy demand. According to (Government of the Netherlands, 2019b) approximately 1.5 million households are required to become energy efficient. In this regard, the government is providing 'low-interest loans' for renovation the buildings and subsidies for switching to sustainable heating alternatives (Ministry of Economic Affairs, 2017) (Government of the Netherlands, 2019a).

In the context of dwindling natural gas reserves and increasing earthquakes in the Groningen region, the national government has set to become natural gas-free by 2050 (RVO, no date)(Exel, Geus and Zeinstra, 2017). It is expected that 'Natural gas' will support the residential sector until 2030; later it is expected to undergo a rapid phaseout between 2030 and 2050 (Honoré, 2017). In line with the goals of the Dutch government, the Metropolitan Region of Amsterdam (MRA) has an ambitious goal to become natural-gas free by 2035 and free from fossil fuel by 2040 (Amsterdam Metropolitan Area, 2016).

Note: In this thesis, the focus with the built environment is restricted to the residential sector and further to the owner-occupied houses. The study focuses on owner-occupied houses because it accounts for 48% of residential buildings in the MRA and 55.8% in the Netherlands (Filippidou, Nieboer and Visscher, 2017)(Klimaatmonitor, 2020). Also, the owner-occupied housing sector has low renovation rates in comparison to social housing sector; and it challenging to implement renovation plans on a large scale because the sector does not have a central decision-making body (Ebrahimigharehbaghi, Filippidou, *et al.*, 2019).

1.2 PROBLEM DEFINITION

In pursuit of 'Natural gas-free (aardgasvrije wijken) – ambition', the MRA is planning to expand its 'District Heating' network (Amsterdam Metropolitan Area, 2016). Though 'District Heating' is a cost-efficient means for freeing the households from natural gas and to reduce emissions, it leads to natural monopoly and limits the household from choosing an energy supplier (Bouw, 2016). Thus in some cases, homeowners are concerned to adopt district heating (Bouw, 2016). As a result, before the local government decides to implement district heating, it has to investigate the attractiveness of other natural-gas alternatives to households.

For this transition to occur, municipalities within the MRA are expected to identify the most efficient and desirable heating method for each neighbourhood within MRA (Amsterdam Metropolitan Area, 2016). Assessing desirability at a neighbourhood level is dependent on the households and the individuals living in the house because each household has varying energy needs and each individual has varying motivations for changing (Jong, 2019)(Gröger, Schmid and Bruckner, 2011). For example, a single-adult household's energy needs are minimal, compared to a single-family household.

Since the households are also expected to become energy-efficient, it is necessary to identify the impact of energy renovations on the final attractiveness. Thus, the attractiveness assessment must evaluate the combined impact of natural gas alternatives and energy renovations (improving building insulation).

Note: The alternative to natural gas for heating purposes is limited to district heat, heat pump and green-gas, based on the three primary alternatives suggested by Amsterdam Metropolitan Area (2016). Also in this study, heating refers to low-temperature heat encompassing space heating and domestic hot water needs.

1.3 RESEARCH QUESTION

Considering the above-mentioned policy initiatives and the emphasis of this study, the study aims to understand the implications of energy transition options (natural gas-free options and energy conservation) on a single neighbourhood within the MRA from the perspective of homeowners.

To achieve emission reduction targets, it is necessary to find attractive options for a homeowner. Along this direction, the research aims to investigate the impact of energy transition options from a homeowner's perspective. As it enables to identify potential opportunities for a homeowner to adopt during the energy transition. The first research question for this research is as follows:

1. *What is the attractiveness of alternatives to the natural-gas and energy-renovation options to the households of an existing neighbourhood from the perspective of 'homeowners'?*

To assess the attractiveness of natural-gas-alternatives (NGAs) and energy-renovation-options (EROs) from a homeowner's perspective, it is useful to perform a techno-economic analysis (TEA). With the help of TEA, it is possible to find the various attractive option for a homeowner using key performance indicators that assess the performance of each option, based on the homeowner's interests.

On the other hand, TEA is insufficient for explaining the adoption of an NGA by the neighbourhood, because switching to an NGA requires significant infrastructural change; change in actors and their roles, change in governance, etc. Thus, TEA is insufficient to fully explain the adoption of an NGA.

For overcoming the limitations of TEA, Hofman and Elzen (2010) propose to complement TEA with socio-technical scenarios. A sociotechnical scenario (STS) is a useful tool, explaining the way through which a new technology/practise is adopted by society. It explains the adoption of new technology by identifying key processes that can facilitate the uptake of technology. The sociotechnical scenario proposed by Hofman and Elzen (2010) uses the multilevel perspective (MLP) for analysing and explaining the transition. MLP is a theoretical framework used in transition studies for analysing and narrating system innovations and transitions. Similarly, in this study, MLP is used to analysing and narrating the transition of a neighbourhood from natural gas to its alternatives for meeting its low-temperature heating needs. Thus, the following research question is phrased.

2. *What is the narrative offered by the MLP for explaining the adoption of District Heating or Heat Pumps or Green Gas by the neighbourhood?*

To conduct a TEA, it is necessary to understand a household based on its existing energy consumption behaviour; and map the impact of energy transition options by integrating potential changes to the behaviour and by considering homeowner's motivations. Thus, following sub-research question are used to obtain household-specific information and to map the performance of EROs and NGAs.

a. What are the various household-specific occupant-behaviours, influencing the energy demand?
b. What are the key performance indicators to assess the attractiveness of NGA and ERO to a homeowner?
c. What is the performance of natural-gas alternatives and energy-renovation options?

To narrate the adoption of an NGA based on the MLP, it is necessary to establish various concepts from MLP for analysing and elaborating the potential adoption process. Thus, the following research questions are phrased to establish the theory and consecutively use it for explaining the adoption process.

d. What are various levels in MLP and how does MLP conceptualize transition using these levels?
e. What are the recent developments influencing the energy transition and how does it compare with MLP?

1.4 THESIS OUTLINE

In this research, a strategy for analysing the impact of the energy transition on a neighbourhood, from the perspective of households is created. The first chapter explains the current developments in the Netherlands, corresponding problems and the research questions. The second chapter elaborates the theoretical framework, used for analysing socio-technical scenarios and it answers the *sub-research question d*. Third chapter is a literature review and it investigates the motivations of homeowners and relevant KPIs for assessing technoeconomic performance. In this chapter the *sub-research question b* is answered. The fourth chapter elaborates about the methods used for performing techno-economic assessment and creating socio-technical scenarios. The fifth chapter elaborates about the case neighbourhood, it identifies the characteristics of neighbourhood buildings and it defines renovation improvements for each building. The sixth presents the energy modelling assumptions and it answers the *sub- research question a.* Seventh chapter present the results for techno-economic assessment and it together answer the r*esearch question 1* and *sub- research question c*. Eighth chapter present the sociotechnical scenarios and it together answer the *research question 2* and *sub-research question e.* The ninth chapter presents conclusions, it summarises findings and various influential factors that are affecting the transition.

1.5 METHODOLOGY

The below figure briefly describes the overall methodology followed for this research. First literature used for reviewing concepts from MLP and for building a theoretical framework. Secondly literature is used for identifying homeowner motivations and KPIs. Thirdly, the case study neighbourhood is thoroughly analysed to identify geometry and insulation values of the building, and the building is modelled in IESVE and then renovation packages for each building is defined. Fourth, various influential occupant behaviours are identified using literature research. Fifth the building model is simulated by integrating various occupant behaviours and then baseline simulation results are verified using the Data set containing building energy consumption data. Sixth, various ERO and NGA combinations are implemented to the simulation models and then it is simulated and then its performance is evaluated. Lastly sociotechnical scenarios are performed using literature research and the abstracted MLP concepts from literature research.

Various data sources used in this study are (National Energy Atlas, no date; Google Maps, no date; Government of the Netherlands, 2012; OpenStreetMap Contributors, 2018).

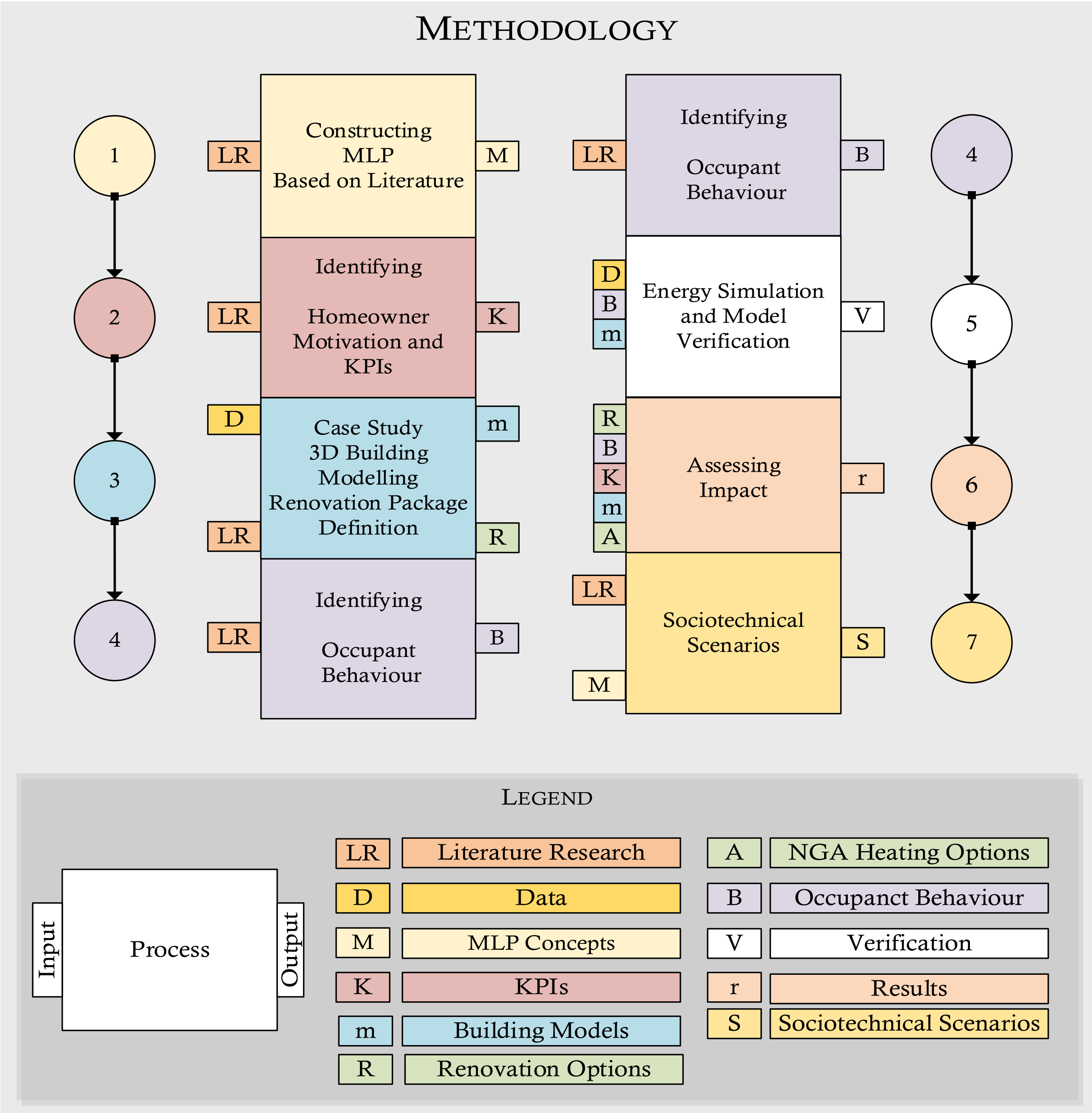

Figure 2 Methodology

2 MULTI-LEVEL PERSPECTIVE

Multi-level perspective (MLP) is a widely used theoretical framework in transition studies for narrating complex dynamics of a socio-technical change (STC). Since a transition entails changes along with multiple domains (technology, policy, markets, etc.) MLP is ideal for analysing and explaining these changes (Geels, 2002, Geels and Schot, 2007, Roberts and Geels, 2019). The framework is also broader in comparison to other frameworks in transition studies such as 'Technology Innovation System', 'Strategic Niche Management' and 'Transition management', because other frameworks' applicability is limited to initial stages of the transition (Roberts and Frank W. Geels, 2019).

MLP explains an STC by structuring the socio-technical system (STS) into three levels and by narrating its internal dynamics (Geels, 2002). According to MLP transition is a result of alignment between three levels and their internal developments. The three levels used in MLP are Landscape, Regime and Niche, where the niche is the lowermost level and Landscape the uppermost level. These three levels are structured in a nested heretical manner, such that lower level is embedded in the one above it (Geels, 2002). The figure presented below gives an overview of levels and their structuring.

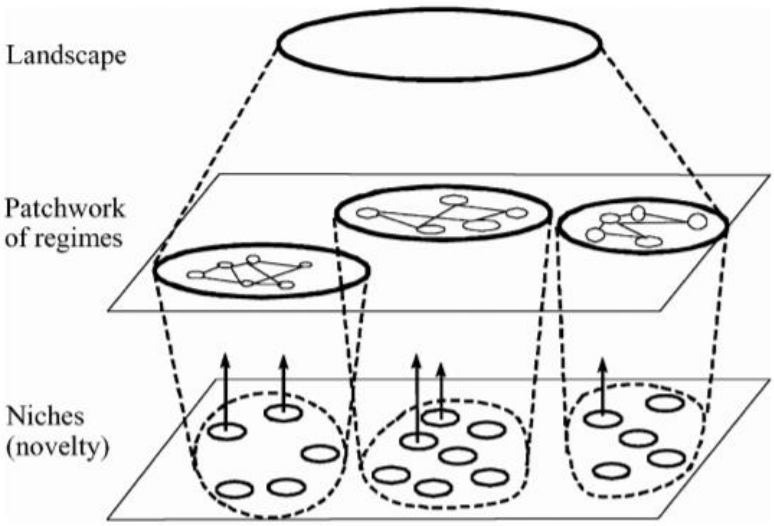

Figure 3 Multiple levels as a nested hierarchy (Geels, 2002)

2.1 LANDSCAPE

The macro-level in MLP is a sociotechnical landscape or landscape, it is exogenous to regime and niche. However, it provides the environment for the development of a niche into the regime or transformation of an old regime into a new regime (Geels, 2005). The landscape is beyond the direct influence of regime and niche actors and it cannot be changed at will, thus landscape is the most rigid element in MLP (Geels, 2005). Though rigid, the landscape can change slowly over long time-periods under the influences of altered regime conditions (Geels, 2002).

"*The landscape represents the broader political, social and cultural values and institutions that form the deep structural relationships of society and only change slowly*" (Foxon, Hammond and Pearson, 2010). In other words, an ST-landscape include factors such as oil prices, economic growth, wars, emigration, broad political coalitions, cultural and normative values, environmental problems; all these factors are external to the context and actors cannot influence in the short-run (Geels, 2002; Geels and Schot, 2007).

2.2 REGIME

The meso-level in MLP is called a sociotechnical regime. An ST-regime encompasses technology regime, user-market regime, socio-cultural regime, policy regime and science regime (Geels, 2002). An ST-Regime broadly can be defined as a set of semi-coherent rules, used by different actor groups (e.g. engineers, users/market, policymakers) for coordinating and guiding their activities (Geels, 2002). Further, an ST-regime can be viewed as a selection and retention mechanism for maintaining stability (Geels, 2002). Various rules present within an ST-system can be classified into three broad categories regulative, normative and cognitive rules.

1. Regulative rules – are used for guiding the behaviour of actors, so they are made explicit to all actors in the network and formalized (in form of policies) to provide stability (Geels, 2004).
   E.g. Economic policies, Regulation, Laws and Standards
2. Normative Rules – are used to confer values, norms, role expectations, duties, rights, responsibilities to actors of an ST-system (Geels, 2004). They become embedded in the system as a result of socialization processes (Geels, 2004).
   E.g. Values, Norms, Duty etc.
3. Cognitive Rules – are used by actors daily to cope with the world around them (Geels, 2004). These rules are the social constructs that guide actors to grasp reality and make decisions by distilling and summarizing society's beliefs and experiences (Greif and Mokyr, 2016). Cognitive rules are self-enforcing and self-confirming in nature and not necessarily coherent (Greif and Mokyr, 2016).
   E.g. Priorities, problem agendas, beliefs, models of reality, Search heuristics, etc (Geels, 2004).

All rules in an ST-system are linked together and organised into rule systems, thus leading to semi-coherent sets of interlinked-rules (Geels, 2004). According to Geels (2004) the alignment between rules give the ST-system the strength and the stability to coordinate activities. Beyond rules, actor networks, material networks and artefacts within an ST-system bolster an ST- regime's stability (Geels, 2004).

Thus, an ST-regime derives the second source of its stability from actors, organisations and their interdependencies, these are manifested in the form of 'trust' between actors and 'organizational structures' in big organizations/markets (Geels, 2004). Third and the powerful source of stability for a regime arises in the form of complementarities between components and the sub-systems in an ST-system. Complementarities are manifested in the form of lifestyles particularly adapted to artefacts, sunk investments on infrastructures, supply chains etc. Thus, it becomes nearly unthinkable for the technology to change in any substantial fashion and the change becomes path-dependent (Geels, 2004).

2.3 NICHE

Niches are hotspots for radical innovation, and they often become the locus point of emergence for radical innovations (Geels, 2004). In the initial stages, the performance of radical innovation (novelty) is low and they are shielded from mainstream market selection mechanism by niches. A Niche nurtures the novelty using 'subsidies' obtained from public authorities and(/or) 'strategic investments' from companies (Geels, 2004). A niche also provides the freedom to deviate from existing regime rules and enable novelty's learning of technical specifications, user preferences, public policies, etc (Geels, 2004).

Unlike an ST-regime a niche's stability is low, and its rules are still emerging and developing, all happening while its actors are continuously entering and leaving. Nevertheless, a niche can become stable 1. by the building of social networks, 2. by learning and aligning the activities, 3. by articulating the expectations and visions to guide the learning process. Once the niche has attained the 10x performance improvements (figurative), it has the potential to break through into the ST-regime on the provision of an opportunity window (Geels, 2004).

2.4 TRANSITION DYNAMICS

Geels (2004) explains transition as a process that changes the configuration of an ST-system. This change can be viewed as a result of alignment between three levels (landscape, regime, niche) and their corresponding developments (Geels, 2005). According to Geels (2005) a transition happens over four phases, in the first phase, novelties emerge in niches with respect to regime and landscape developments (changes). In this phase, the technical dimension of the niche can house multiple technologies that compete. Role of actors in this phase is to engage in experiments and find out the best design that corresponds to users' needs.

In the consecutive phase, the novelty is introduced in small market niches, leading to the development of technical specialisation. Also in this phase, a dedicated community of engineers and producers emerge, directing new technology development along a trajectory of its own (Geels, 2005). This results in the gradual development of technology, and users interacting with it and incorporating it in their lives. Result of this phase is the prominence of the dominant design, articulated user preferences and stabilized rules.

In the third phase, novelty breakthroughs into ST-regime; becomes widely diffused and competes with established technology-regime. Breakthrough is a result of internal factors (e.g. internal technical problems in regime, actors' interest to expand technology scope) on the one hand and external factors creating opportunity window in the form of landscape's pressure, changing user preferences, stricter regulations on the other hand to existing technology-regime.

In the fourth phase, the new technology replaces the old regime by changing the ST-regime on a wider dimension. This is a gradual process because the creation of the socio-technical regime takes time. On the establishment of new ST-regime, the new regime can lead to landscape developments (e.g. global warming from wider-industrialization).

Above explained 'transition process' is limited to explaining transitions that have a bottom-up emphasis (radical innovations emerging from niches) (Geels, 2005). In a broader sense, the transition can be viewed as a product of 'timing' and 'the nature of the interaction' and 'endogenous enactments' (Geels and Schot, 2007; Geels *et al.*, 2016).

2.4.1 Timing of interactions

Geels and Schot (2007) emphasize that interaction timing has a direct influence on transition outcome. Potential for new technology transition is dependent on the alinement between niche's 'maturity' (Mature/Immature) and landscape's pressure on the regime (Present/Absent) (Geels and Schot, 2007). If a niche is not fully developed, then it cannot take advantage of the opportunity window provided by the landscape. As a result, it may lose its opportunity to enter the regime and influence it.

Geels and Schot (2007) have identified four 'pressure influences' that can drive ST-transitions. They are called Regular change, Specific shock, Disruptive change and Avalanche change. Except 'Regular change', all other changes create an opportunity for the niche to interact with the regime.

1. Regular Change – denotes gradual change and it leads to stable regime conditions and incremental innovations.
2. Specific Shock – is a rapid-high intensity environmental change that occurs rarely, and it quickly dissipates and disappears after a while.
3. Disruptive Change – is infrequent in occurrence and it is a result of gradual build-up. It has a high-intensity effect in one dimension.
4. Avalanche Change – occurs very rarely, it is of high intensity, high speed and affects the environment permanently and multidimensionally.

2.4.2 Nature of interaction

Nature of interaction is introduced to identify if the resulting interactions between 'Landscape developments' and 'Niche innovations' have a '*reinforcing*' or '*disruptive*' effect on the 'Regime'. Reinforcing developments have a stabilizing effect on the regime, while disruptive developments tend to disrupt the regime.

Niche innovations that have symbiotic relationships with the regime, tend to enhance the competence of existing regime (reinforcing); When they try to replace the existing regime, they are in direct competition with the regime and they are disruptive (Geels and Schot, 2007).

2.4.3 Endogenous Enactments

Based on the interactions of '*Timing of Interaction*' and '*Nature of Interaction*' components, Geels and Schot (2007) have identified four transition pathways '*Substitution, Transformation, Reconfiguration and De-alignment & Re-alignment'*. However, conceptualizing a transition based on 'T*iming*' and '*Nature'* components has a limited explanatory capacity for transitions that can shift from one pathway to another, over time. Thus, (Geels *et al.*, 2016) have identified endogenous components, primarily 'Institutions' (formal rules) for explaining the shit from one pathway to during the mid-run.

Geels *et al.* (2016) have identified four types of changes in institutions for explaining the shift and it is expected that changes are expected to have a vice-versa effect on the transition process.

1. Layering – is when new institutions are layered on top of existing institutions, keeping old rules intact.
2. Drift – is when implementations that are happening at ground-level changes the policies in use, without official decisions.
3. Conversion – is when goals of the existing policy are adjusted to accommodate change, without changing the instruments in use.
4. Displacement – is when new institutions gradually replace the existing ones.

2.5 Transition Pathways

2.5.1 Technological Substitution

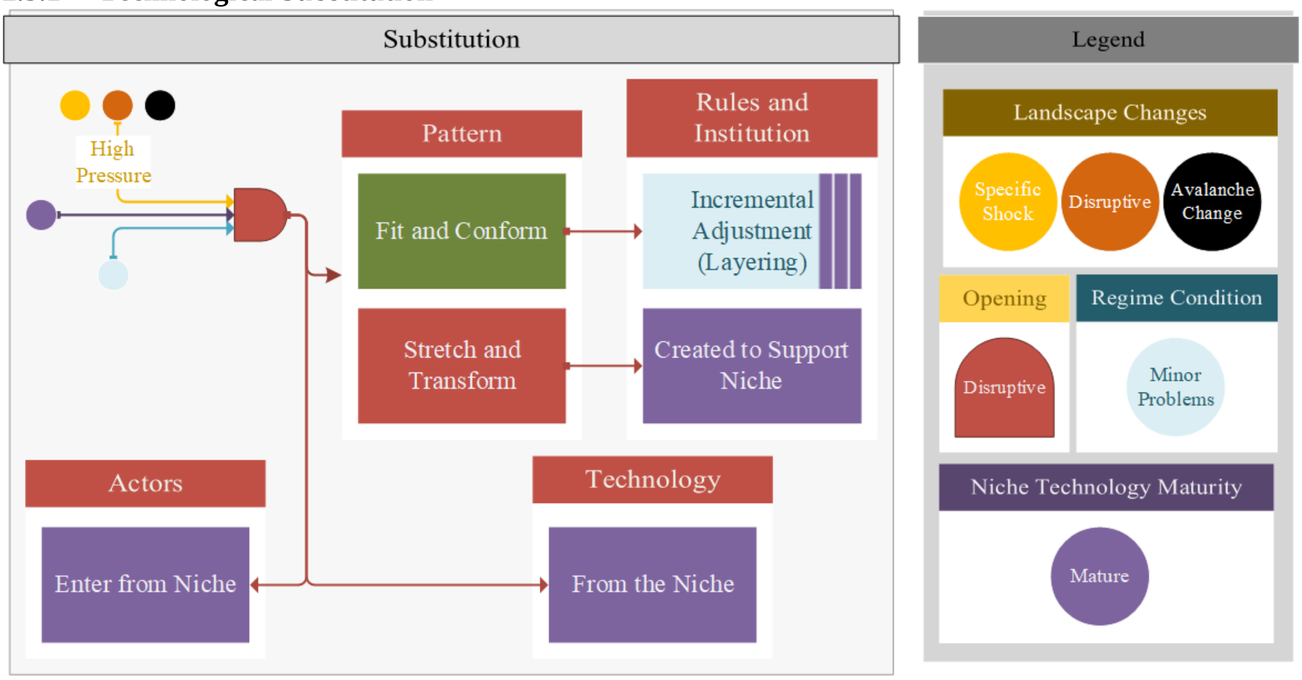

Figure 4 Substitution Pathway (Geels and Schot, 2007*;* Geels *et al.*, 2016)

In a substitutional pathway, Niche technologies are developed separate from the Regime and they are shielded by the protective policy. This pathway would result, only when Regime is affected by a highly uncongenial Landscape pressure (e.g. avalanche change) and when there is a matured alternative in Niche.

Under these conditions, the Niche technology will break into the Regime and replace the existing Regime's Technology (Geels and Schot, 2007). The actors that enter the Regime during this process are the actors from the Niche; these actors can be new entrants or incumbents that have diversified from other sectors (Geels *et al.*, 2016).

In the context of institutions, a substitutional pathway has two patterns 1. 'Fit-and-conform' and 2. 'Stretch and Transform'. For the first pattern, there is limited institutional change and institutions are incrementally adjusted (Layering) because changes brought forward by Niche innovation offer only price/performance improvements compared to Regime technology. For the second pattern, rules and institutions are adjusted to suit the niche-innovation (Displacement) (Geels *et al.*, 2016).

2.5.2 Transformation

This pathway happens under the context of a moderate landscape pressure and an immature Niche technology. In this pathway, the Regime actors re-orient themselves by modifying their development paths and innovation activities. The 'Landscape changes' cannot directly exert pressure on the Regime, because it has to be perceived and acted upon by the Regime actors. In certain cases, Regime actors tend to neglect these pressures. Thus Outside actors (social groups) become crucial in translating 'Landscape changes' to 'Landscape Pressure' for invoking regime's transition (Geels and Schot, 2007).

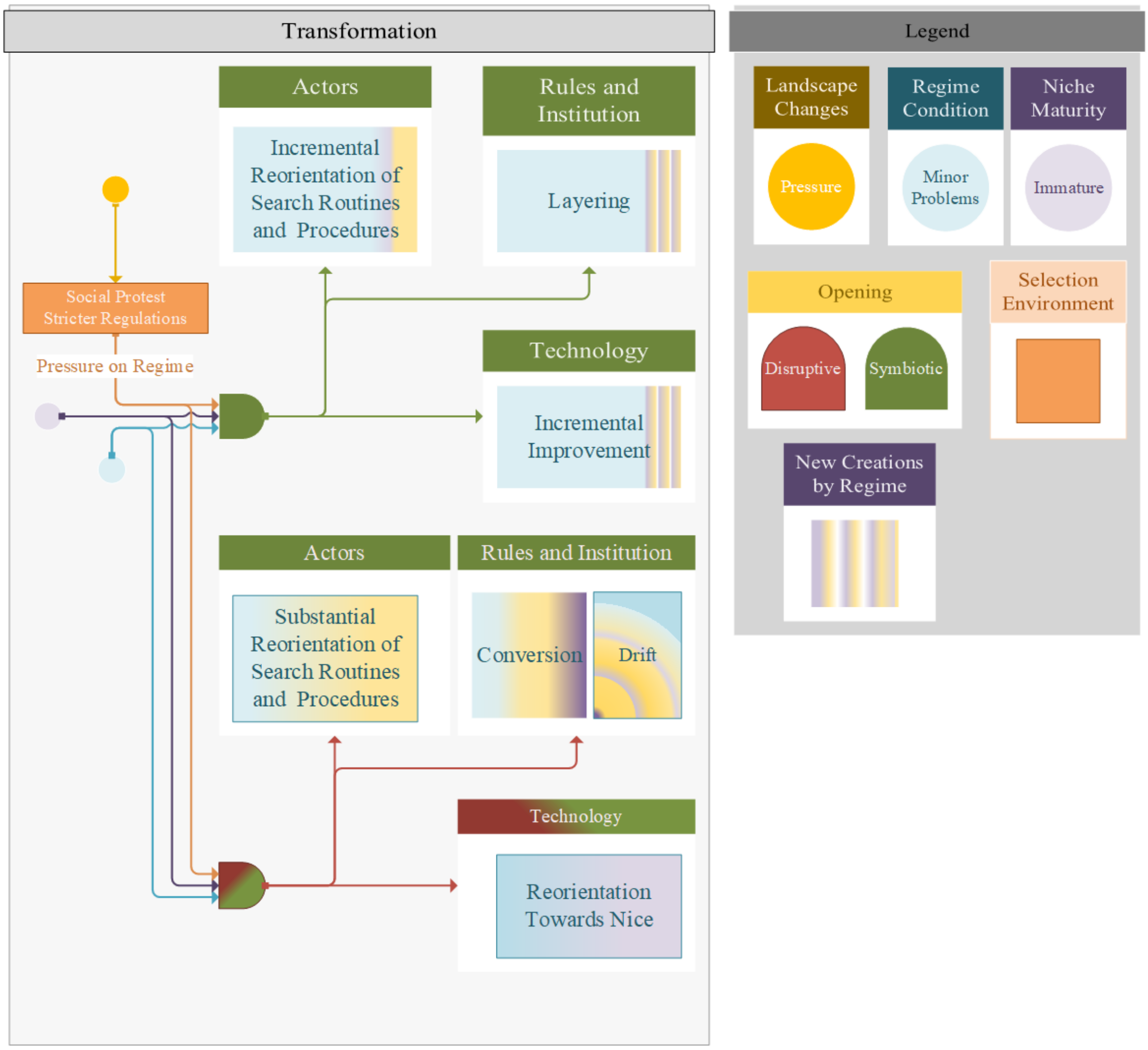

Figure 5 Transformation Pathway (Geels and Schot, 2007; Geels *et al.*, 2016)

According to Geels *et al.*, (2016) the degree of reorientation can occur in different depths 'Incremental Reorientation' or 'Full Reorientation'. For 'Incremental Reorientation' guiding motive is to enhance performance largely, here institutional change is also incremental, and 'Layering' of new institutions can be expected. While for changes in 'Actor groups', the incumbents incrementally reorient themselves to new 'search routines' and procedures.

For 'Substantial Reorientation', there can be significant changes to the technology or even a new technology substitution. While institutional change is either 'Conversion' or 'Displacement' depending on the changes to the technology. In this path, incumbent actors reorient towards radical niche-innovation, thus preventing a lock-in (Geels *et al.*, 2016).

2.5.3 Reconfiguration

The transition, along this pathway, is symbiotic. Here innovations developed in the Niche are used to address the Regime's local problems. Subsequently, these adoptions lead Regime to adjust its basic architecture, in the hope for improving its performance or solving even more internal problems using novelties. Thus, regime actors try different combinations of old and new elements in the system and learn more about niche-innovations. Which may lead to technical changes, changes in user practices, perceptions and search heuristics. Finally, with time and under the influence of 'Landscape pressure' it adds up to major reconfigurations and technology architecture of the regime has significant changed. It is a process through which a new regime grows out of an old regime (Geels and Schot, 2007).

It is likely that there will be alliances between 'new entrants' and incumbents rather than an overthrow. In the beginning phase, limited institutional change in the form of 'Layering' is expected. For the later phase, institutions either undergo 'Drift' or 'Conversion' to cater actor goals and interest as they find new opportunities (Geels *et al.*, 2016).

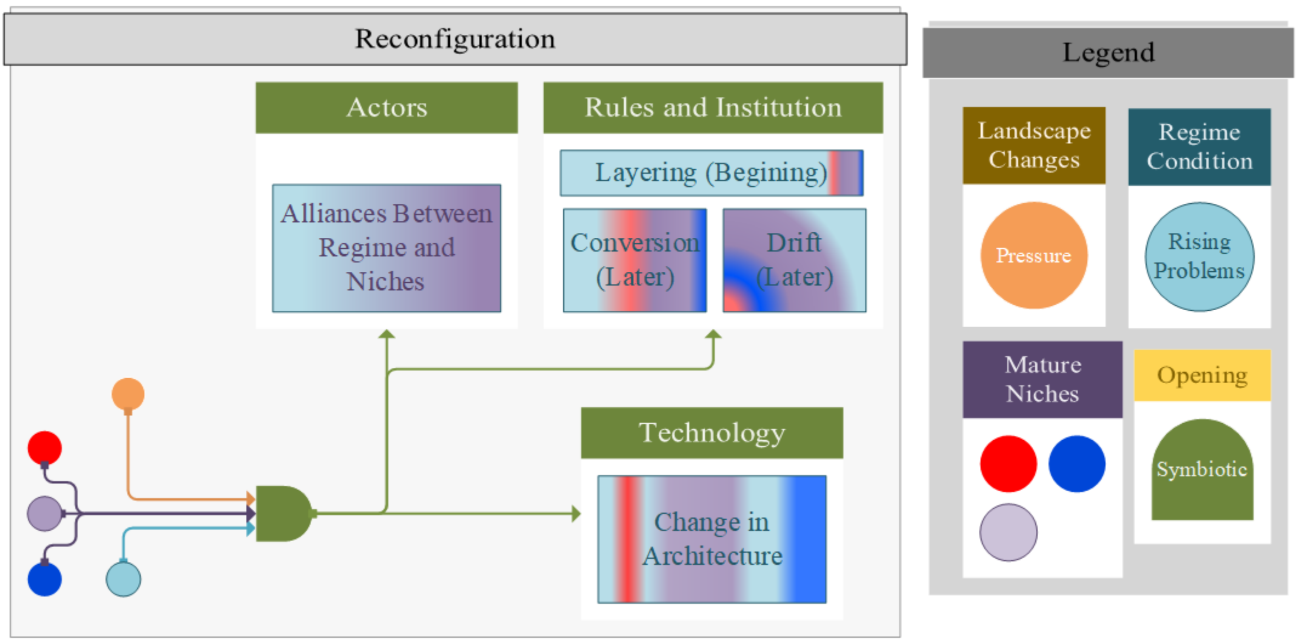

Figure 6 Reconfiguration Pathway (Geels and Schot, 2007; Geels *et al.*, 2016)

2.5.4 De-alignment and Re-alignment

This pathway results when the regime is disrupted (by Avalanche or Externa shocks), but there are no viable Niche alternatives. First, regime actors lose their faith as a result of increasing problems, as a result the regime starts to erode and becomes de-aligned. This creates a space for the emergence of multiple niche innovations, where these innovations co-exist and compete for attention and resources. Eventually, one innovation will come to dominance and leads the re-alignment of new regime (Geels and Schot, 2007).

Here actors from the Niche and the Regime are temporarily separated and there are no direct contact, eventually new entrants from Niche come to dominance. In terms of Institutional change, a period of vacuum is expected after de-alignment. During this period multiple actor groups struggle over shaping new institutions, and stability returns when one group dominates the other groups (Geels *et al.*, 2016).

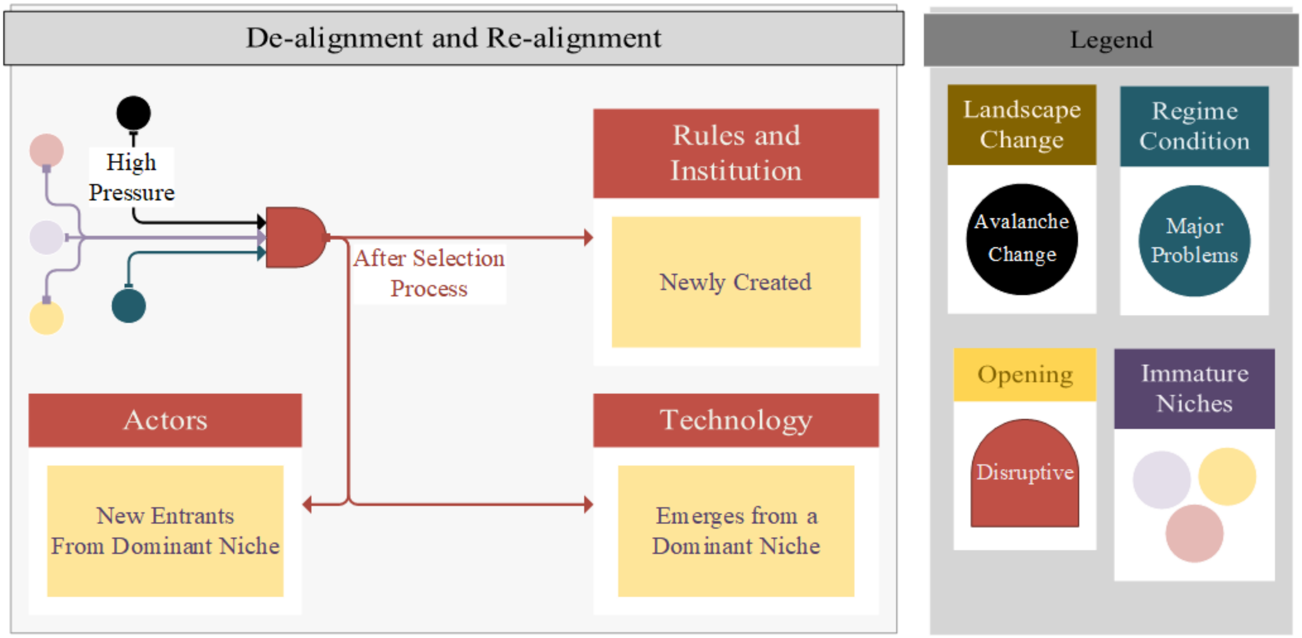

Figure 7 De-alignment and Re-alignment Pathway (Geels and Schot, 2007; Geels *et al.*, 2016)

3 LITERATURE REVIEW

In this chapter, the aim is to identify the primary motivations of the homeowners for performing energy renovations. Then, the aim is to identify suitable KPIs from the literature that can evaluate the performance of energy renovation options (ERO) and natural gas alternatives (NGA) based on the homeowner's motivation.

3.1 HOMEOWNER MOTIVATIONS AND KEY PERFORMANCE INDICATORS

One of the primary goals of this research is to assess attractiveness from a homeowner's perspective, hence it is necessary to understand the homeowner's needs and motivations for investing in energy-related household changes. This subsection list various important characteristics of renovations, that are important according to homeowners.

According to (Baginski and Weber 2017; Broers et al. 2019) homeowners are motivated by three major aspects of energy renovation 'financial benefit', 'protecting the environment, and 'increasing comfort'. In general, a majority of households perform energy-renovations because they perceive 'saving on gas as saving money' (Achtnicht and Madlener 2014; Baginski and Weber 2017). Based on a survey conducted in the Netherlands, it has been identified that almost 65% of homeowner-renovators have listed 'financial benefit' as a primary driver for renovating the building (Ebrahimigharehbaghi, Qian, *et al.*, 2019). Further, it has been noted that among 62% of homeowner-renovators, '*improving comfort*' was a driver for renovation; while only 25% of homeowner-renovators have listed 'environmental protection' as a driver for energy renovation (Ebrahimigharehbaghi, Qian, *et al.*, 2019).

3.1.1 Discounted Cost Savings

In energy performance studies for evaluating financial performance (discounted) *cost savings*, *global costs*, *payback period* and *savings to investment ratio* are often used (Gorgolewski 1995; Amstalden et al. 2007; Kotireddy 2018). For this study, discounted cost-savings, described in Amstalden et al. (2007) is used for financial performance. The KPI is selected because it evaluates the cost performance of a renovation concept against the existing performance of the building.

Cost-saving refer to costs that can be saved by renovating a building (ERO), or by adopting an alternative heating device (NGA). The cost savings can be obtained by subtracting the costs a homeowner would incur by renovating the building and by switching to a new heating alternative (NGA), from the costs for the base scenario. Base scenario refers to the case where the homeowner does not perform a renovation and continues to rely on natural gas for meeting low-temperature heating needs (space heating and domestic hot water).

Discounted Cost Savings (Euros)

$$Cost\ Saving = Cost_{Base\ Case} - Cost_{NGA,EER} \qquad - (1)$$

$$Cost_{Base\ Case} = I_{InvF=NG} + \sum_{n=1}^{p} \frac{(E_{F=NG,R=B_n} \times P_{NG_n} + M_{F=NG_n})}{(1+i)^n} \qquad - (2)$$

$$Cost_{NGA,EER} = I_{InvF} + I_{InvR} + \sum_{n=0}^{31} \frac{(E_{F,R_n} \times P_{F_n} + M_{F_n})}{(1+i)^n} \qquad - (3)$$

The above equation '$Cost_{NGA,EER}$', calculates the costs for an alternative scenario in which homeowner invests in renovation (EER) and switches to other fuel alternatives. $E_{F,R}$ represents the fuel demand for fuel 'F', after implementing the renovation option 'R'. $'P_F'$ represents the unit price for fuel 'F'. $'M_F'$ represents the annual maintenance cost for maintaining the heating equipment. 'I_{InvR}' represents the investment cost for implementing the renovation option and 'I_{InvF}' represents the investment cost for buying the necessary heating equipment. 'i' represents the discount rate.

The subscript $'F'$ represents the fuel type and the heating equipment, together; The fuels considered are *Natural gas (NG)*, *Electricity*, *District Heating*, and *Green gas;* and the corresponding heating equipment is *Gas boiler*, *Heat pump*, *Delivery equipment* and *Gas boiler*. The subscript $'R'$ represents the renovation option under consideration (e.g. Base case (B), option 1, option 2, etc.). The subscript $'n'$ represents the year in which the costs are incurred.

The unit for E_F is $\frac{kWh}{year}$; P_F is $\frac{€}{kWh}$; M_F is $\frac{€}{year}$; I_F and I_R is €.

3.1.2 CO_2 Savings

For evaluating environmental performance, the key performance indicators used by building performance research are *'primary energy usage', 'CO_2 emissions', 'CO_2 emissions-avoided'* (Dodoo, Gustavsson, and Sathre 2010; Cellura et al. 2013; Kotireddy 2018). For this study *'CO_2 emissions-avoided' or 'CO_2 savings'* is used as the KPI for evaluating environmental performance because the national government wants to reduce CO_2 emissions.

'CO_2 savings' refers to a reduction in CO_2 emissions that can be achieved by successfully implementing the renovation option and by switching to a natural gas alternative for providing low-temperature heat. It is calculated by subtracting new design's CO_2 emissions from the base case's CO_2 emissions.

CO_2 Saving

$$CO_{2_{Savings}} = CO_{2_{Base\ Case}} - CO_{2_{new}} \quad \text{- (18)}$$

$$CO_{2_{Base\ Case}} = \sum_{n=1}^{31} E_{F=NG,R=B} \times f_{F=NG} \quad \text{- (19)}$$

$$CO_{2_{new}} = \sum_{n=1}^{31} \left(E_{F,R} \times f_{F_n}\right) \quad \text{- (20)}$$

$E_{F,R}$ represents the demand for Fuel 'F' during the time step $'n'$ and 'f_{F_n}' represents the emissions factor for the consumed fuel for during the same time step. The subscript $'F'$ represent the fuel type and it can vary between 'Natural gas', 'Electricity', 'District Heating' and 'Green gas'. The unit for $'E_F'$ is kWh and $'f_F'$ is $\frac{tons}{kWh}$.

3.1.3 Thermal Comfort

To measure occupant comfort, the study uses thermal comfort for assessing the performance. This indicator has been selected because renovators according to Baginski and Weber (2017) perform renovations for improving thermal comfort.

Further, the are two key approaches for evaluating thermal comfort *steady-state* and *adaptive* approach. Steady-state approach (e.g. ISO 7730) use lab experiments and steady conditions for determining acceptable indoor condition. While adaptive models determine comfort based on the occupant's clothing, activity, indoor and outdoor climatic conditions. For this study, the adaptive thermal comfort strategy proposed by Peeters *et al.* (2009) is used because the approach has a dynamic emphasis and it determines comfort based on varying comfort requirements of the users. Particularly in residential building, building users are dynamic and they different activity levels and different clothing levels. Thus using steady-state for evaluating thermal comfort is suboptimal (Peeters *et al.*, 2009).

For measuring adaptive thermal comfort Peeters et al. (2009) determine acceptable temperature limits (indoors) by calculating reference outdoor temperature and neutral comfort temperature.

The reference outdoor temperature is the weighted average of today's outdoor temperature and past three day's outdoor temperature. T_{today} and $T_{today-x}$ is calculated by taking the arithmetic average of the day's maximum and minimum temperatures. The neutral temperature in the formula represents the temperature at which the majority of building occupants are comfortable.

Adaptive Thermal Comfort

$$Comfortable\ Occupancy\ = (1 -\ Over\ Heating\ Ratio - Under\ Heating\ Ratio) \times 100 \quad \text{- (4)}$$

$$Over\ Heating\ Ratio = \frac{\sum_{h=1}^{8760}\left(\left[T_{upper_h} < T_h\right] \times O_h\right)}{\sum_{h=1}^{8760} O_h} \quad \text{- (5)}$$

$$Under\ Heating\ Ratio = \frac{\sum_{h=1}^{8760}\left(\left[T_{lower_h} > T_h\right] \times O_h\right)}{\sum_{h=1}^{8760} O_h} \quad \text{- (6)}$$

T_h is indoor air temperature at hour h in °C

O_h is occupancy at hour h in $people$

T_{upper} is maximum comfortable room temperature for hour h in °C

T_{lower} is minimum comfortable room temperature for hour h in °C

8760 is total number of hours present in a year

Comfortable Temperature Range for bedrooms

$$T_{upper} = \min(26°C\ , T_n + w\alpha) \quad \text{- (7)}$$

$$T_{lower} = \max(16°C\ , T_n - (1-\alpha) \times w) \quad \text{- (8)}$$

Comfortable Temperature Range for living room

$$T_{upper} = T_n + w\alpha \quad \text{- (9)}$$

$$T_{lower} = \max(18°C\ , T_n - (1-\alpha) \times w) \quad \text{- (10)}$$

T_n is the neutral comfort temperature in °C

Neutral Temperature in bedrooms

$$T_n = 16°C\ for\ T_{e,ref} < 0°C \quad \text{- (11)}$$

$$T_n = 0.23 \times T_{e,ref} + 16°C\ for\ 0°C \leq T_{e,ref} \leq 12.6°C \quad \text{- (12)}$$

$$T_n = 0.77 \times T_{e,ref} + 9.18°C\ for\ 12.6°C \leq T_{e,ref} \leq 21.8°C \quad \text{- (13)}$$

$$T_n = 26°C\ for\ T_{e,ref} \geq 21.8\ °C \quad \text{- (14)}$$

Neutral Temperature in living room

$$T_n = 0.06 \times T_{e,ref} + 20.4°C\ for\ T_{e,ref} < 12.5°C \quad \text{- (15)}$$

$$T_n = 0.36 \times T_{e,ref} + 16.63°C\ for\ T_{e,ref} \geq 12.5°C \quad \text{- (16)}$$

$T_{e,ref}$ is reference outdoor temperature in °C

Reference Temperature

$$T_{e,ref} = \frac{\left(T_{today} + 0.8 \times T_{today-1} + 0.4 \times T_{today-2} + 0.2 \times T_{today-3}\right)}{2.4} \quad \text{- (17)}$$

w in the equations *7,8,9 and 10* represents the width of comfort band in ℃ and α represents a constant between 0–1. In this study width of the comfort, the band is set to 5℃ and α at 0.7 based on (Kotireddy, 2018).

4 METHODS

The research consists of two parts, a scenario study and techno-economic analysis. To conduct this research, a case study was conducted on an existing neighbourhood in Amsterdam. In Chapter 5, the case study neighbourhood (Buurt 9) is elaborated further. In this chapter, first, the method for performing the techno-economic assessment is explained and then the methodological steps for conducting the socio-technical study is explained.

4.1 TECHNO-ECONOMIC ANALYSIS

The purpose of the techno-economic assessment is to quantify the impact of each energy-renovation-options (EROs) and natural-gas-alternatives (NGAs). To accomplish the task, following performance indicators: *Cost Savings, Thermal Comfort, and CO_2 emissions,* identified in the literature review are used. Hence, the below method described is aimed to convert the equations identified in the literature review chapter into a quantified measure.

STEP 1 – ENERGY ANALYSIS

The first step of the techno-economic analysis is energy analysis. The purpose of energy analysis is to understand the impact of various building renovation measures on energy demand and indoor conditions. According to the literature, energy analysis can be performed with the help of 'top-down' and 'bottom-up' models. Top-down models derive building energy demand, based on the correlation between energy consumption and socioeconomic/socio-technical factors. However, top-down models are not suited for assessing the impact of building-level renovation changes, as they have a macro-focus (Brøgger and Wittchen, 2018).

In this regard, bottom-up models based on engineering methods are more useful. These models perform energy simulations by taking into consideration building-specific information (Brøgger and Wittchen, 2018) and weather conditions. Thus, these models can provide a better understanding of the renovation measures and their impact on energy demand and indoor conditions.

In this study, energy simulations are used for finding the impact of building insulation (ERO) on *annual energy demand* and *indoor temperature*. The scope is restricted to finding *annual energy demand* and *indoor temperature* because they are the influential variables affecting the KPIs. Refer to equations *2,3,19,20* (*energy demand*) and equations 5,6(*indoor temperature*) in the Chapter 3.

SOFTWARE FOR ENERGY SIMULATION

For this study, IES VE, a dynamic energy simulation software, was chosen to perform energy simulation. The software was selected because it has been tested and validated based on ASHRAE Standard 140 and it can produce accurate thermal simulations (Attia and De Herde, 2011). As IES VE is dynamic simulation software, it calculates the energy demand and indoor variations for shorter time steps by considering pretexting indoor and outdoor conditions, hence results are more accurate in comparison to software that aggregate and calculate for longer time durations. Further, the IES VE produces indoor variations and resulting energy demand for each hour and this information can be used for calculating thermal comfort and annual energy demand on a granular scale.

ENERGY MODELLING FOR ENERGY SIMULATION

For performing the energy analysis, the user of IES VE must provide various relevant information for computing the energy demand and indoor conditions. One of the key requirements for the simulation is the information about the physical aspects of the building, the users and weather. These physical aspects of the building are detailed in the Case Study chapter and the information about building geometry, initial thermal insulation, glazing, etc are used for creating the building models in IESVE. Refer to Chapter 5 for more details.

For user-related aspects such as occupancy, occupant behaviour, domestic hot water consumption, electric appliance usage, refer to Chapter 6 – Building Energy Modelling and Assumptions. Also, the assumptions regarding ventilation and weather are discussed in Chapter 6. The identified assumptions in Chapter 6 are integrated into the building model created in IESVE and it is simulated for energy demand. Refer to Chapter 6 for more detailed information.

MODEL VERIFICATION

To increase the confidence of simulation results, the annual energy consumption stimulated based on the baseline conditions (without implementing the renovation changes) for all the neighbourhood buildings is compared against the annual energy consumption information obtained from the WooN data set.

To obtain relevant energy consumption data, key building parameters such as construction period, energy label, floor area and building type are used for shortlisting equivalent buildings from the WooN Onderzoek data set. Then the annual gas consumption data for shortlisted buildings are converted into energy consumption data. In the first step, 65 m^3 gas of is reduced from total consumption (gas used for cooking purpose by an average Dutch household for a year (Garufi, 2015)); then the reduced gas consumption value is converted into kWh based on the calorific value of natural gas (1 m^3=9.8 kWh); then the converted value is multiplied with a constant of 0.95 (efficiency of gas boiler) to obtain the actual energy demand of the building. Further, the kWh value is converted into energy use intensity (EUI) by dividing the total energy required with the total floor area of the building. The calculated EUI value for actual buildings is compared with simulated EUI value, for verification.

ENERGY SIMULATION FOR RENOVATION IMPROVEMENTS

Similar to the energy simulations performed for the baseline model, the simulations for the renovation models are performed by implementing the insulation improvements. Other factors are left unchanged.

STEP 2 – THERMAL COMFORT ASSESSMENT

In this step, thermal comfort is calculated based on the adaptive thermal comfort assessment strategy proposed by (Peeters *et al.*, 2009). This step requires three key variables, indoor temperature, outdoor temperature and occupancy for calculating thermal comfort. Refer to Chapter 3 – Literature review for the detailed calculation strategy. The inputs for calculating thermal comfort are indoor room temperature, outdoor temperature and the occupancy; these values are generated by IES VE simulation for each hour of the year.

STEP 3 – ENVIRONMENTAL PERFORMANCE ASSESSMENT

In this step, the environmental performance of the renovation options is calculated based on the fuel used by the household. The environmental impact of renovations and natural gas alternatives are evaluated in terms of CO_2 emissions. The calculation strategy is elaborated in Chapter 3 – Literature review. Key inputs for the performing this step are annual energy demand, the emissions factor of the fuel and the efficiency of the heating equipment. Annual energy demand is obtained from the energy simulation, while the other two factors are obtained through secondary research. They are presented below.

Table 1 Heating Efficiency and Emissions Factors from [1]Bekhuis, 2018, [2]Cetin-Öztürk, 2018, [3]Vattenfall, 2018, [4]Kircher, 2019

	Option-0	Option-1	Option-2	Option-3
Fuel	Natural Gas	District Heat	Electricity	Green Gas
Heating Equipment	Gas Boiler	Heat Exchanger	Air Source Heat Pump	Gas Boiler
CO_2 Emissions Factor kg/kWh	0.203[1]	0.0943[3]	0.452[1]	0[1]
Efficiency	0.95[2]	1[2]	3[4]	0.95[2]

STEP 4 – ECONOMIC PERFORMANCE ASSESSMENT

In this step, the economic performance of renovation is calculated based on the fuel used by the household. Economic performance is measured in euros. The calculation strategy is elaborated in Chapter 3 – Literature review. Key inputs for the performing this step are annual energy demand, the fuel costs, efficiency of the heating equipment, investment cost for the heating equipment, maintenance cost for the heating equipment and the renovation costs for increasing insulation. Annual energy demand is obtained from the energy simulation, while the other factors are obtained through secondary research. They are presented below.

FUEL COSTS

The fuel costs for natural gas and electricity have been obtained from (Engie, 2020; Vattenfall, 2020); fuel costs for district heating is obtained from (ACM ConsuWijzer, 2020); the potential retail price for green gas is obtained from (Bekhuis, 2018).

Table 2 Fuel Costs

	Option-0	Option-1	Option-2	Option-3
Fuel	Natural Gas	District Heat	Electricity	Green Gas
Fuel Variable Cost (€/kWh)	0.0809	0.0932	0.219	0.175
Fuel Fixed Cost (€/Year)	253	490.12	-204.6	253

EQUIPMENT COSTS

The purchase and installation costs for the gas boiler is obtained from (CVtotaal, 2020). The price for heat pumps is obtained from (CV Totaal, 2019a)(CV Totaal, 2019b). Since the heat pump's cost is dependent on its peak heating capacity, peak heating demand is used for selecting an appropriate heat pump. The installation and maintenance costs of district heating are obtained from (Authority Consumer & Market, 2020). Maintenance costs for heating equipment are assumed to be 2% of heating equipment's purchase cost (Cetin-Öztürk, 2018). The lifetime for gas boiler and air source heat pump is assumed to be 15 years based on (Kircher, 2019). Thus, it is assumed that new heating equipment is purchased every 15 years.

Table 3 Equipment Purchase, Installation and Maintenance Costs

	Option-0	Option-1	Option-2	Option-3
Equipment	Gas Boiler	Heat Exchanger	ASHP	Gas Boiler
Purchase and Installation Cost (€)	1300	4,510.73	6000 (average)	1300
Maintenance Costs (€/Year)	132	0	120 (average)	132

Table 4 Air Source Heat Pump (ASHP) Investment and Installation Costs (CV Totaal, 2019a; CV Totaal, 2019b)

Heat Pump (Capacity)		Cost (Including Tax)	Subsidy
Space Heating	5 kW	€5,000.00	€1,900.00
Space Heating	7 kW	€6,000.00	€1,900.00
Hot Water	90 L	€1,900.00	€1,250.00
Hot Water	200 L	€3,100.00	€1,250.00

CONNECTION AND DISCONNECTION COSTS

To disconnect from gas grid, households have to pay a one-time disconnection fee (Liander, 2020). Similarly, to upgrade the electricity connection to 3-Phase, households have to a one-time fee (Liander, 2020).

Table 5 Connection and Disconnection Costs (Liander, 2020)

	Costs
Disconnecting from Gas Grid	€722.72
Upgrading Electricity Connection	€347.51

RENOVATION COSTS

The renovation costs for performing renovations is obtained from (Arcadis, 2017) and the cost for insulation materials is obtained from (De Isolatieshop, 2020). Further, the prices for various insulation thickness values is interpolated based on the prices from (Arcadis, 2017) and De Isolatieshop, 2020). In figure 8 below, the prices for performing renovation is presented. The costs for improving windows from double glass to HR++ is assumed to be 65 €/m^2 and it is based on (Arcadis, 2017).

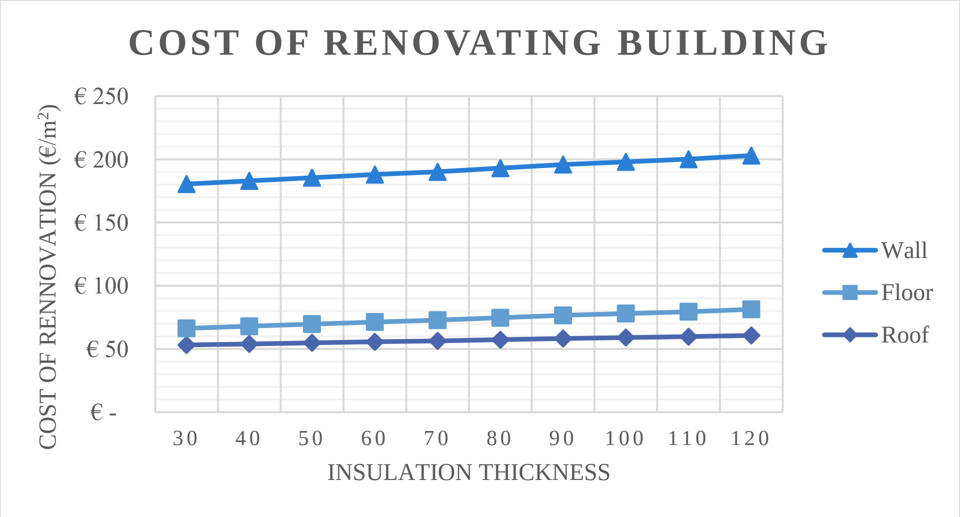

Figure 8 Renovation Costs from (Arcadis, 2017) and (De Isolatieshop, 2020)

DISCOUNT RATE

To calculate the present value of various future costs 'discounted cash flow' method is used. A discount rate of 3.8% is assumed based on Lazzarin (2012) because the authors have used the discount rate for assessing energy renovations. The method is further elaborated in the Literature review Chapter.

STEP 5 – DELAYING RENOVATION OR/AND DELAYING SWITCH TO NATURAL GAS ALTERNATIVE

In prior studies, the performance of energy renovation options (ERO) or natural-gas-alternative (NGA) options is predicted by having the year of adoption same for ERO and NGA. Also, the year of adoption is assumed to be constant, throughout the study. However, while analysing the potential of various EROs and NGAs during a particular time frame (2020-2035 the period for transition), it is necessary to introduce variations in the year of adoption for ERO and NGA options.

Thus, in this study, the variations are introduced by first keeping year of adoption constant (2020) for NGA and the year of renovation is delayed for ERO (2025,2030,2035). Similarly, in the second case, the year of adoption for NGA is varied (2025, 2030, 2035) by keeping year of renovation constant (2020). In the third case, the year for renovation and adoption of NGA are delayed together (2025, 2030, 2035). Through this analysis, it is possible to find what are the various important and imminent measures.

4.2 SOCIOTECHNICAL SCENARIO STUDY

A techno-economic analysis is useful for assessing the attractiveness for a homeowner to adopt a particular design option; however, it is inadequate for explaining an infrastructural change (e.g. implementing an NGA or adopting an EER at a neighbourhood level). Besides homeowner's willingness to change, an infrastructural change is a result of coordination among various actors, institutional changes, rule changes and artefact changes. Hence, Hofman and Elzen (2010) suggests to complement techno-economic analysis with sociotechnical scenario, for creating a reflexive understanding of transition. The sociotechnical scenarios in this study are based on the Multi-Level Perspective(MLP) because it is an analytical framework used in transition literature for studying transitions (Berlo, 2014). MLP is previously used in innovation sciences for understanding and narrating the past energy transitions (Rogge, Pfluger and Geels, 2018; Geels and Johnson, 2018).

In this research, MLP is used in a similar way to narrate the 'history of future', in which each STS is a realized implementation of NGA (Elzen and Hofman, 2007). The purpose of the STS in this study is to outline basic features, that are required for realizing an adoption of an NGA. Transition scenarios within this study are elaborated based on the methodological steps elucidated by Hofman and Elzen (2010). The steps described in Hofman and Elzen (2010) are based on the multilevel perspective.

As the study uses the multi-level perspective for analysing transition scenarios, the study pools various factors that are directly enabling the current energy transition into the landscape(macro-level) factors. The Regime(meso-level) in this study, encompasses the current system (natural gas) though which households heat their houses and produce domestic hot water (DHW). The micro-level in this study corresponds to the alternatives of natural gas (District heat, Air source heat pump and Green gas) for heating purposes.

Seven methodological steps for analysing and developing socio-technical scenarios are described below.

STEP 1 – SPECIFICATION OF OBJECTIVE

As scenarios can be used by different users and they can serve multiple functions. Thus, it is necessary to identify the primary user(s) and the function(s) it must fulfil; then the domain and the nature of the scenario development process.

STEP 2 – ANALYSIS OF RECENT AND ONGOING DYNAMICS

In the second step, the recent domain developments corresponding to landscape, regime and niche is analysed. The analysis will elucidate about the current landscape factors and their impact on the regime; regime actors, their setup and roles, problems faced by the regime and the trends; the niche's dynamics, opportunities and barriers for the transition.

STEP 3 – INVENTORY OF POTENTIAL LINKAGES

In the third step, seeds to transition are identified. It includes potential linkages between landscape, regime and niche, that can shape the transition towards a direction. The linkage is qualitative in nature and it is generally a new relationship between different elements. For example, it can connect landscape pressure to a niche or regime technology or user behaviour (Elzen and Hofman, 2007).

In transition theory, the are several articulation processes that can result in niche's breakthrough. Each of the influential processes is defined from a dimension. Dimensions creating an opportunity for transition include technical, policy, cultural-psychological, market, production, infrastructure-maintenance and societal-environment (problems). Thus, potential linkages can arise from any of the above-identified dimensions (Elzen and Hofman, 2007).

STEP 4 – DESIGN CHOICES

This step elaborates about the distinctive feature of each scenario. These features include time frame of transition, the niche of choice, the role of socio-technical landscape, the pathway (Geels and Schot, 2007) through which transition can happen.

STEP 5 – DEVELOP SCENARIO ARCHITECTURES

This step indicates primary driving forces, actor networks, rules and institutional changes, technology developments, and sequence of linkages (Hofman and Elzen, 2010).

STEP 6 – ELABORATE ON ALL SCENARIOS

Here each transition scenario is elaborated in detail along with various factors crucial for inducing and supporting the niche are discerned (Hofman and Elzen, 2010).

STEP 7 – REFLECTION AND RECOMMENDATIONS

In this step, each scenario is evaluated against its objectives (defined in step 1).

5 CASE STUDY

To conduct this research, an existing neighbourhood within the MRA is used for understanding the implications of the energy transition. The MRA comprises 32 Dutch municipalities, that are present in the provinces of North Holland and Flevoland. The Municipality of Amsterdam is one of the 32 municipalities within the MRA and it is one of the big energy consumers – accounting for 30% of MRA's energy demand (Ministry of Infrastructure and Environment, 2017; Klimaatmonitor, 2019). Further, the Amsterdam municipality is subdivided into eight boroughs.

For this study, the borough of Nieuw-West is selected because it is primarily a residential area, with no nationally protected areas (historic value) and it has very few historic buildings (Doeschate, 2014a; Doeschate, 2014b). This selection was made to eliminate the special influence of historic significance on energy-renovation decisions.

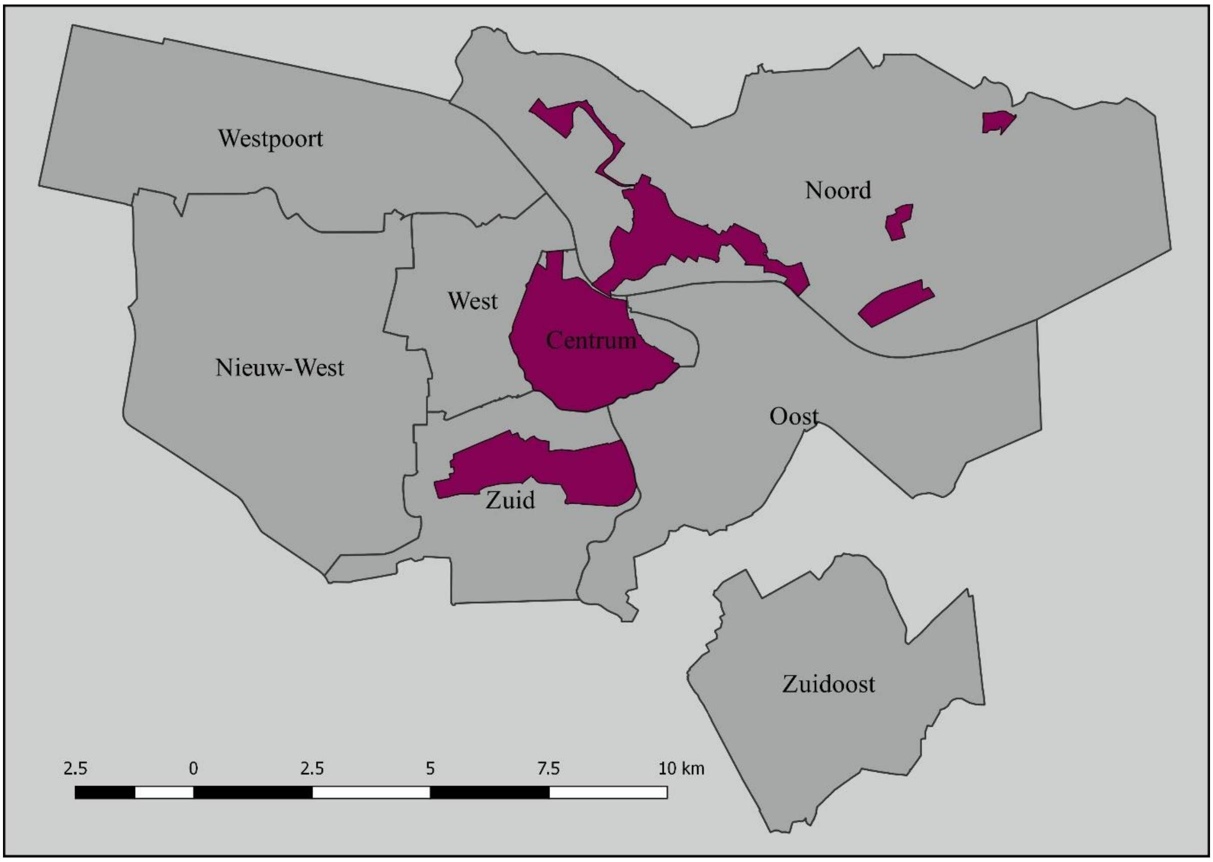

Figure 9 Boroughs of the Municipality of Amsterdam and Nationally Protected Areas in Red (Doeschate, 2014b)

5.1 NEIGHBOURHOOD SELECTION

Buurt 9 is a neighbourhood within the Nieuw-West region – it has been selected for performing the case study. The neighbourhood was selected because it is one of the biggest neighbourhoods (>2000 households) in the borough with different types of buildings. Further, the energy performance of the neighbourhood can be considered poor in comparison to Dutch regulations for new buildings, because many buildings are achieving nearly zero energy standards and they have an energy index close to zero (Filippidou, Nieboer and Visscher, 2017). The energy index is a theoretical measure used for calculating the primary energy consumed by a building. So a building with zero energy index consumes zero primary energy.

Whereas many buildings in the Buurt-9 neighbourhood have an energy label *D or C* and their energy index is varying between 2.0–1.3. Additionally, the neighbourhood is not connected to district heating yet, so it is possible to investigate other alternatives to natural gas in Buurt 9.

The image below shows the information about Nieuw-West borough, presenting the number of households, average energy label and district heating penetration in each neighbourhood of Nieuw-West.

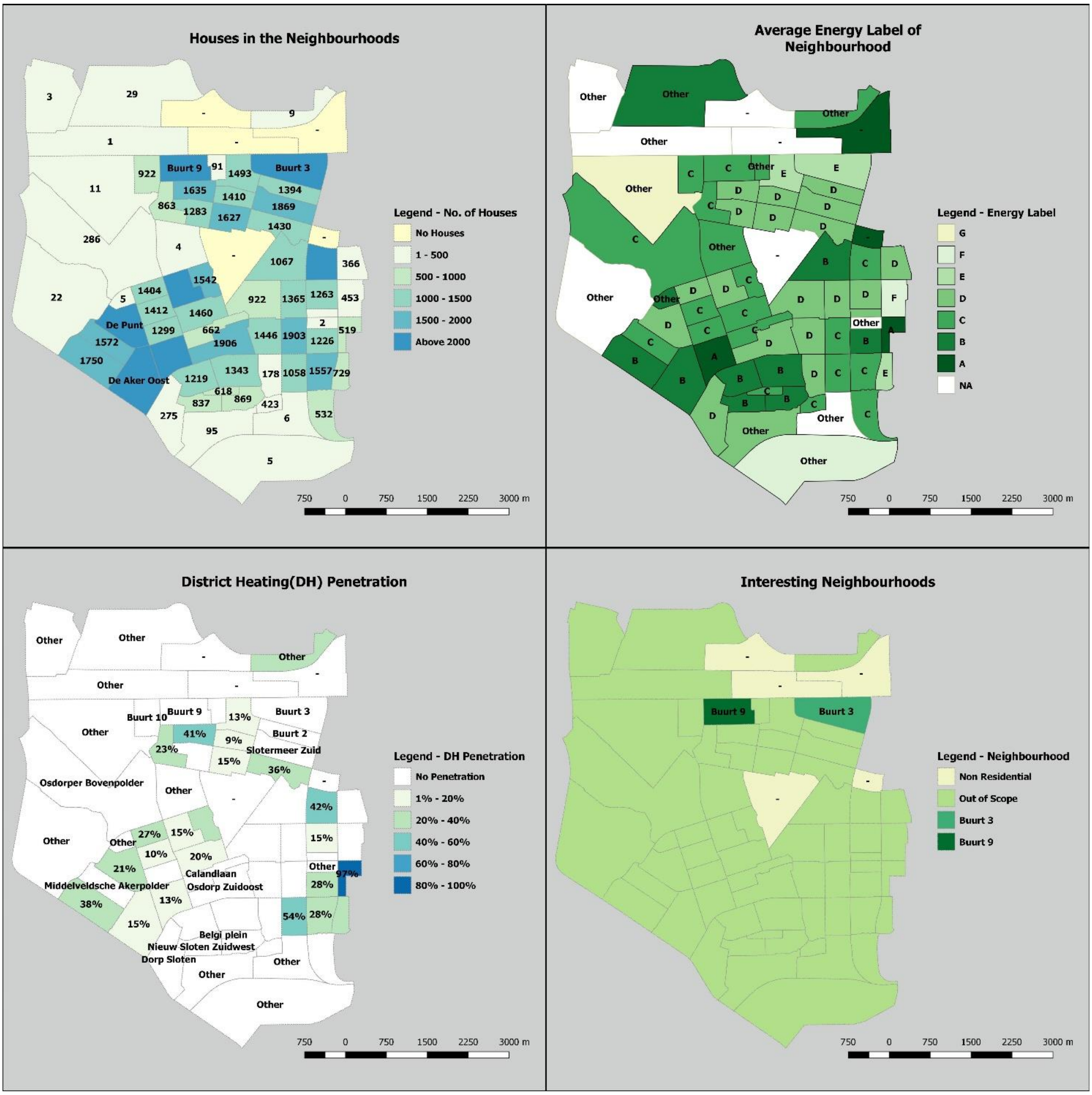

Figure 10 Neighbourhoods Status in Nieuw-West

The map is developed in QGIS with the help of neighbourhood level data obtained from (Klimaatmonitor, 2018a; Klimaatmonitor, 2018c) and the geospatial data of the neighbourhood obtained from (Municipality of Amsterdam, 2016).

5.2 BUURT 9

Buurt 9 is part of the Geuzenveld city district in Nieuw-west. The neighbourhood houses 2215 households and the average size of a household is 2.3 people per household. The average income per inhabitant is €17,000 per year and the average income per household is €39,100 per year (AlleCijfers, 2019).

The district is 100% connected to the gas grid and electricity grid. An average household in the neighbourhoods consumes on average 900 m^3 (9280 kWh) of gas and 2300 kWh of electricity per year (Klimaatmonitor, 2018b). The energy expenditures for an average household in the neighbourhood is 2.7% of the household's annual income (Klimaatmonitor, 2017).

5.2.1 Buildings in the Neighbourhood

There are different types of buildings in the neighbourhood, the table presented below elaborates about various building-related parameters. These parameters are indented using three primary sources (National Energy Atlas, no date), (OpenStreetMap Contributors, 2018) and (Google Maps, no date). See to 0.

Table 6 Description of Neighbourhood Buildings

Building Parameters	1955 Row House Type1	1955 Row House Type2	1955 Apartment	Above 2000 Row House	Above 2000 Apartment
Energy Label	D	C	B	A	A
Construction Year	1955	1955	1955	2004	2004
Ground Floor Area	43.5 m^2	35 m^2	70 m^2	60 m^2	108 m^2
Number of Floors	2	2	1	3	1
Total Floor Area	87 m^2	70 m^2	70 m^2	180 m^2	108 m^2
Building Type	Row House	Row House	Apartment	Row House	Apartment
Number of Houses*	380	164	444	171	734

*The number of houses under each building category is identified by analysing the household data present in (OpenStreetMap Contributors, 2018) using QGIS and by surveying the neighbourhood in the street view provided by google maps. Refer to Appendix A for information related to building count.

Figure 11 Buildings in Buurt -9 (Google Maps, no date)

5.2.1.1 *Defining Building Envelope*

To define the building envelope of various identified buildings (see Table 6) in Buurt-9, the data provided by Government of the Netherlands (2012) on the residential buildings are used for identifying insulation levels. Then the identified insulation values are complemented with the building envelope arrangement described by Gaetani *et al.* (2019) for residential buildings to identify thermal properties of the building.

Note: The data provided by Government of the Netherlands (2012) is selected because certified inspectors have collected the data by conducting an extensive physical home survey. The inspectors note among many things the insulation levels, type of windows, gas and electricity demand of the household and the other physical properties of buildings. As the surveyed data contains information about different types of houses from different periods, the data is used for defining building envelope properties.

5.2.1.1.1 Building Insulation Levels

To find building insulation values, the process described below is used. Inputs parameters such as 'building period', 'energy label' (National Energy Atlas, no date), 'building floor area' (OpenStreetMap Contributors, 2018) and 'building type' (Google Maps, 2019) are fed to WooN Onderzoek data set (Government of the Netherlands, 2012) and corresponding building insulation values are obtained for each building type.

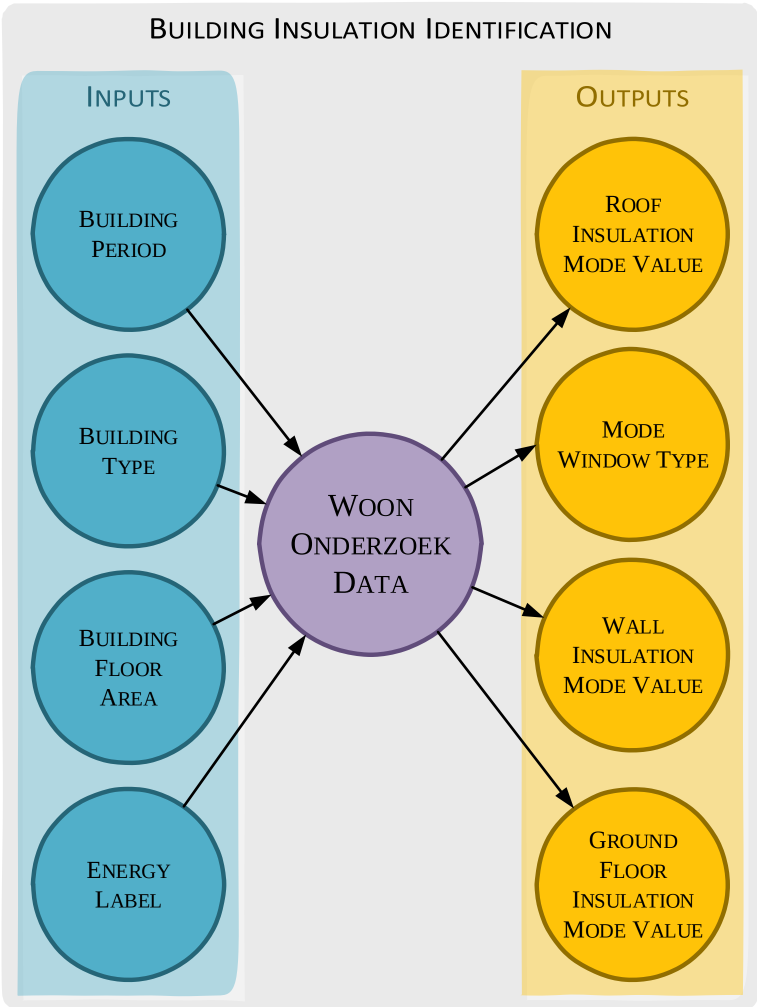

Figure 12 Building Properties Identification

The table below lists the most probable 'insulation thickness' for each building type, based on the input parameters of the building (presented in Table 6). For all the buildings it is assumed that expanded polystyrene foam (EPS) is used as the insulating material. EPS is used because of its significant market share and better price-performance when compared to other insulating materials (Duijve, 2012).

Table 7 Building Insulation Values Obtained from (Government of the Netherlands, 2012)

Building Element	1955 Row House Type 1	1955 Row House Type 1	1955 Apartment	Above 2000 Row House	Above 2000 Apartment
Ground Floor	-	-	50 mm	230 mm	130mm
External Wall	50 mm	50 mm	60 mm	120 mm	100mm
External Wall Cavity	Yes	Yes	Yes	-	-
Roof	50 mm	50 mm	100 mm	90 mm	100 mm
Window	Double Glazing	Double Glazing	Double Glazing	Double HR	Double HR

The obtained values for insulation thickness are integrated into building 'Envelope-Construction' for Dutch buildings described by (Gaetani *et al.*, 2019) to obtain thermal properties. The table presented below describe the expected thermal properties of various buildings in Buurt-9.

Table 8 Thermal Properties of the Buildings in Buurt-9

Building Element	1955 Row House Type 1	1955 Row House Type 1	1955 Apartment	Above 2000 Row House	Above 2000 Apartment
Ground Floor Insulation $\frac{m2.K}{W}$	0.1	0.1	1.6	6.8	4.0
External Wall Insulation $\frac{m2.K}{W}$	1.9	1.9	2.1	3.7	3.1
Roof Insulation $\frac{m2.K}{W}$	2.0	2.0	3.2	2.8	3.0
Window $\frac{W}{m2.K}$	3.3	3.3	3.3	1.1	1.1

5.3 RENOVATION PACKAGES

Energy renovation is an important step towards energy conservation. Previous studies evaluating the impact of energy renovation, have defined renovation packages based on standards (new building/net-zero building) and identified the best performing package (Costa, 2017; Cetin-Öztürk, 2018). One of the limitations of using a predefined package is that the best performing package may or may not meet the energy-loan requirements (Nationaal Energiebespaarfonds, 2018). As a result, financially constrained homeowners cannot adopt the best performing option. Also, in some cases, predefined renovation packages lead to marginal energy savings, as a result of the building's existing insulation.

Hence, this subsection uses an alternative strategy for defining the renovation packages that can meet the energy loan standards and lead to significant energy savings. Firstly, three basic renovation options are defined, then an alternative strategy is used to adapt the renovation options based building's pre-existing insulation condition and energy loan requirements.

5.3.1 Options for Renovating Building

For renovating the building, three renovation options are considered. These options are defined based on predefined standards and based on building renovation research.

5.3.1.1 Renovation Option 1 – Comprehensive Basic

For the first option, all aspects of the building fabric are considered equally important. Thus, it is named *comprehensive-basic*. This option is defined based on two criteria 1. the renovation requirements for old buildings (Netherlands Enterprise Agency, no date); and 2. the findings of Gaetani *et al.* (2019).

Firstly, it is required by law, that households must meet minimum criteria mentioned by the Netherlands Enterprise Agency (no date) for performing energy renovations. Secondly, in the research conducted by Gaetani *et al.* (2019), it has been identified that "*increasing the insulation levels of a roof or floor element has minor/insignificant impact on energy-savings*". Also, in the same research, it has been identified that "higher *insulation values of wall and glazing, has a significant and positive effect on energy savings*".

Thus, the renovation option-1 is defined such that, it meets the minimum renovation requirements specified by (Netherlands Enterprise Agency, no date) and take into consideration higher insulation values for wall and glazing from (Gaetani *et al.*, 2019). The table presented below is the requirements for renovation option 1.

Table 9 Insulation Requirements for Renovation Option 1 - [1]Gaetani et al., 2019, [2]Netherlands Enterprise Agency, no date

	Wall $\frac{m^2.K}{W}$	Roof $\frac{m^2.K}{W}$	Floor $\frac{m^2.K}{W}$	Window $\frac{W}{m^2.K}$
Minimum Requirement	2.3[1]	2[2]	2.5[2]	1.1 (HP Glazing)[1]

5.3.1.2 Renovation Option 2 – Extensive Wall

The renovation option 2 is similar to the renovation option 1. The only significant difference between renovation option 1 and renovation option 2 is that the insulation value for the wall has been increased significantly. The wall insulation has been increased because walls with higher insulation lead to higher energy savings (Gaetani *et al.*, 2019).

The maximum R-value for the wall is restricted to "7" because further values can lead to increased risk of overheating and negatively impact occupant comfort (Cetin-Öztürk, 2018). Other aspects of the building fabric are left unchanged because the roof and floor has a minor effect on energy savings. The glazing is left unchanged because the return on investment for triple HP glazing is low (Except, 2009).

Table 10 Insulation Requirements for Renovation Option 2

	Wall $\frac{m^2.K}{W}$	Roof $\frac{m^2.K}{W}$	Floor $\frac{m^2.K}{W}$	Window $\frac{W}{m^2.K}$
Minimum Requirement	7	2	2.5	1.1 (HP Glazing)

5.3.1.3 Renovation Option 3 – Comprehensive High

Third renovation option is called comprehensive high and it is to be one of the highly energy-efficient options by (Nationaal Energiebespaarfonds, 2018). This option is based on the minimum insulation requirements for new buildings (BRISwarenhuis, no date). The motivation for choosing this renovation option is based on the results of (Alavirad, 2018) and (Cetin-Öztürk, 2018). In their corresponding studies, it has been found that this option is economical and leads to low risks, compared to other highly insulated options.

Table 11 Insulation Requirements for Renovation Option 3 (Nationaal Energiebespaarfonds, 2018)

	Wall $\frac{m^2.K}{W}$	Roof $\frac{m^2.K}{W}$	Floor $\frac{m^2.K}{W}$	Window $\frac{W}{m^2.K}$
Minimum Requirement	5.0	6.5	4.0	1.1 (HP Glazing)

5.3.2 Minimum Loan Requirement

In the above text, three renovation options are defined based on the literature and other standards. However, only 'renovation option 3' is eligible for an energy efficiency renovation loan. To qualify for energy loan, the homeowner must meet the minimum requirements specified by (Nationaal Energiebespaarfonds, 2018). Thus, the renovation options must be further adapted to meet the minimum loan requirements (specified in the table below).

Table 12 Minimum R-Value for Loan Qualification (Nationaal Energiebespaarfonds, 2018)

	Wall $\frac{m^2.K}{W}$	Roof $\frac{m^2.K}{W}$	Floor $\frac{m^2.K}{W}$
Minimum Requirement	3.5	3.5	3.5

5.3.3 Sub-economical Renovation Improvements

Also, it can be noted that in the Buurt 9 neighbourhood, there are different types of buildings, with different insulation levels. By directly improving the insulation value of all buildings to a particular level, mentioned by each 'renovation option', it can be uneconomical for a few buildings to renovate.

This situation is expected because, for some cases, the building may marginally fail to meet the minimum criteria of the package. As a result, marginally improving the building's insulation can lead to marginal energy savings. In such cases, the cost of renovation outweighs the energy savings costs.

Thus, to avoid marginal improvement and to make a building qualifiable for an energy renovation loan, an alternative approach is required for defining renovation packages. Hence, the next sub-section elaborates about the method for updating the *renovation options* (defined above) to qualify for an *energy renovation loan*, and also lead to significant improvement.

5.3.4 Customizing Renovation Option Based on Building's Exiting Insulation

To explain 'how' the renovation requirement for each building is defined, an example (presented below) is used for the illustration. In the example, a hypothetical building 'A' is required to be upgraded to a hypothetical renovation option 'H'. So, in the first step – the building's current insulation value (R-Value) is subtracted from the hypothetical renovation option's insulation values, to obtain the difference. Then in the second step – the building's current insulation value (R-Value) is subtracted from the loan requirement's minimum insulation values. In the third step – if the resulting difference in the step-1 is greater than 0, then it will be compared with the difference obtained in the step-2. If the difference from the step-2 is greater than the difference from step-1, then the difference from the step-2 will be used for increasing the R-value. Otherwise, the (positive) difference from step-1 will be used. Further, to avoid marginal improvements, the values from step-3 will be compared with the minimum R-values increment required for renovating the building. If the R-value increment from step-3 is smaller than the minimum required R-value increment, then the latter's value will be used for improving the R-value. Minimum R-values are defined based on the findings from (Gaetani *et al.*, 2019).

Table 13 Minimum R-Value Addition for Renovation (Gaetani et al., 2019)

	Wall $\frac{m^2.K}{W}$	Roof $\frac{m^2.K}{W}$	Floor $\frac{m^2.K}{W}$
Minimum Requirement	2.3	1.14	1.14

5.3.5 Renovation Packages

The renovation values for each neighbourhood buildings are defined using the process explained above and they are presented as renovation packages below. The below-listed insulation values will be used for testing the implications of energy efficiency renovations, on various neighbourhood buildings.

Table 14 Renovation Package -1 Comprehensive Basic for the Buildings in the neighbourhood

Building Element	1955 Row House Type 1	1955 Row House Type 1	1955 Apartment	Above 2000 Row House	Above 2000 Apartment
Ground Floor Insulation $\frac{m2.K}{W}$	3.5	3.5	3.2	2.9	3.2
External Wall Insulation $\frac{m2.K}{W}$	4.0	4.0	4.0	3.7	3.1
Roof Insulation $\frac{m2.K}{W}$	3.5	3.5	3.5	6.7	3.8

Window $\frac{W}{m2.K}$	3.5	3.5	3.2	2.9	3.2

Table 15 Renovation Package -2 Extensive Wall for the Buildings in the neighbourhood

Building Element	1955 Row House Type 1	1955 Row House Type 1	1955 Apartment	Above 2000 Row House	Above 2000 Apartment
Ground Floor Insulation $\frac{m2.K}{W}$	3.5	3.5	3.2	2.9	3.2
External Wall Insulation $\frac{m2.K}{W}$	7.0	7.0	7.0	7.0	7.0
Roof Insulation $\frac{m2.K}{W}$	3.5	3.5	3.5	6.7	3.8
Window $\frac{W}{m2.K}$	3.5	3.5	3.2	2.9	3.2

Table 16 Renovation Package -3 Comprehensive High for the Buildings in the neighbourhood

Building Element	1955 Row House Type 1	1955 Row House Type 1	1955 Apartment	Above 2000 Row House	Above 2000 Apartment
Ground Floor Insulation $\frac{m2.K}{W}$	6.5	6.5	6.5	6.5	6.5
External Wall Insulation $\frac{m2.K}{W}$	5.0	5.0	5.0	6.0	5.4
Roof Insulation $\frac{m2.K}{W}$	4.0	4.0	4.0	6.7	4.9
Window $\frac{W}{m2.K}$	6.5	6.5	6.5	6.5	6.5

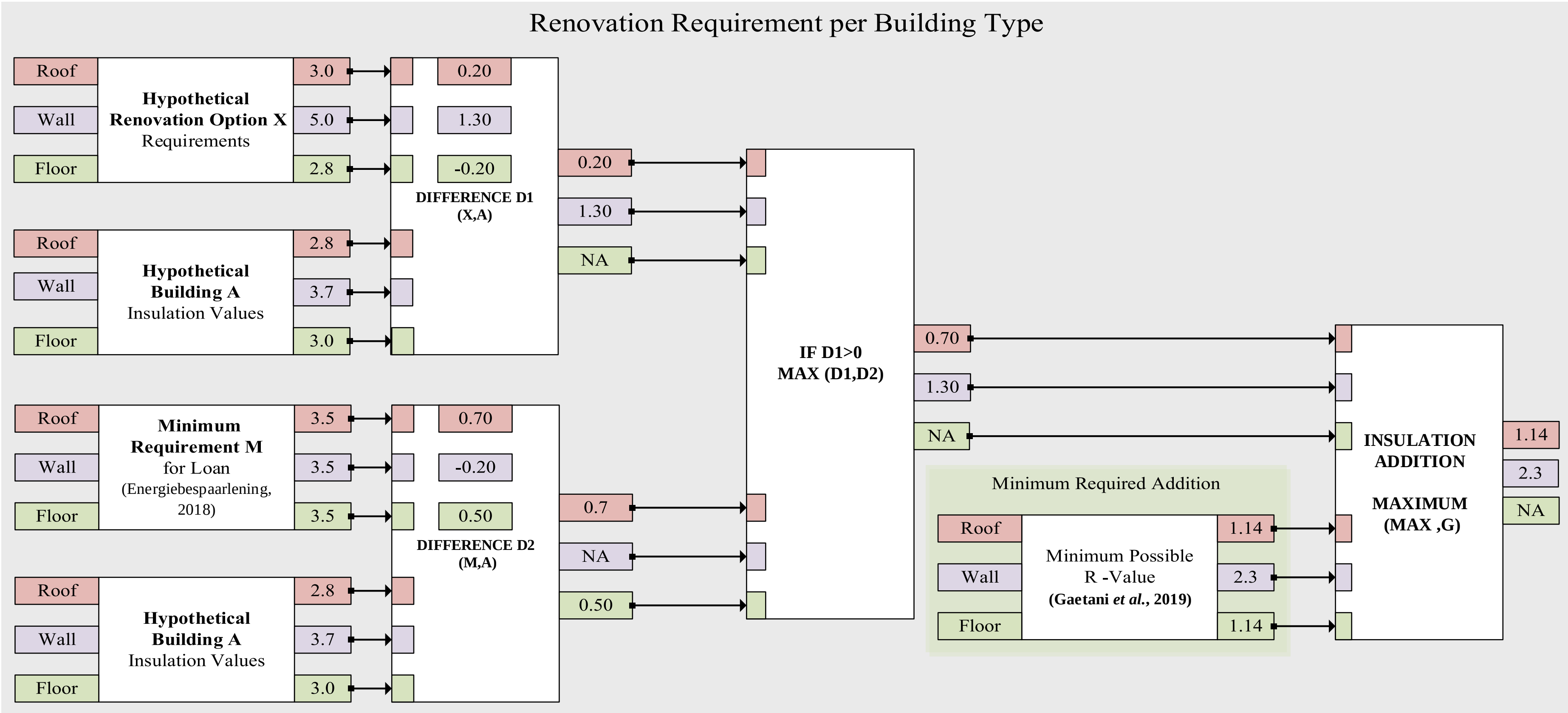

Figure 13 Example for Defining Minimum Renovation Requirement

6 BUILDING ENERGY MODELLING AND ASSUMPTIONS

6.1 MODELLING RESOLUTION AND COMPLEXITY

Model complexity has an impact on energy demand simulations. To develop simulation models, previous master theses investigating the impact of energy renovation on row houses Alavirad (2018) and apartment building Cetin-Öztürk (2018) are used as references. The identified master theses have been used for developing simulation models because the simulation scope of identified studies is aligning with the simulation scope of the current study. Alavirad (2018) investigates the energy-saving potential for renovating row houses in Rotterdam area. Cetin-Öztürk (2018) uses building simulation for examining the potential of converting an apartment building into an energy-neutral building.

6.2 OCCUPANT BEHAVIOUR

According to Schipper *et al.* (1989) and Santin (2016) occupant's behaviour has a significant influence on energy consumption. According to Schipper *et al.* (1989) half of the building's energy use is dependent on the occupants and their behaviour. Occupant behaviour includes aspects such as occupancy pattern, heating setpoint, ventilation rate, domestic hot water demand (DHW) and electricity demand. To make accurate predictions of energy demand, it necessary to have an accurate depiction of occupant's behaviour (Kotireddy, 2018). Thus, the section discusses various household specific attributes that influence heating energy demand of a building.

This research focuses on four major types of households - '*Single Adult*', '*Two Adult*', '*Single Senior*' and '*Family*' for assessing the impact of transition. The choice is limited to the identified households because, it has people of different age groups, with distinguishable lifestyles (Guerra-Santin *et al.*, 2018)

6.2.1 Occupancy Pattern

Occupancy profile refers to the usage probability of a building or a building space, and it is represented as a probability plot, continuously varying between 0 and 1 for different time-periods of the day (Barbosa, Mateus and Bragança, 2016). Occupancy factor of 1 at a given time, means that the building is fully occupied during that time. Similarly, 0 means that the building is always empty, at the given time. In many cases, the occupancy patterns are developed to represent typical days (e.g. working days, holidays and weekends). Further occupancy pattern can be used for representing the occupancy of an entire building or space (e.g. living room, bedroom). Further, depending on the type of household, the occupancy patterns are expected to vary from household to household (Guerra-Santin and Silvester, 2016). To create representative occupancy profiles, some studies have used Time Use Surveys (TUS) data for deriving the occupancy pattern (Wilke, 2013; Aerts *et al.*, 2014; Barbosa, Mateus and Bragança, 2016). The TUS data is a national-level activity-archive, that contains information about individuals of a household and their activity patterns (activity name, time of execution and duration of execution) (Eurostat, 2019). Due to unavailability of TUS data, this study uses occupancy profiles derived from WooN dataset (Government of the Netherlands, 2012) by (Guerra-Santin and Silvester, 2016). Regarding household occupancy, the WooN dataset is similar to TUS dataset, and it collects occupant and household information using a 'household questionnaire' (Government of the Netherlands, 2012). For this study, the occupancy profiles derived by Guerra-Santin and Silvester (2016) for each day of the week was simplified to weekday and weekend profiles. The simplified occupancy profiles based on Guerra-Santin and Silvester (2016), for each type of considered household, is presented in the Appendix.

6.2.2 Heating Setpoint

According to Kotireddy (2018), heat setpoint is a major influencer of heating demand. Heating setpoint captures the indoor temperature preference of a household and it varying from household to household (Ministerie van VROM, 2009). The hourly heating setpoint temperatures for living room is derived from WooN data set Government of the Netherlands (2012) and from Cetin-Öztürk (2018). The setpoint temperatures for the bedroom, are based on the temperature values suggested by Cetin-Öztürk (2018). The setpoint temperature used for building simulations is presented in the Appendix.

6.2.3 Domestic Hot Water

Domestic hot water (DHW) refers to hot water requirements for a household and these requirements are assumed to be insensitive to external conditions (size of a building, weather etc.). However, these requirements are largely dependent on the household size and number of people living in the household. For this study, it is assumed that on average the demand for domestic hot water is 40 l/person/day (Kotireddy, 2018). The consumption profile for DHW is derived from Johann Alrutz (2019) because the profile is based on the pattern, described in NEN 7120:2011 standard for DHW consumption.

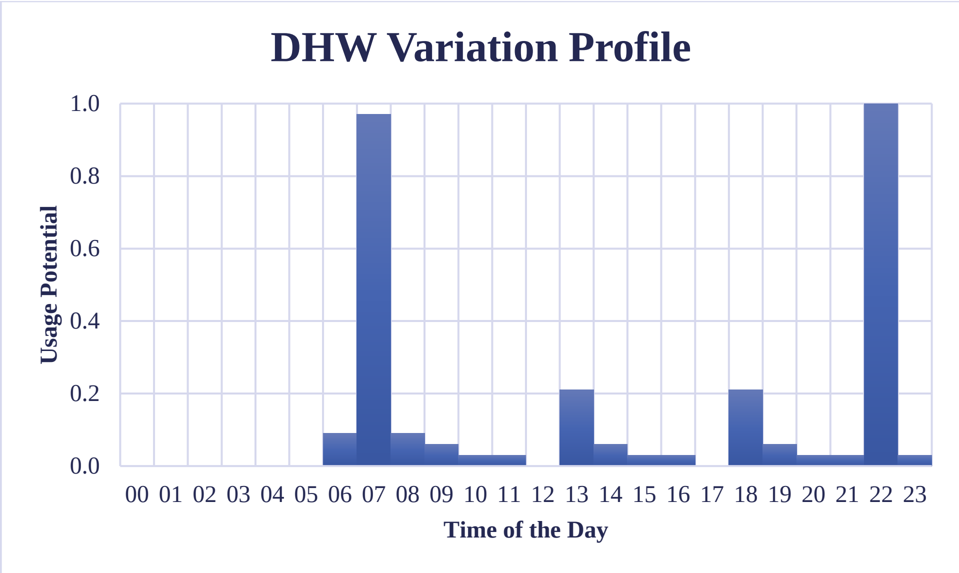

Figure 14 Domestic Hot Water Demand Profile for Household from (Johann Alrutz, 2019)

6.2.4 Internal Heat Gains

Internal heat gain refers to sensible and latent heat emitted within an internal space of the building. Unlike, the above-identified factors, internal heat gains have a negative impact on the heating demand, and it reduces the total energy demand. Two primary factors that contribute to internal heat gains are occupants and electric and lighting appliances.

6.2.4.1 Occupants

Internal heat gain caused by occupants is a result of their metabolic activity. According (*Internal Heat Gains*, no date) the average metabolic activity of an adult male is 130 W (75W Sensible heat, 55W Latent heat) seated or while performing light work. Further, the metabolic activity of an adult female is 85% of the adult male, and for children, the metabolic activity is 75% of adult male (Johann Alrutz, 2019). For this study, the metabolic activity of an average individual living in the Buurt-9 neighbourhood is calculated by combining the metabolic variations for male, female and children with their corresponding share of percentages in the neighbourhood (CBS StatLine, 2016). Thus, for Buurt-9 the metabolic activity of an individual is assumed to be 89% the metabolic activity of an adult male while performing light work.

Since the household is not always occupied, the average metabolic activity of the occupant and size of the household is coupled to the occupancy profile of the household.

6.2.4.2 Lighting and Electric Appliances

For lighting and electric appliances, the internal heat gains are defined based on the average value for electricity consumption identified by Guerra-Santin and Silvester (2016).

Table 17 Electricity Consumption for Different Types of Households

	Source	Two Adults	Single Adult	Single Senior	Family
Yearly Consumption	(Guerra-Santin and Silvester, 2016)	3479.4	2341.3	2162.2	4309.1

The load profile for electric appliances and lighting has is derived from Cetin-Öztürk (2018), as the electricity consumption profile is representative of usage pattern for electric and lighting appliances.

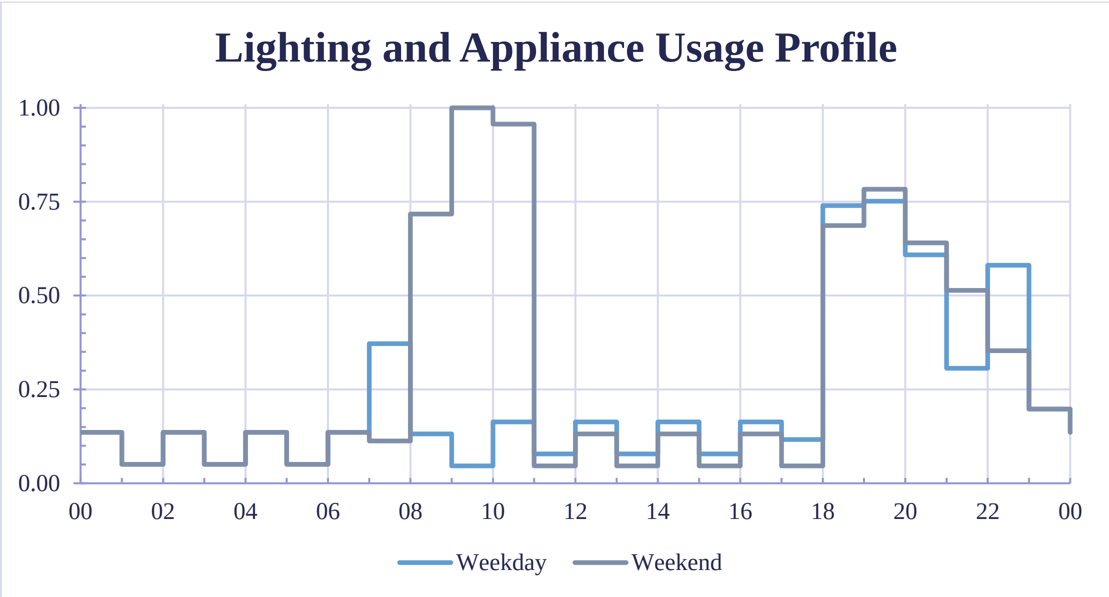

Figure 15 Lighting and Appliance Usage Profile from (Cetin-Öztürk, 2018)

6.3 Ventilation and Infiltration

According to the Dutch building code, the minimum required ventilation for residential buildings is 0.8 ach. However, for this project, a constant ventilation rate of 0.8 ach is assumed based on Kotireddy (2018). For cooling purposes, the study uses natural ventilation and sets the maximum ventilation rate to 5 ach. This value is determined based on the typical airflow rate when the windows are kept fully open (Kotireddy, 2018).

6.4 Variations to Occupant Behavior

As the occupant behaviour influences 50% of energy demand, it becomes important for this study to investigate the impact of behavioural changes. In this regard, the rebound effect is an actual situation where the expected energy reductions from energy conservation are offset by the behavioural changes of the users. According to Santangelo and Tondelli (2017), the energy demand of a household increases after energy renovation because the occupants pay less attention to their energy-related behaviour and consume more energy. This attitude is a result of cognitive belief "*…increase of energy efficiency in buildings should automatically be translated to a decrease of consumption, no matter the level of usage and their behaviour*" (Santangelo and Tondelli, 2017).

Thus, the study will assess the impact of changing the heating set-point temperature. The heating setpoint has been selected as the key variable for influencing the occupant behaviour because it is the only behavioural variable according to Kotireddy (2018) that has a significant impact on economic aspects of energy renovations. Also in other studies, the heating setpoint has been recognized as an influential variable affecting energy demand of a building significantly (Owen, Mitchell and Unsworth, 2013; Guerra-Santin *et al.*, 2018; Hamburg and Kalamees, 2018).

According to Hamburg and Kalamees (2018), the maximum indoor temperature for an average household after renovation is found to be 22 ºC. Further, it can be observed from energy-intensive households (>20 ºC, all day) that indoor temperature is always constant, irrespective of the occupancy (Guerra-Santin and Silvester, 2016). Thus, the alternative heating setpoint for the living room is set at 22 ºC, all day. Whereas for bedroom, the temperature is assumed to be 18 ºC, based on senior households (Guerra-Santin and Silvester, 2016). Further, to investigate the impact of moderate rebound behaviour, an alternative setpoint temperature of 20 ºC for the whole-day is assumed based on Love (2012).

6.5 CLIMATE AND WEATHER

Climate influences the energy demand of a building and it is necessary to use weather data for simulating the energy demand. Thus, for this study, the weather file of Amsterdam is used for modelling the energy demand

7 RESULTS – ENERGY SIMULATION AND TECHNO-ECONOMIC ANALYSIS

This chapter presents the results of the simulation and techno-economic assessment. First, the energy demand for various buildings is compared using the WooN Onderzoek data set (Government of the Netherlands, 2012). Then the simulated energy demand for various buildings is presented. Thirdly, the impact of energy renovation on thermal comfort is presented. Consecutively, the impact of EROs and NGAs on CO_2 emissions and Cost savings are presented for Type-1 1955-Between House, occupied by a family.

Later the key performance evaluations (Cost savings, CO_2, thermal comfort) for EROs and NGAs are combined into a scatter plot and then the attractive options for a family household are presented. Followed by which, the impact of delaying the EROs or/and NGOs on the attractiveness is presented for the family household.

After which, the attractiveness evaluation for Type 1 1955-Between House, occupied by a single adult, single senior and two adult households are discussed briefly (i.e. the renovation and NGA adoption are performed in 2020). Then an overview of various neighbourhood buildings concerning economic performance, environmental performance and thermal comfort is provided.

7.1 SIMULATED MODELS – OVERVIEW

This subsection gives an overview of various building simulation models, performed for this case study. The below figure is a parallel coordinates plot and it gives a pictorial overview of various combinations of all the performed simulations (building type, orientation, household type, temperature and renovation preference). Parallel coordinates plot is used for visualizing high dimensional data. In the below-presented image, the plot is used to picturising the aspects of each simulation model. For example, model 487 is a renovated east/west oriented corner house2 constructed in 1955, occupied by a senior citizen, operating at set point 20 ºC. The house is renovated to extensive wall conditions. Similarly, model 192 is a non-renovated north-oriented corner house, constructed after 2000, occupied by two adults, and it is operating at set point 22 ºC.

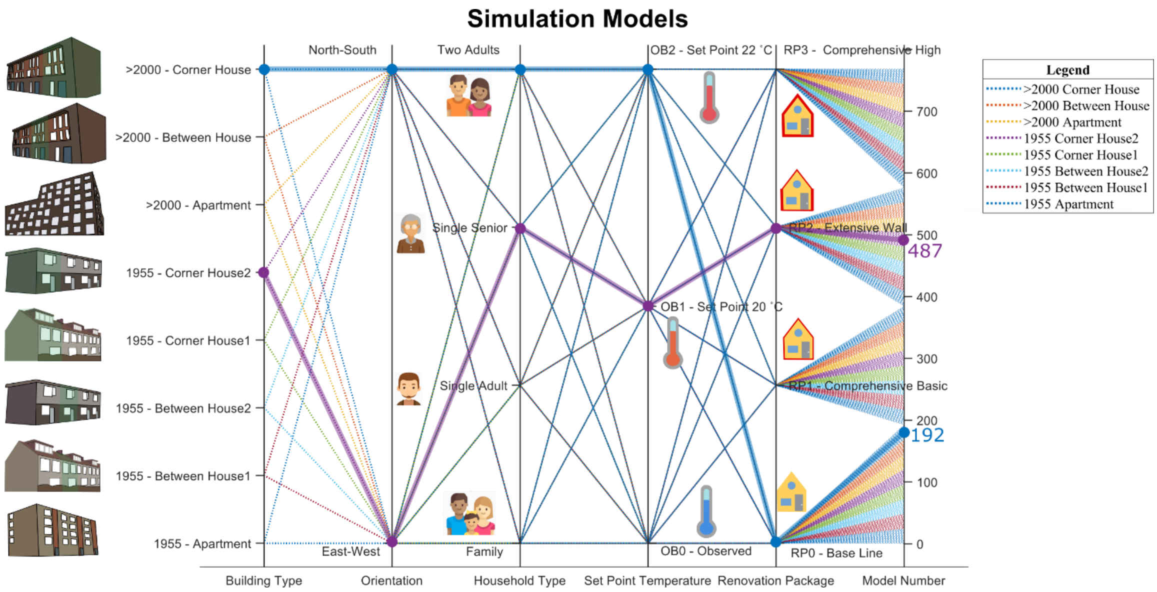

Figure 16 Overview of Simulation Models using Parallel Coordinates Plot

For this case study, a total of 768 simulation models are created for understanding the impact of energy renovations on households. A total of 768 models are created for this case study, each model is a result of combining 8 "*building types*" with 2 "*building orientation*", 4 types of "*household*", 3 "*set point"* preferences and 4 "*renovation*" conditions.

$$Simulation\ models = 8 \times 2 \times 4 \times 3 \times 4 \quad - (21)$$

7.1.1 Energy Demand Baseline Model

In this subsection, the building simulation results for "*1955 – Between House1*" with respect to baseline conditions is presented. The bases line refers to the criteria when the building is simulated using 'observed set point temperature' and without any insulation improvements. Only one type of building is selected for presenting results because it gives the reader a sufficient overview, eliminating superfluous graphs. For other buildings' simulation results, please refer to the attached data set.

In the graph presented below it can be observed that single-senior household has the highest demand for overall heating needs. Since single senior households have a preference for higher setpoint temperatures >20 ºC and it leads to higher space heating needs. Among all the considered households, a single adult household has the lowest heat demand because the temperature preference is lowest and hot water demand is also lowest (Refer to appendix). The space heating demand is lowest for a family household because it has high internal heat gains, in comparison to other households. High internal gains are a result of high electricity usage and high household occupancy. For family household, hot water demand is highest, because it has more residents.

Overall, it can be noted that the north-south oriented house has low heating demand in comparison east-west oriented house. This observation is a direct result of the building's design because a north-south building has high solar exposure in comparison to east-west oriented building.

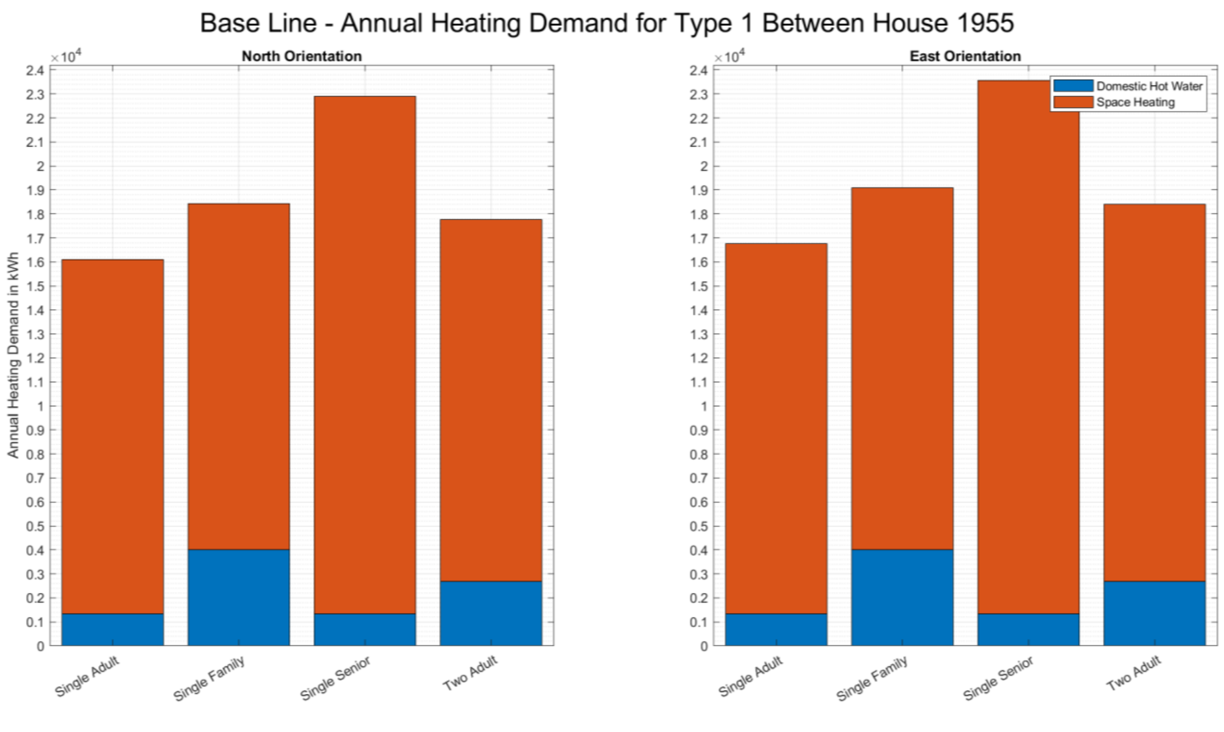

Figure 17 Baseline Annual Heating Demand for 1955 Between House 1

7.1.2 Energy Demand Comparison

In this subsection, the baseline models for various neighbourhood buildings is validated using actual energy consumption data. Actual data is obtained from WooN Onderzoek data set provided by (Government of the Netherlands, 2012). One of the limitations of WooN data is that the building's geometric is not included in the data. Thus, a proxy-metric 'energy use intensity (EUI)' is used for comparing simulated energy demand with actual gas consumption. With the help of EUI, it is possible to compare buildings with different geometry. Since the EUI normalizes the building's annual energy demand as a unit of building's gross floor area (geometric feature). EUI calculation procedure is further explained in the Chapter 4 Methods.

In the figure presented below, the bar plot presents the actual annual-energy-consumption in $\frac{KWh}{m^2}$ for various types of buildings from WooN dataset (buildings from data set is selected using building features presented in Table 6 Description of Neighbourhood Building). The scatter plot presents the simulated annual-energy-demand in $\frac{KWh}{m^2}$ for the neighbourhood buildings. The colour of 'scatter' represents the type of household and its corresponding overall heating energy demand. As the simulated heating demand for north-south and east-west houses is approximately the same, only the heating demand for a north-south house is plotted.

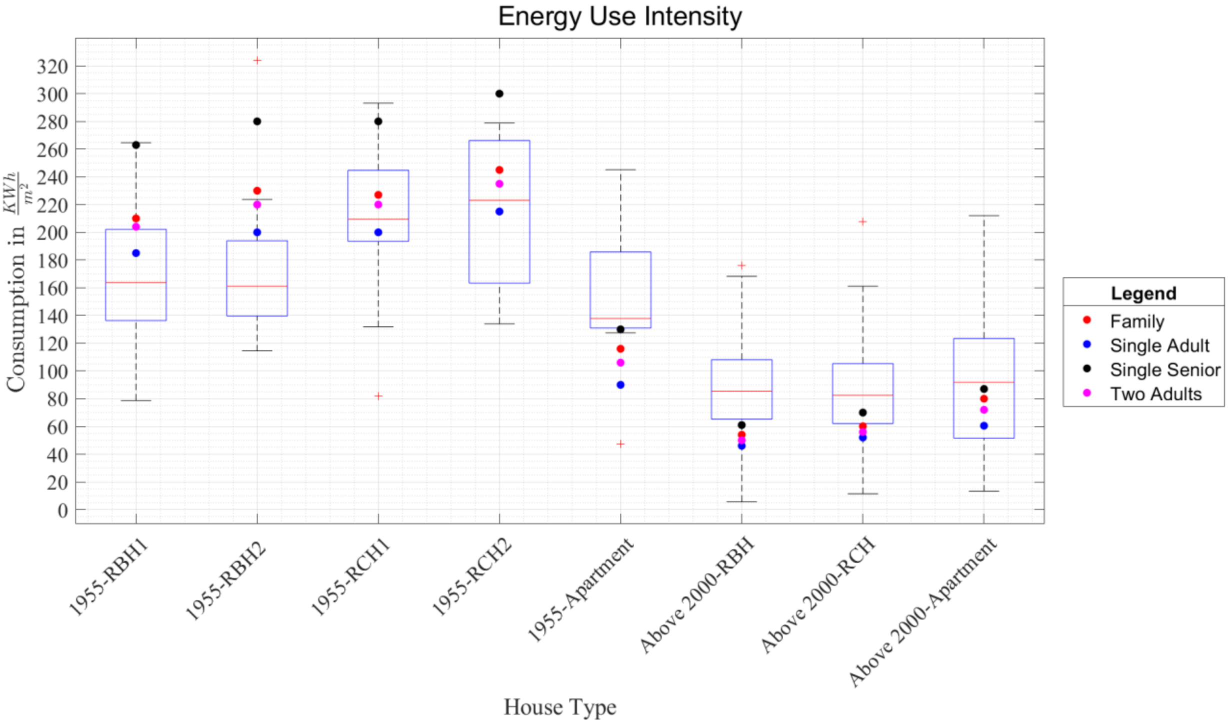

Figure 18 Energy demand Comparison - Energy demand Bar plot from (Government of the Netherlands, 2012) vs Energy demand Scatter Plot from Simulation

It can be observed from the above figure – that for all neighbourhood buildings, the values for simulated energy demand is mostly within the minimum-maximum range of the box plot. Thus, baseline models are considered an appropriate representation of actual buildings. As a result, the base-line models are further used for investigating the impact of energy renovations.

It is intriguing to note that for older buildings (less insulated), the simulation model's estimates are greater than the median values. For relatively new buildings, the simulation model's estimates are lower than the median value. One of the reasons for this key observation is dependent on the baseline "*occupant behaviour*" assumption. In the above plot, for all types of buildings, the simulated energy demand is based on the "*observed setpoint temperature*".

Concerning the above-identified deviation between old and new buildings, Guerra Santin (2013) provides an explanation. A key differentiating aspect of both types of buildings is their insulation levels. Usually, older buildings in the Netherlands are less-insulated in comparison to newer buildings. According to (Guerra Santin, 2013) occupants from well-insulated buildings have a higher setpoint preference. Thus, their actual energy consumption is greater than the energy demand predicted by simulation models (assuming a regular observed-behaviour).

7.1.3 Energy Demand - Renovation Models

This sub-section presents the simulated energy demand for various renovation packages.

In the below-presented image, it can be observed that energy renovations decrease energy demand significantly. Within this study, *Between House1 – 1955* reaches maximum energy saving under the influence of *RP3 – Comprehensive High* option. The energy-saving potential for RP3 is 11000 kWh for Two Adults; 10250 kWh for Single Adult; 14700 kWh for Single senior; and 10900 kWh for Family households. 10000 kWh of heat is equal to 1077.5 m^3 of natural gas, based on 95% gas efficiency boiler.

From the below figure, it can be noted that renovation has no impact on domestic hot water demand. A family household has the highest demand for hot water, followed by two adults and then by single adult/senior. Post-renovation, it is interesting to note that *Family* household's demand for hot water is greater than the demand for space heating. *Family* households have a smaller demand for space heating because they have very high internal heat gains.

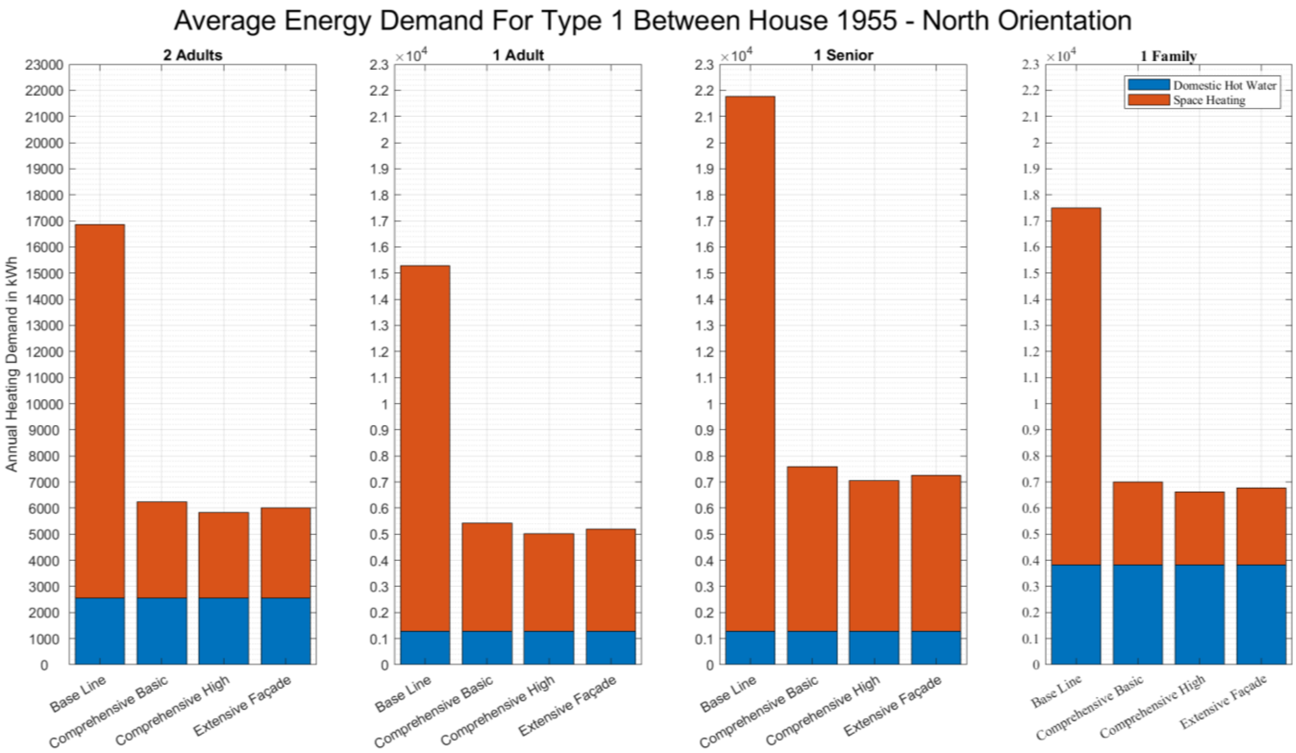

Figure 19 Stacked Energy Demand (simulated) Bar Plot for 1955 Between House1

Below-presented figure 20 shows the performance of various renovation options with respect to setpoint temperature variations. As a result of performing renovations, all households can achieve significant energy savings, despite shifting to a higher set point temperature 22˚C. *A single Adult* household has the lowest (45%) energy savings if the household switches to 22 ˚C setpoint temperature.

Additionally, it can be remarked from the figure – *Single Senior* household's energy savings is less sensitive to setpoint temperature variations; whereas *Single Adult* household's energy savings is more sensitive to setpoint variations (refer to Part: Reduction in Heating Demand). Energy reduction sensitivity is a result of the distance between "observed setpoint temperature" and other higher setpoint temperatures. For a single adult household, this distance is larger (≥3˚C) in comparison to a single senior household (≈1.5˚C).

The lower portion of the below-presented figure picturizes overall heating demand in kWh. From the box plots, it can be noted that after renovations all households have a maximum heating demand of 9000 kWh (from comprehensive basis). Only Family household has a demand of 1000 kWh and this exception is a result of very high hot water demand coupled with space heating needs.

Note: For all households except Senior household, the average daily setpoint temperature is ≤ 20˚C. For a senior household, the average daily setpoint temperature is marginally >20˚C. Hence, a senior household's energy consumption with setpoint temperature 20 ˚C is small compared with observed behaviour.

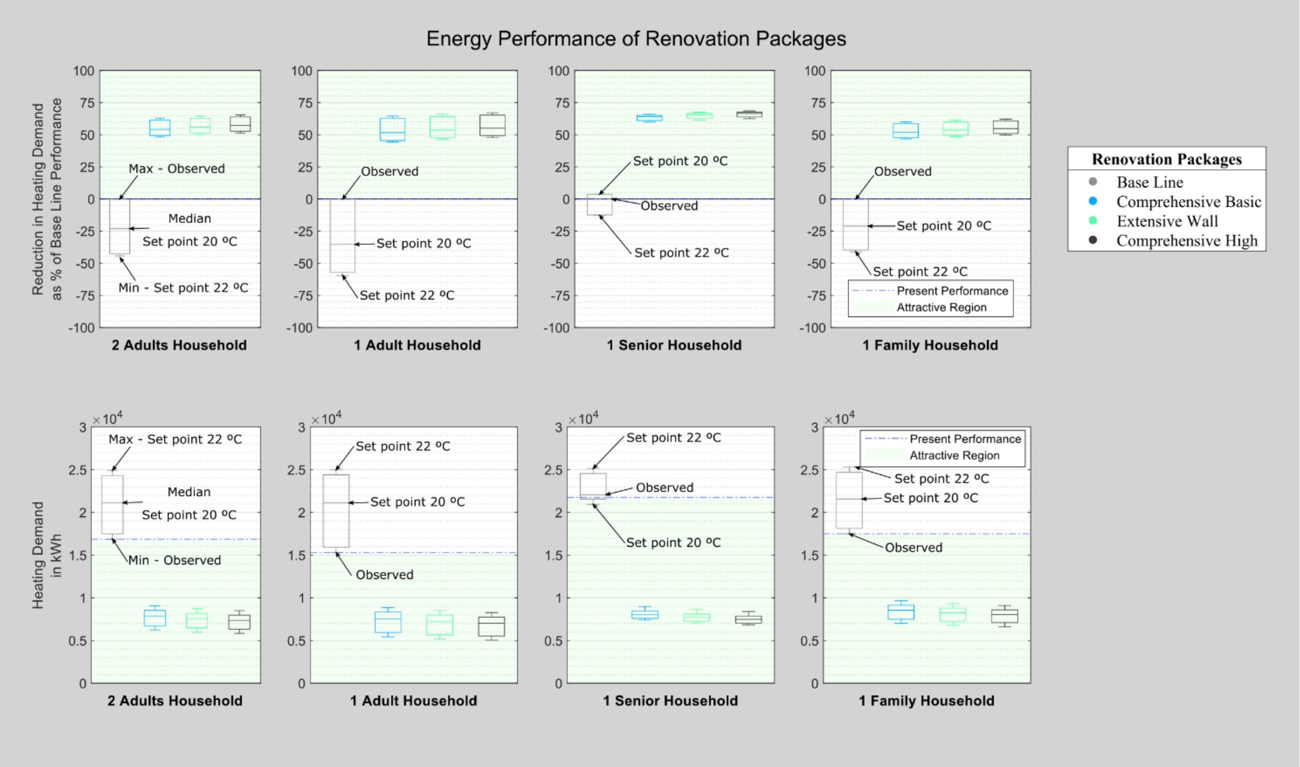

Figure 20 Energy Performance of Renovation Measures for 1955 Between House1

7.2 Thermal Comfort

The following figure presents the impact of energy renovations on occupant's thermal comfort. It can be noted that energy renovations have a positive impact on overall thermal comfort (upper box plot - % Occupancy within adaptive comfort limit). For instance – a *Two adult* household operating at observed behaviour experiences 46% of its annual occupancy within adaptive-comfort limits. Post-renovation, the occupancy-comfort increases from 46% to 56%, without changing the setpoint temperature of the household.

Thus, it can be said that by improving the insulation levels of a household, the occupants will experience higher comfort. Occupants experience higher comfort because the building capacity to lose heat has decreased with an increase in insulation. Insulation enables the building to store heat from various internal heat sources such as electric appliance and heating equipment for longer periods. So, when occupants re-enter the house after an outdoor activity, the need to reheat the house has decreased due to stored heat; also, the building is losing heat relatively slow (post-renovation). As a result, the building needs a shorter time to re-heat.

On the other hand, the limitation of energy renovation is that it causes overheating during summers. During summers, the building receives a significant amount of heat from the sun. Due to warmer weather, the building retains the heat from the sun and the internal process for longer periods. Thus, households experience hot indoor temperatures.

Least affected households by overheating are single adult and senior (≈7% of occupancy) households, as these households have minimum occupancy and the usage of electric appliances is also minimal. Whereas family household is most affected (≈18% of occupancy) by overheating because it has very high occupancy and electric appliance usage.

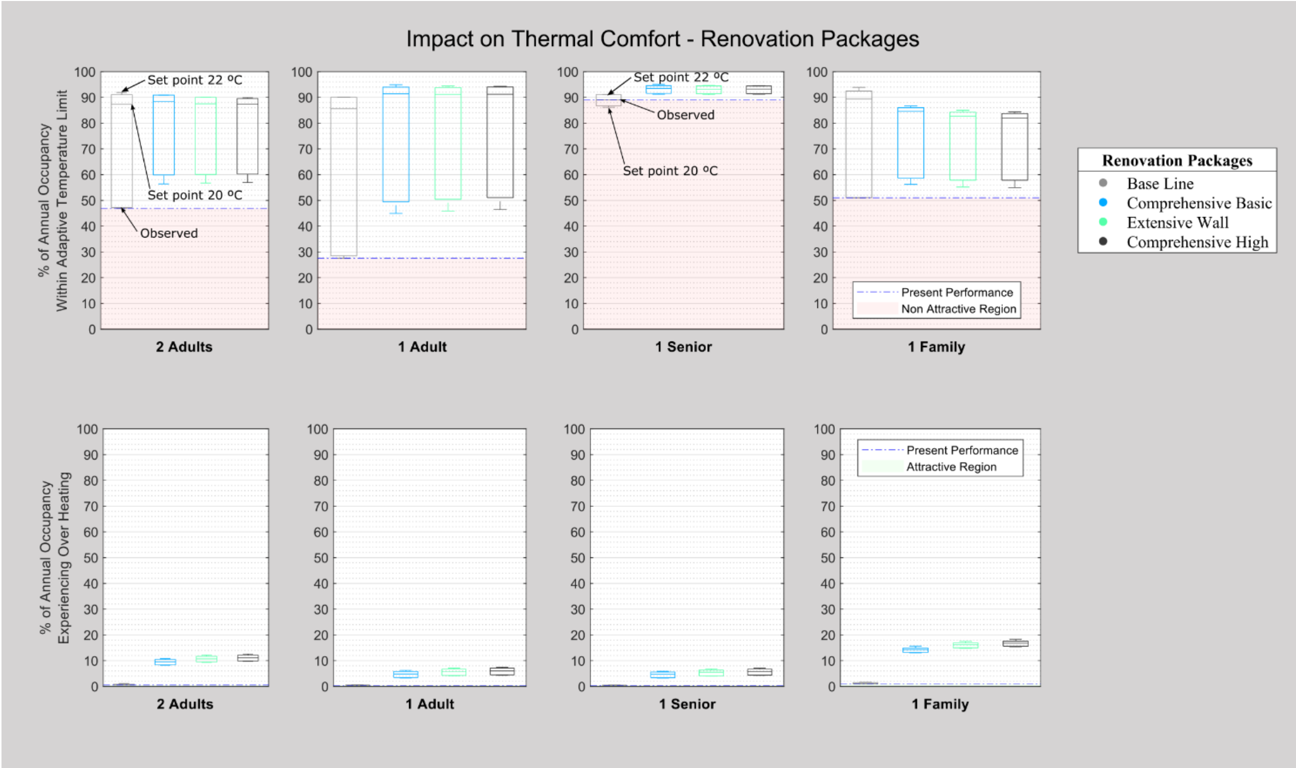

Figure 21 Impact of Renovations measures on Thermal Comfort for 1955 Between House 1

Note: In this study, it considered that thermal comfort is not affected by the heating equipment.

7.3 TECHNO-ECONOMIC ASSESSMENT MODELS OVERVIEW

This subsection presents an overview of various techno-economic models for evaluating the impact of renovations and heating options. The below figure is a parallel coordinate plot, visualizing the potential operating conditions for each neighbourhood building. Within this study, a total of 4608 techno-economic models are created for assessing the techno-economic impact.

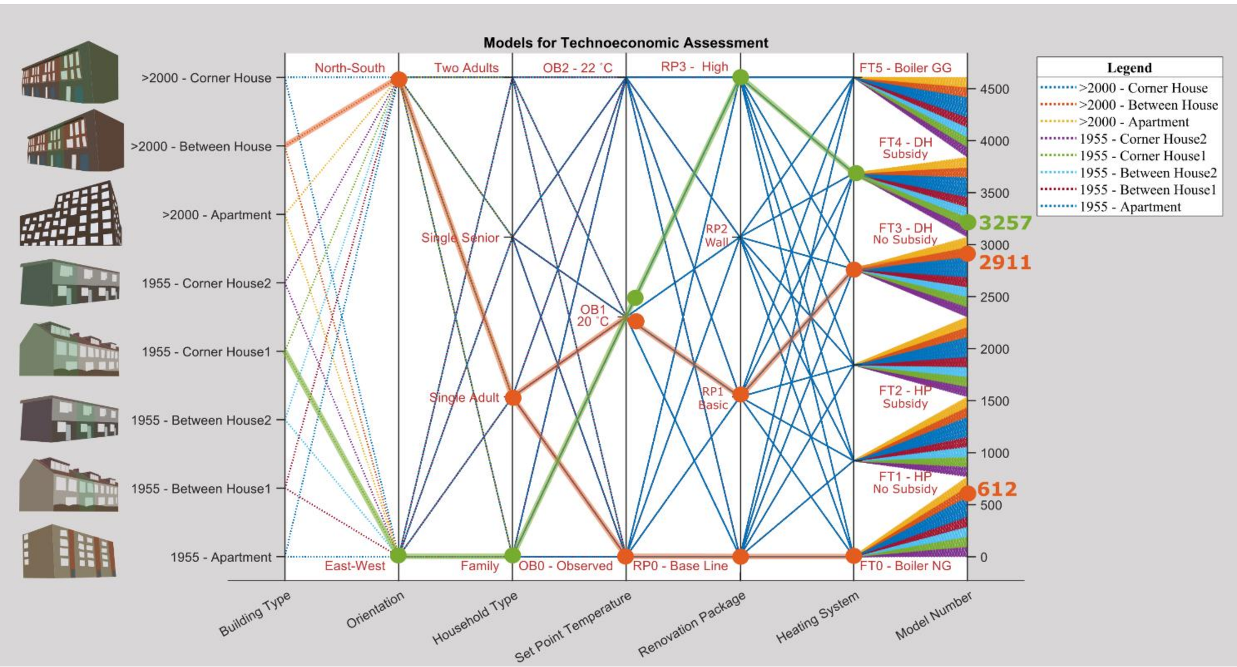

Figure 22 Parallel Plot Overview for Techno-economic Assessment Models

In the above figure 22, the techno-economic model 3257 represents a renovated corner house1 from 1955 with east/west orientation. A family household occupies the building, and the preferred setpoint temperature is 20 ºC. Further, the building is renovated to renovation levels of comprehensive high and it is using district heat with the help of subsidy. Model 612 is a non-renovated between-house from the 2000s with north/south orientation. The building is occupied by single adults, and the household's preferred setpoint temperature is equivalent to 'observed' behaviour. Further, the building uses natural gas and gas boiler for heating the household.

Note: Each building in the case study neighbourhood has 576 techno-economic models and it is not feasible to present results for each techno-economic model. Thus, the consecutive subsections will use family occupied Between House-1 constructed in 1955 as a reference sub-case to explain the results.

7.4 Environmental Performance

The image presented below shows the impact of renovation packages and various heating options on CO_2 emissions. A family household can emit 3.7 tons of CO_2 per year when it uses natural gas for heating its household to observed-set point temperature levels. When a household switches to higher setpoint temperatures, the CO_2 emissions increase to 4.6 tons (set point 20 ºC) and 5.4 tons (set point 22 ºC).

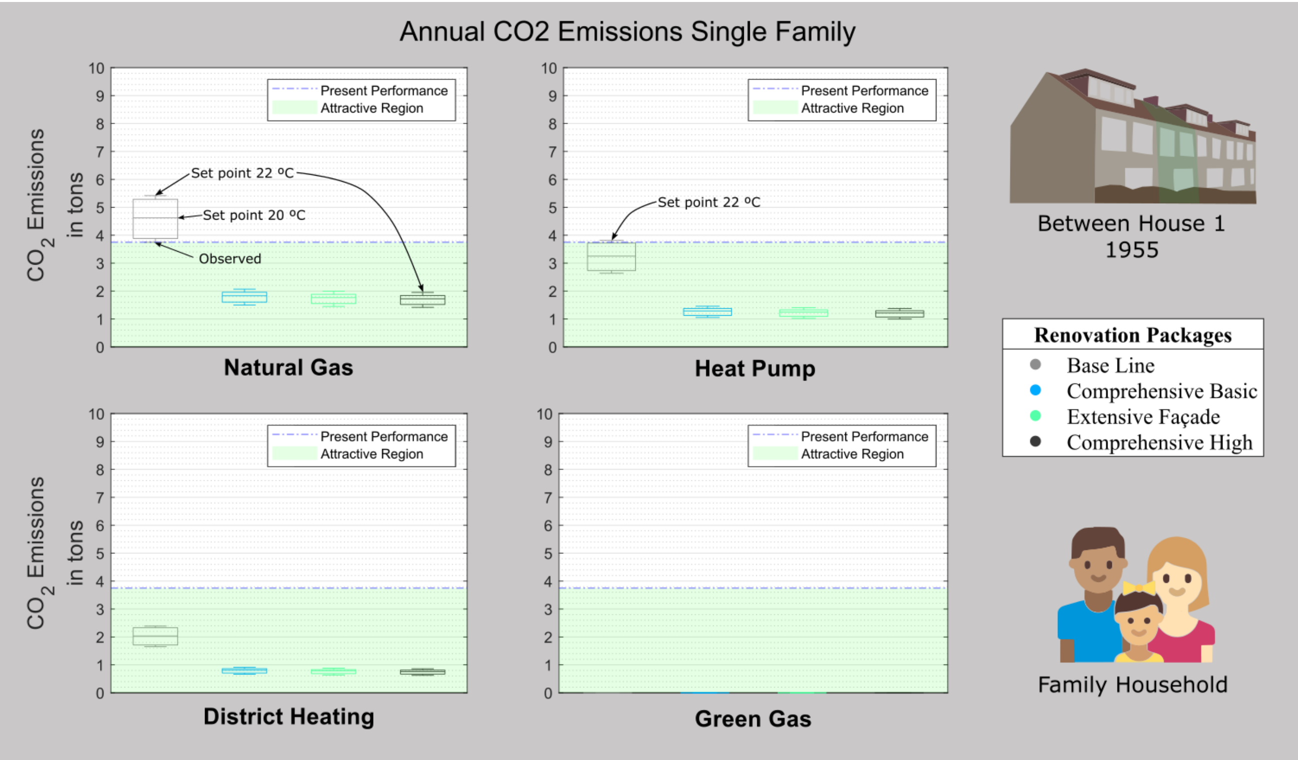

Figure 23 CO_2 Emissions of a Family Household

After renovating the building to "*comprehensive basic*" levels, CO_2 emissions of the household will drop to 1.5 tons per year. On the other hand, when the household switches to heat pump without renovating the building, the CO_2 emissions can drop to 2.6 tons (at observed setpoint temperature). If the household switches to 22º C setpoint temperature, using a heat pump will cause CO_2 emissions to increase marginally.

If a household directly switches to district heating without renovating the building, the CO_2 emissions can drop to 1.6 tons (at observed setpoint temperature). The emissions from using district heating are similar to a renovated household (*comprehensive basic*) using natural gas.

On the other hand, if a household uses green gas for all its heating purposes, the emissions are nil.

7.5 ECONOMIC PERFORMANCE

Figure 24 presented below shows the discounted global costs for a single-family household, over 30 years. It can be noted that if the household uses natural gas for the next 30 years without renovating the building, the household would spend €38000. If the household increases the setpoint temperature (22 ºC) for better thermal comfort without renovating the building, the household would spend €50000. If the household would renovate the building to "comprehensive basic" and continue to use natural gas for the next 30 years, then a household would spend €32500 (saving €5500). If the household renovates the building and switches to setpoint temperature 22 ºC, then the household would spend €36000 (saving €2000).

Figure 24 Discounted Global Costs for a Family Household

Heat Pump

By switching to the heat pump, a household can reduce costs to €35200 (saving €2800). On the other hand, if the household renovates the building and adopts heat pump then costs reduce to €30000 (saving €8000).

If the household can obtain subsidies for heat pump, the cost will reduce to €33300 (saving €4700). On the other hand, if the household renovates the building and adopts heat pump with the help of subsidies then costs reduce to €28000 (saving €10000).

District Heating

By switching to district heating, the costs of a household will increase to €45500 (costing €7500 more). On the other hand, if the household renovates the building and adopts district heating then total costs for a household is €38500.

If the household can obtain subsidies for adopting district heating, the cost will reduce to €40300 (costing €2200 more). On the other hand, if the household renovates the building and adopts district heating with the help of subsidies then costs reduce to €33200 (saving €4900).

Green Gas

By switching to green gas in 2035, the costs of a household will increase to €45500 (costing €7500 more). On the other hand, if the household renovates the building and adopts district heating then total costs for a household is €38500.

If the household can obtain subsidies for adopting district heating, the cost will reduce to €50500 (costing €12500 more). On the other hand, if the household renovates the building and starts using green gas from 2035, it will cost 37600 (saving €400).

Green gas is expected to be available for commercial purposes in 2035, thus until 2035 household will use natural gas and from 2036 household is expected to use green gas after the final switch in 2035.

7.6 ATTRACTIVE OPTIONS FOR THE FAMILY HOUSEHOLD

Figure 25 below presents various attractive options for a family household. The image is calculated for the period between 2020-2030. Further, it is assumed that the household would renovate the building and/or adopt a natural gas alternative (excluding green gas) in 2020. For green gas, it assumed that green gas will be available only in 2035 for the household's heating purposes until it is assumed that the household will use natural gas.

Green region in the image is used for identifying options that can reduce CO_2 emission and save energy costs for a household. The green region is attractive to homeowners motivated by environmental and economic concerns. The yellow region is attractive to homeowners that are motivated by economic concerns and that are agnostic to environmental concerns. The purple region is attractive to homeowners who are motivated by environmental concerns and those agnostic to economic concerns. The red region can be attractive to homeowners, that are agnostic towards costs and CO_2 emissions.

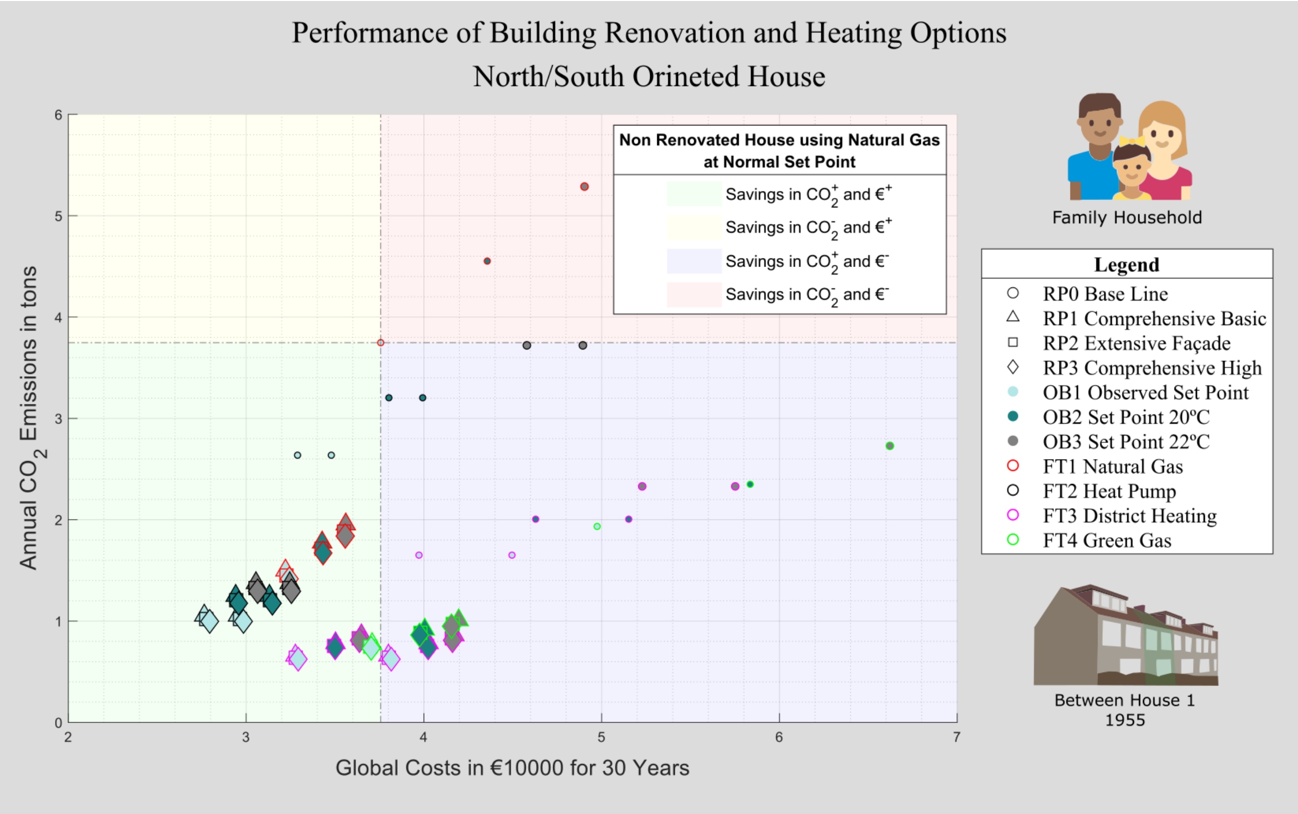

Figure 25 Performance of Building Renovations and Heating Options for North/South Oriented House

Further, for homeowners who are concerned with thermal comfort, the size of 'scatter' is used to present the variations. The base scatter is present at the intersection point of all regions (green, yellow, purple, red). The size of base scatter represents the initial overheating condition. While the size of other scatters represents the overheating percentage of renovation packages. Thus, for a homeowner concerned with overheating, he/she can refer to the size of 'scatter' and determine attractiveness. For example, it can be observed that baseline model (non-renovated house - circle, with pale blue face colour and red edge) has a smaller surface area compared to the renovated house (comprehensive basic – triangle with pale blue face colour and red edge). Thus, it can be said that the house is overheating, as a result of a renovation.

In the above-presented figure 25, the shape of the scatter determines the renovation condition of a household. A *circle* represents a non-renovated house; *triangle* represents a building renovated to “Comprehensive Basic”; *square* represents a building renovated to “Extensive wall”; and the *diamond* represents a building renovated to “Comprehensive high” standard.

Face colour of the scatter is used for representing the setpoint temperature of the household. *Pale blue* is used for representing “observed behaviour”; *dark-blue* is used for representing set point temperature 20 ºC; *dark-grey* is used for representing set point temperature 22 ºC. Edge colour of the scatter is used for representing the heating equipment. A *red edge* represents natural gas; *black edge* represents heat pump; *pink edge* represents district heat; *green edge* represents green gas;

To assist the reader, figure 25 is simplified into four scatter plots (refer to figure-26). Each sub-scatter-plot is used for marking the performance of renovation options concerning various heating options (NGA).

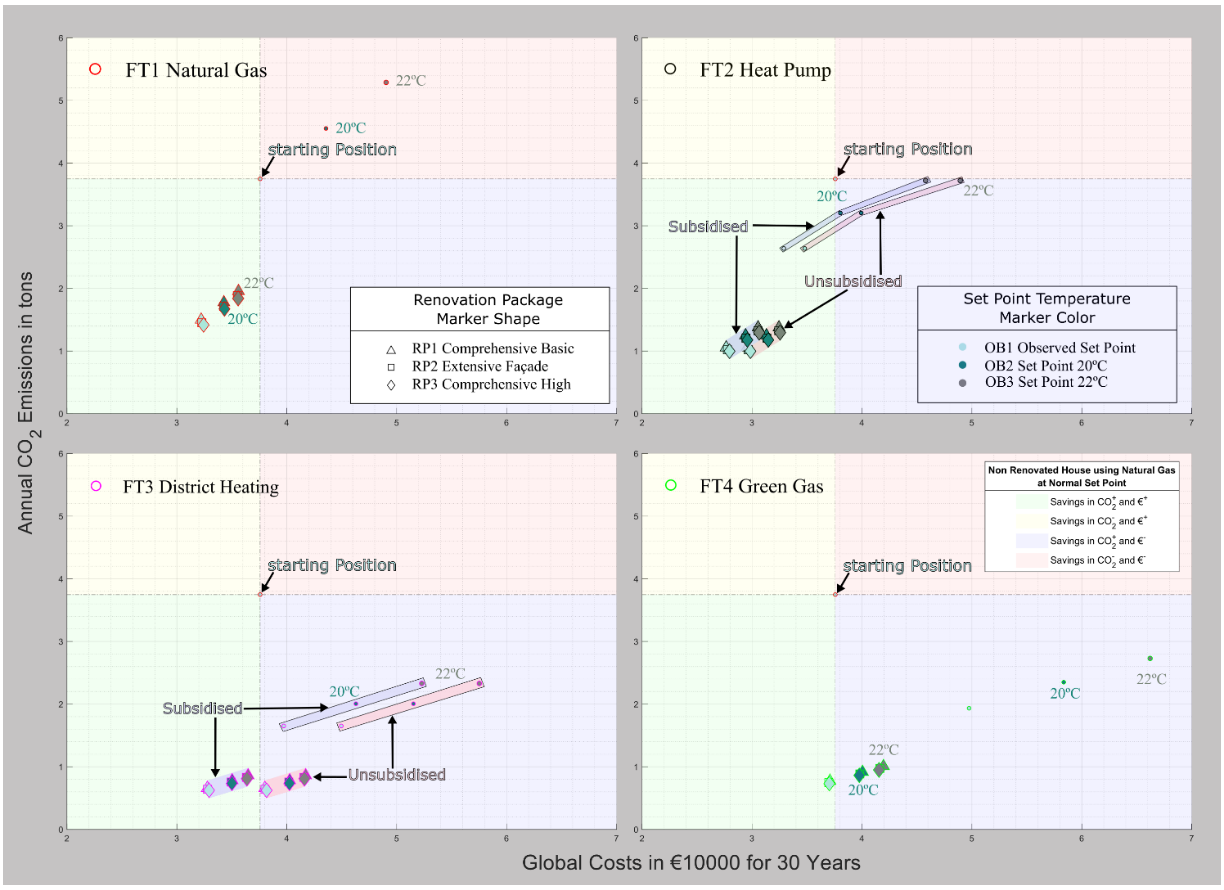

Figure 26 Scatter Plot of Building Renovation and Heating Option Performance for a Family Household

Natural Gas

When a household switches to higher setpoint temperature without renovating the building, the global costs and CO_2 emissions increase significantly. With the help of renovation, CO_2 emissions drop significantly. However, the decrease in global costs is marginal, when household switches to setpoint temperature 22 ºC after renovation.

Heat Pump

For a heat pump, it can be noted that a household can readily adopt a heat pump and save on CO_2 emissions. However, it required that the household maintains its initial set-point conditions. If a household renovates the building and adopts heat pump, it can achieve maximum savings in energy costs. Also, it can be noted that a heat pump is an attractive option, despite subsidy.

District Heating

By renovating the building and by adopting district heating, a household can achieve maximum CO_2 saving. It can be noted that district heat is an uneconomical option for a nonrenovated building. District heating is an economical option, only with the help of reimbursements provide by (Gemeente Amsterdam, 2019).

Green Gas

As it is assumed that green gas is available for household purposes from 2035, the resulting CO_2 emissions until 2035 from natural gas is comparable to CO_2 emissions of using district heating (from 2020-20350). Though green gas is environmentally attractive, it is economically unattractive. If a household plans to use green gas, then the building should be renovated, and indoor air temperature should not increase after renovation.

7.6.1 Delaying Renovation

The below-presented figure shows the impact of delaying the renovation. In the previous subsection, it is assumed that a building will be renovated in 2020. But a homeowner can renovate the building in other points of time between 2020-2035 or keep the building non-renovated. Hence, it is interesting to assess the impact of delaying renovation, on attractiveness.

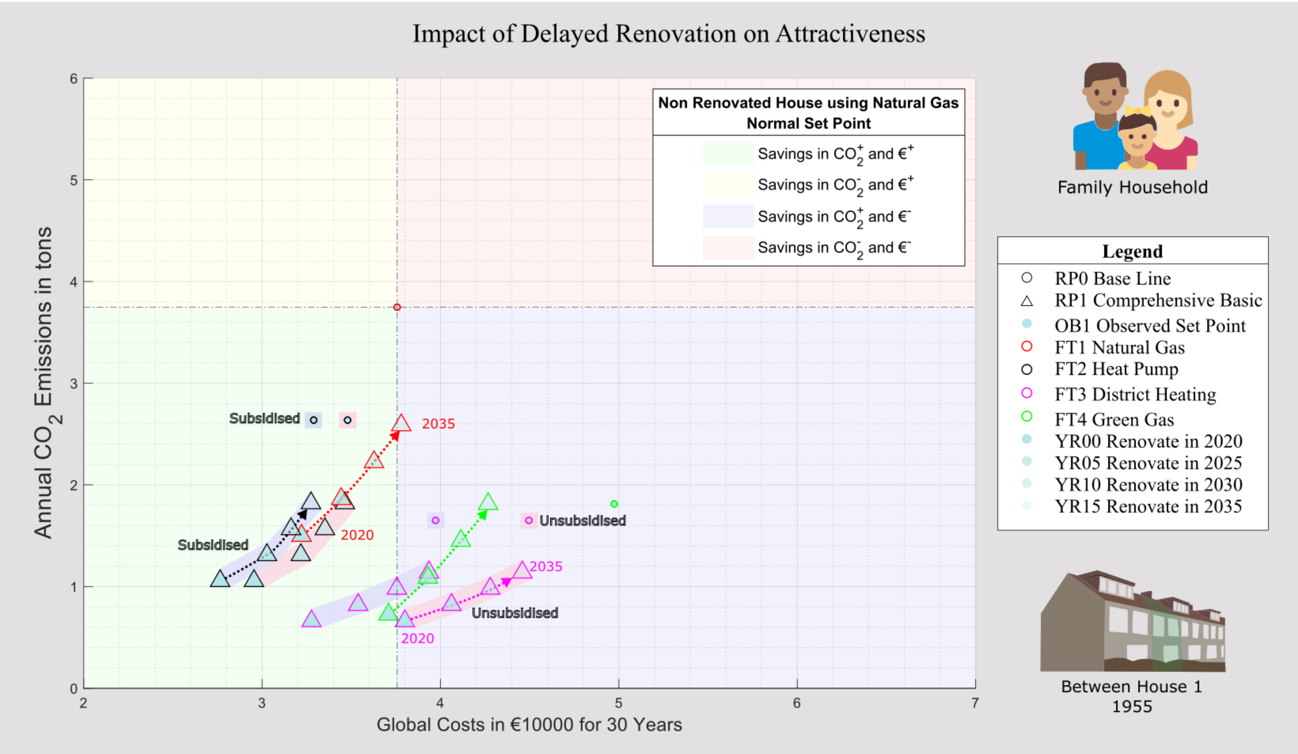

Figure 27 Impact of Delayed Renovation on Attractiveness

Note: To maintain simplicity only “comprehensive basic” and “Observed behaviour” are included in the above plot.

Natural Gas 2020-2050

The option for natural gas in the above figure is marked using red coloured edges. It can be observed that by renovating the building before 2030, a household can save on energy costs. When a household renovates the building in 2035, then the energy costs are marginally greater. On the other hand, the resulting CO_2 emissions are similar to using a heat pump from 2020, without any renovation improvements.

Heat Pump Adopted in 2020

The option for a heat pump in the above figure is marked using a black coloured edge. When a household adopts heat pump in 2020, despite delaying renovation to 2035, renovation is an economically attractive option. This effect is directly related to cost savings resulting from using a heat pump in 2020.

District Heating Adopted in 2020

The option for district heating in the above figure is marked using a pink coloured edge. When a household adopts district heating in 2020, renovation decision can be delayed until 2030. Beyond 2030, renovation becomes economically uninteresting. The renovation becomes uninteresting because the costs for district heat is higher than the costs for natural gas. Further, district heating is attractive to the household, only under the presence of subsidy.

Green Gas from 2035

The option for green gas in the above figure is marked using a green coloured edge. For a household to use green gas from 2035, the building has to be renovated in 2020. Delaying renovation beyond 2020 can increase costs for the household because green gas is costly compared to natural gas. As a result, the energy-saving resulting from renovation are offset by higher green gas prices.

7.6.2 Delaying the Adoption of NGAs

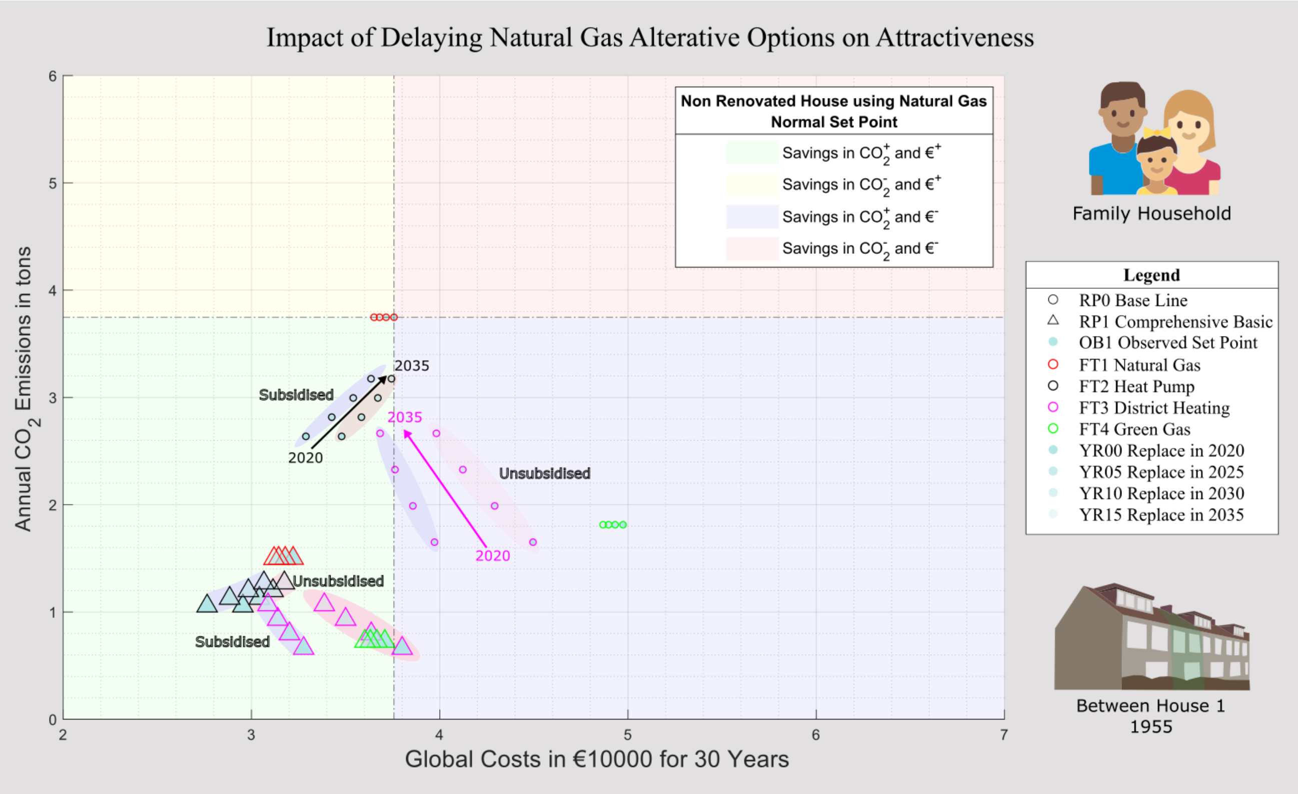

Figure 28 Attractiveness of Delaying the Adoption of Natural Gas Alternatives to Family Household

From the above figure, it can be identified that is important to renovate the building in 2020, because it leads to significant cost saving and CO_2 savings, despite using natural gas until 2050 (red triangles). Further, when a building does not adopt a heat pump before 2035, and it is enforced by the local municipality to adopt district heat in 2035. Then CO_2 emissions resulting from using district heating (2035 onwards – uppermost pink triangle) is similar to CO_2 emissions resulting from using heat pump (from 2020 - lowermost black triangle).

In the event, when a homeowner is heavily dependent on natural gas and is reluctant towards heat pump or district heat, then green gas can be a potential solution. In this regard by using green gas from 2035, the CO_2 emissions are similar to using district heating from 2020 (lowermost pink triangle).

However, when the building is left non-renovated then switching to other natural gas alternatives in 2035 can be uneconomical for a family household. Green gas is an uneconomical option without renovation because the costs increase by €11000 (refer to right-most green circle). District heat is also uneconomical, as the household will spend additional €2000 for heating purposes (uppermost and rightmost pink circle). District heating can become an economical option, only with the help of subsidies (uppermost and leftmost pink circle). Switching to a heat pump in 2035 is economically interesting, only with the help of subsidies (uppermost and leftmost black circle).

7.6.3 Delaying Renovation and NGA Adoption

The below image presents the impact of delaying renovation and natural gas alternative options. It can be observed from the image that for a family household renovating the building (between 2020-2035) is interesting when the renovation is also coupled with switching to other heating alternatives (excluding green gas). For a household, it is interesting to perform renovation at the earliest (2020), as it can reduce either maximize economic and CO_2 saving or minimize the costs when a household switches to costly heating options such as green gas (refer lowermost green triangle). Without the presence of subsidy, district heating is an uneconomical option for households driven by costs.

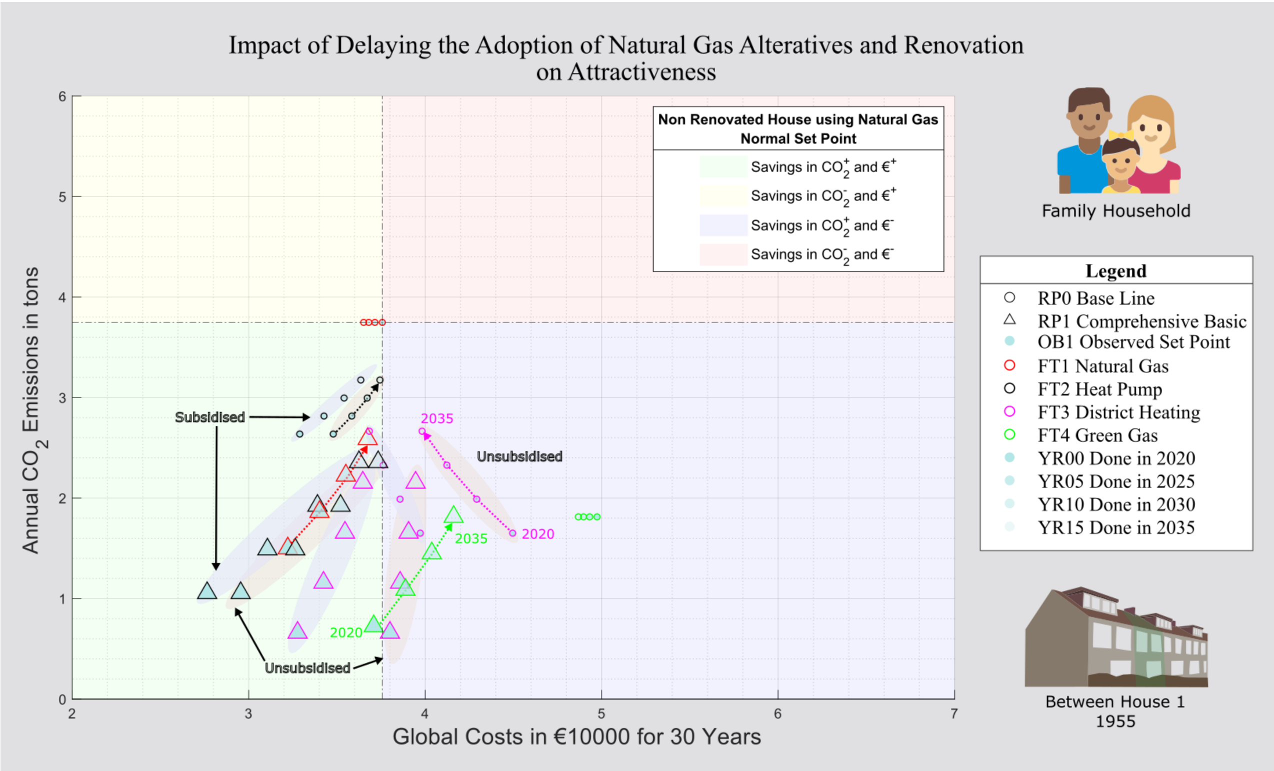

Figure 29 Impact of Delaying the Adoption of NGAs and Renovation on a Family Household

7.7 Attractive Options for Other Households

Figure 30 shows the attractiveness of various renovation and NGA options for different neighbourhood households.

7.7.1 Senior Household

Senior household is the most energy-intensive household. As a result, by performing energy renovation, the household has the highest potential among other households for saving money €11,500 and CO_2 emissions $3.2 \frac{\text{tons of } CO2}{year}$. A senior household can save maximum money €16,500 by renovating the building to comprehensive basic and by adopting a heat pump. Maximum emission savings of $4.05 \frac{\text{tons of } CO2}{year}$ is possible for a senior household through comprehensive high renovation (in 2020) and by adopting (in 2020) district heat.

7.7.2 Adult Household

Adult household is the least energy-consuming household. As a result, the impact of energy renovation on energy savings is the lowest among other households. A household can save a maximum of €4000 and CO_2 emissions $2.15 \frac{\text{tons of } CO2}{year}$ by renovating the building to comprehensive basic. A family household can save maximum money €7,500 by renovating the building to comprehensive basic and by adopting a heat pump. Maximum emission savings of $2.75 \frac{\text{tons of } CO2}{year}$ is possible for an Adult household by renovating the building to comprehensive high and by using district heat from 2020.

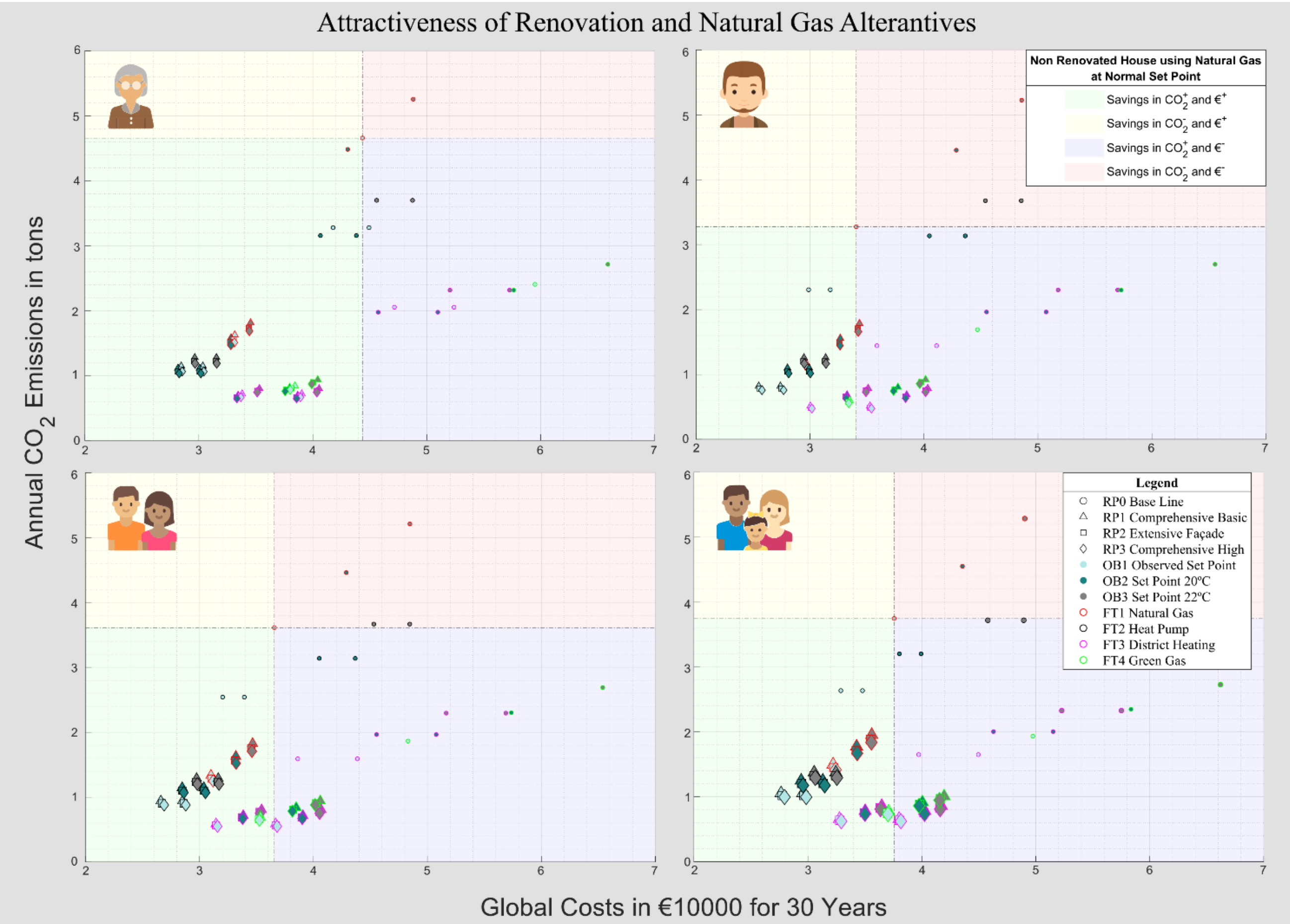

Figure 30 Attractiveness of Renovation and Natural Gas Alternatives for 1955 - Between House 1

7.7.3 Two Adult Household

Energy Performance of Two Adult households is between the energy performance a family household and an adult household. By renovating the household to comprehensive basic, the household can save a maximum of €5500 and CO_2 emissions $2.05 \frac{\text{tons of } CO2}{year}$ by renovating the building to comprehensive basic. A family household can save maximum money €10000 by renovating the building to comprehensive basic and by adopting a heat pump. Maximum emission savings of $2.8 \frac{\text{tons of } CO2}{year}$ is possible for a two-adult household by renovating the building to comprehensive high and by using district heat from 2020.

Note: As the family household has been extensively explored in earlier subsections, the household is not discussed in this sub-section.

7.8 Attractive Options for Other Neighbourhood Buildings

In this subsection, various attractive options for all the neighbourhood buildings are discussed. In this section, various options for the neighbourhood are performing better than baseline models are

7.8.1 Economic Performance

Note: There are 32 types of neighbourhood households, considered in this case study (8 buildings and 4 household types).

Considering all household types, it can be identified that adopting a heat pump without renovating the building is economically attractive for all households. The second option that is economically interesting for various households (20 households) is the option to combine a heat pump with renovation.

District heating is the third interesting option for the neighbourhood, and it is interesting to 10 households. It can be observed that district heating is only interesting when the building is renovated. For both non-renovated and energy-efficient buildings, district heating is not interesting. Since the energy demand for both buildings remains the same, the buildings will experience higher costs due to higher prices of district heat. On the other hand, by improving insulation levels of inefficient buildings (older 1955 buildings), significant energy savings can be attained. Thus, the huge decrease in energy demand offsets the higher fuel price of district heating and green gas in older and inefficient buildings.

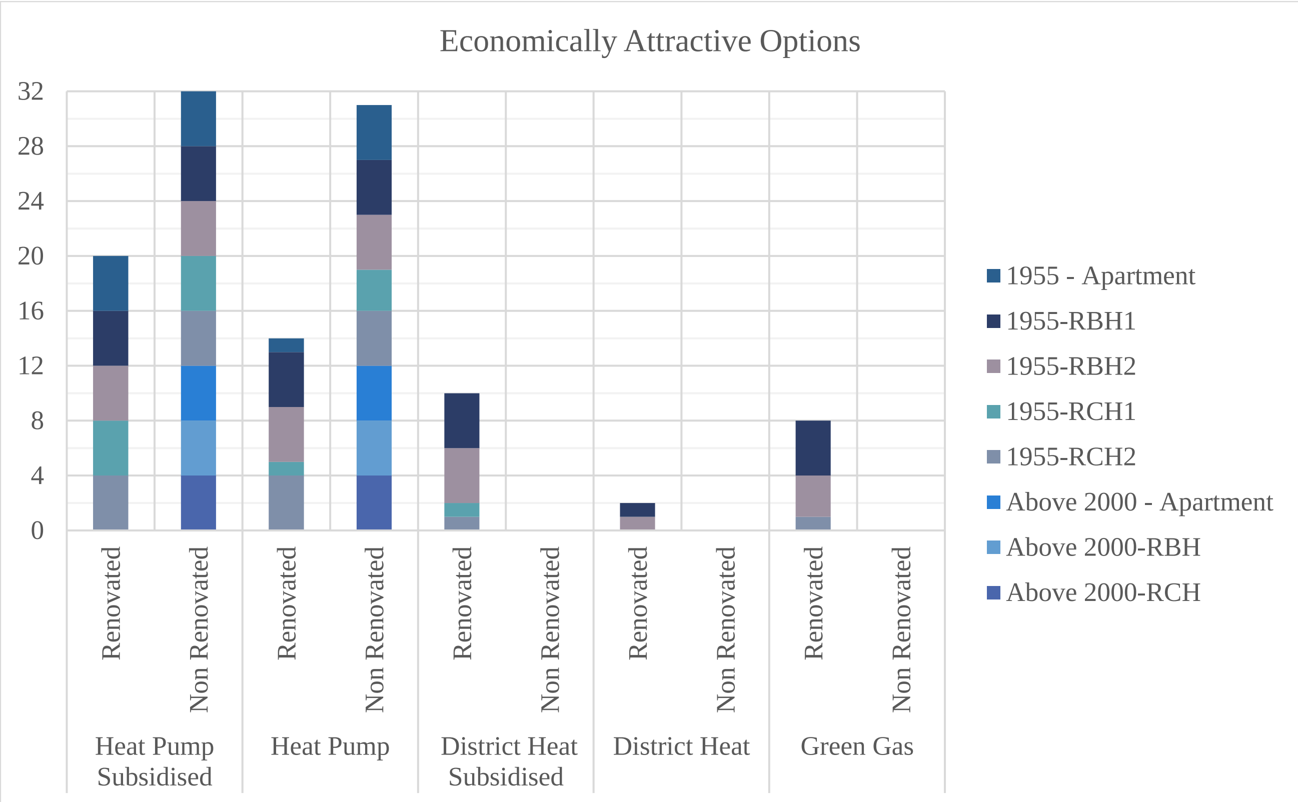

Figure 31 Economically Attractive Options for the Neighbourhood Considering Adoption of Renovation and NGAs in 2020

7.8.2 Carbon Emissions

The below box plot presents simulated CO_2 emissions for various (considered) households that are using "*Natural Gas*" alternatives for heating. It can be observed that by renovating the building, CO_2 emissions are reduced in general; while, for energy-intensive buildings, they are reduced significantly. Irrespective of the heat source, building renovation is considered to be an attractive option for reducing CO_2 emissions.

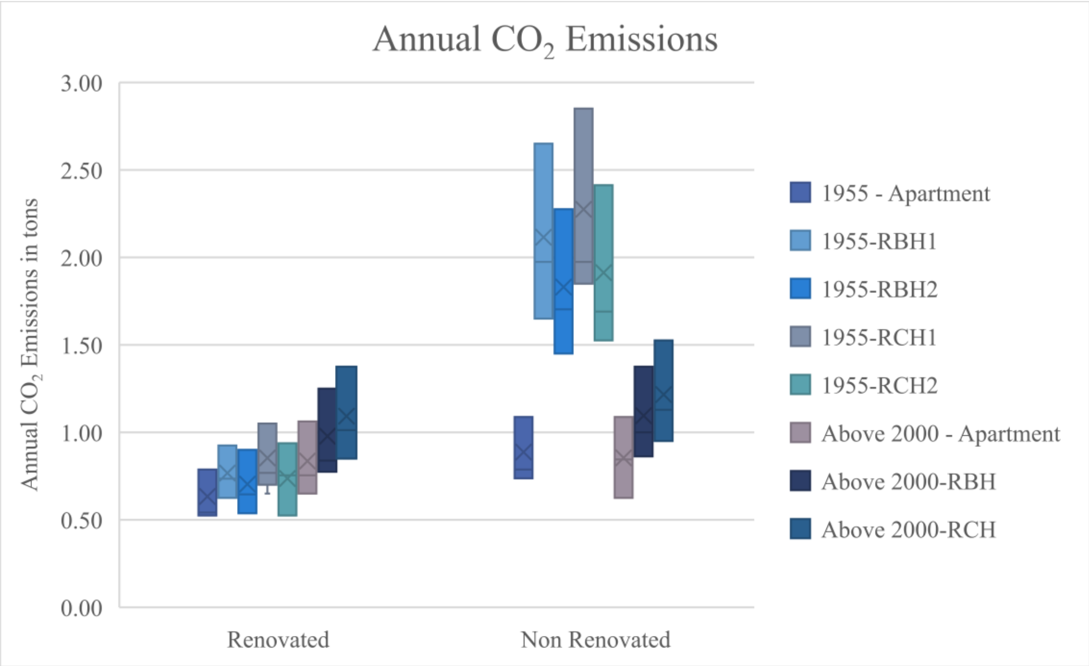

Figure 32 Attractiveness of Renovation concerning CO_2 emission

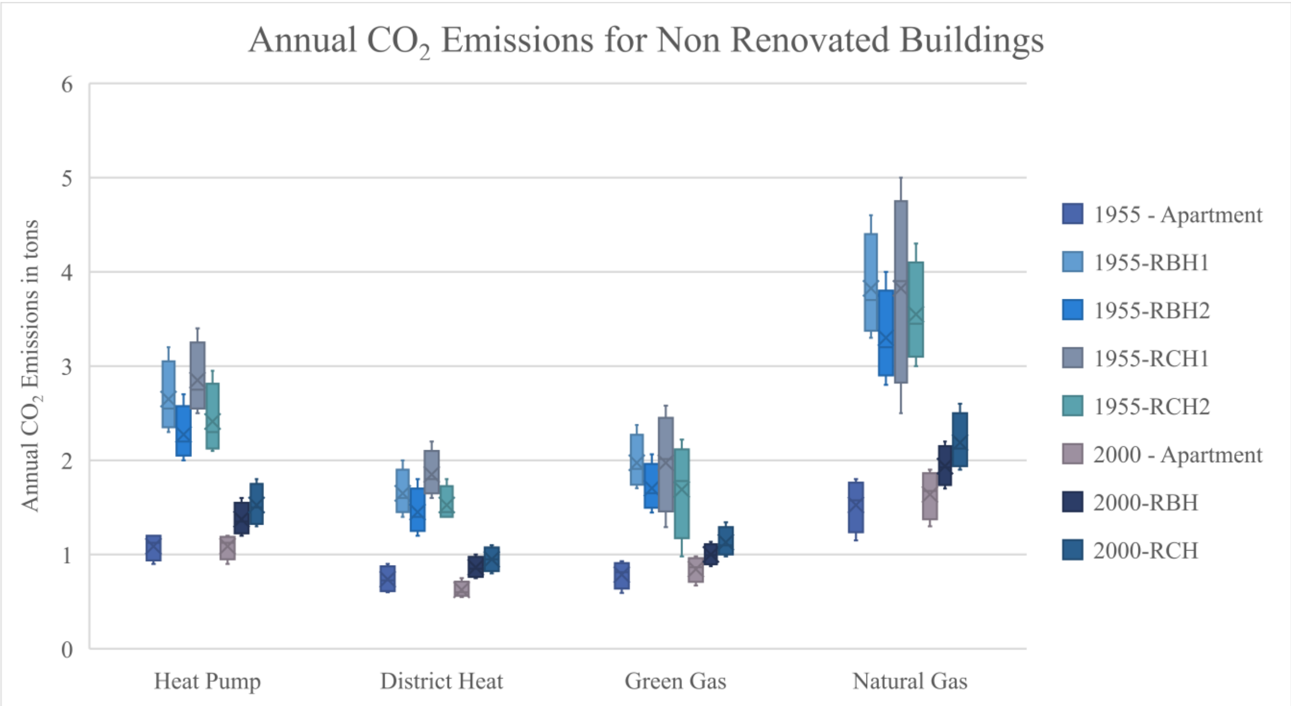

Figure 33 Annual CO_2 Emissions Based for Various Fuel Sources

The most interesting fuel source for reducing CO_2 emission over the next 30 years is District heat. Though green gas is considered to be a renewable source, the homeowner has to wait until 2035 for using green gas. As a result, it is expected that the homeowner will use natural gas until 2035 and then switches to green gas once it is available. So, the emissions from green gas are the result of its dependence on natural gas. Green gas is the second interesting option for reducing CO_2 emission if the neighbourhood can use green gas from 2035. A heat pump is a third interesting option for reducing CO_2 emissions. It can be viewed that all considered options are saving on CO_2 emissions, thus they are considered attractive.

7.8.3 Thermal Comfort

7.8.3.1 Over Heating

The below graph presents the impact of renovation on overheating for various households. It can be observed that by renovating the building, the households experience overheating. Here, the overheating (%) is dependent on the internal gains and the gains are different from household to household. E.g. Family household is significantly overheated because of its high electric consumption (internal gains) before and after renovation.

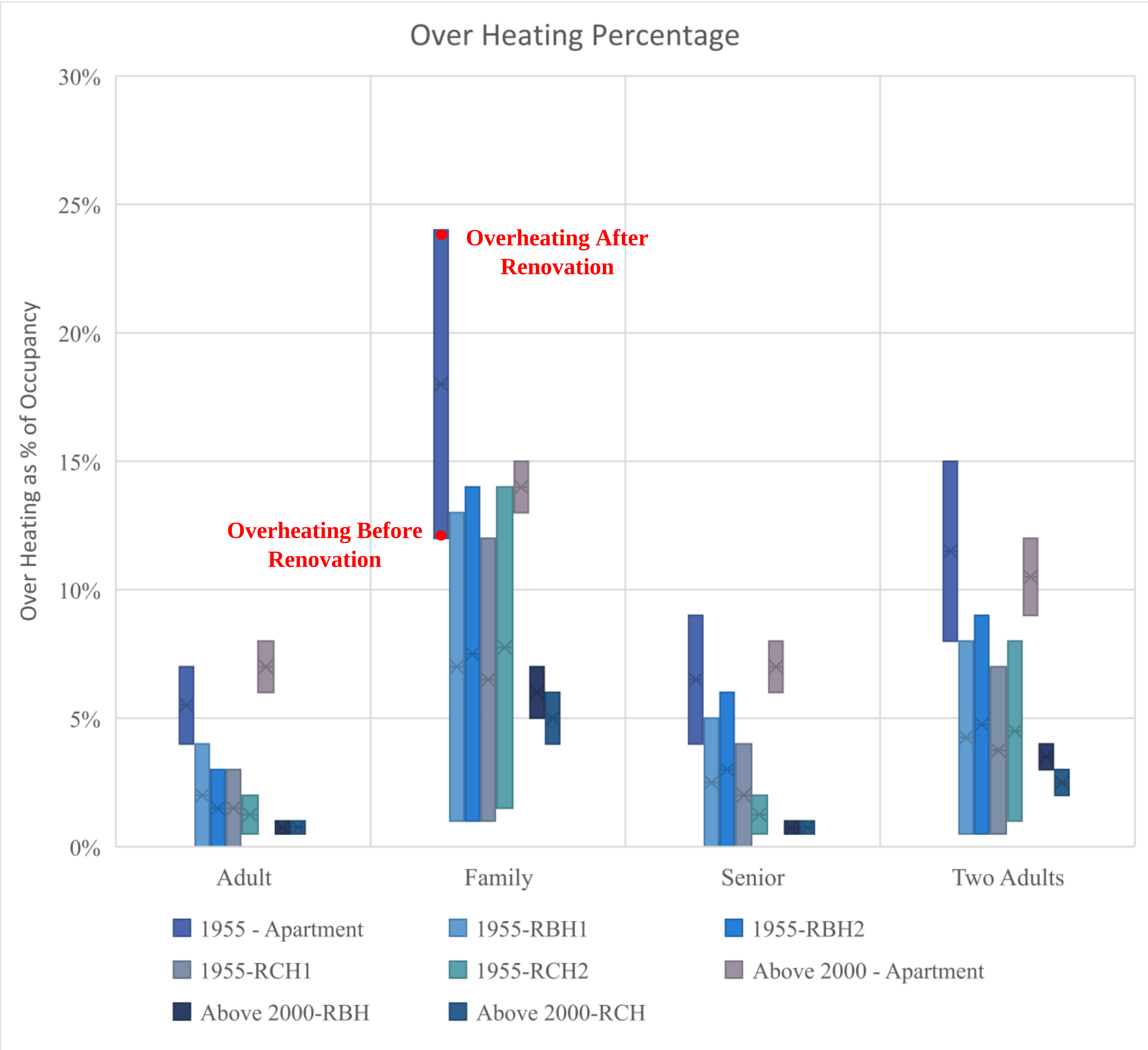

Figure 34 Over Heating Percentage for Various Buildings

7.8.3.2 Adaptive Thermal Comfort

It can be observed that for buildings with low-insulation levels (buildings from1955), the adaptive thermal comfort increase with building renovation. While for buildings with high insulation (constructed from 2000 onwards) the change in adaptive thermal comfort is minimal or insignificant. Thus, it is interesting for homeowners to renovate the older buildings (constructed in 1955) for improving the adaptive thermal comfort. On the other hand, for homeowners that are averse to overheating, then building renovation is not an interesting option.

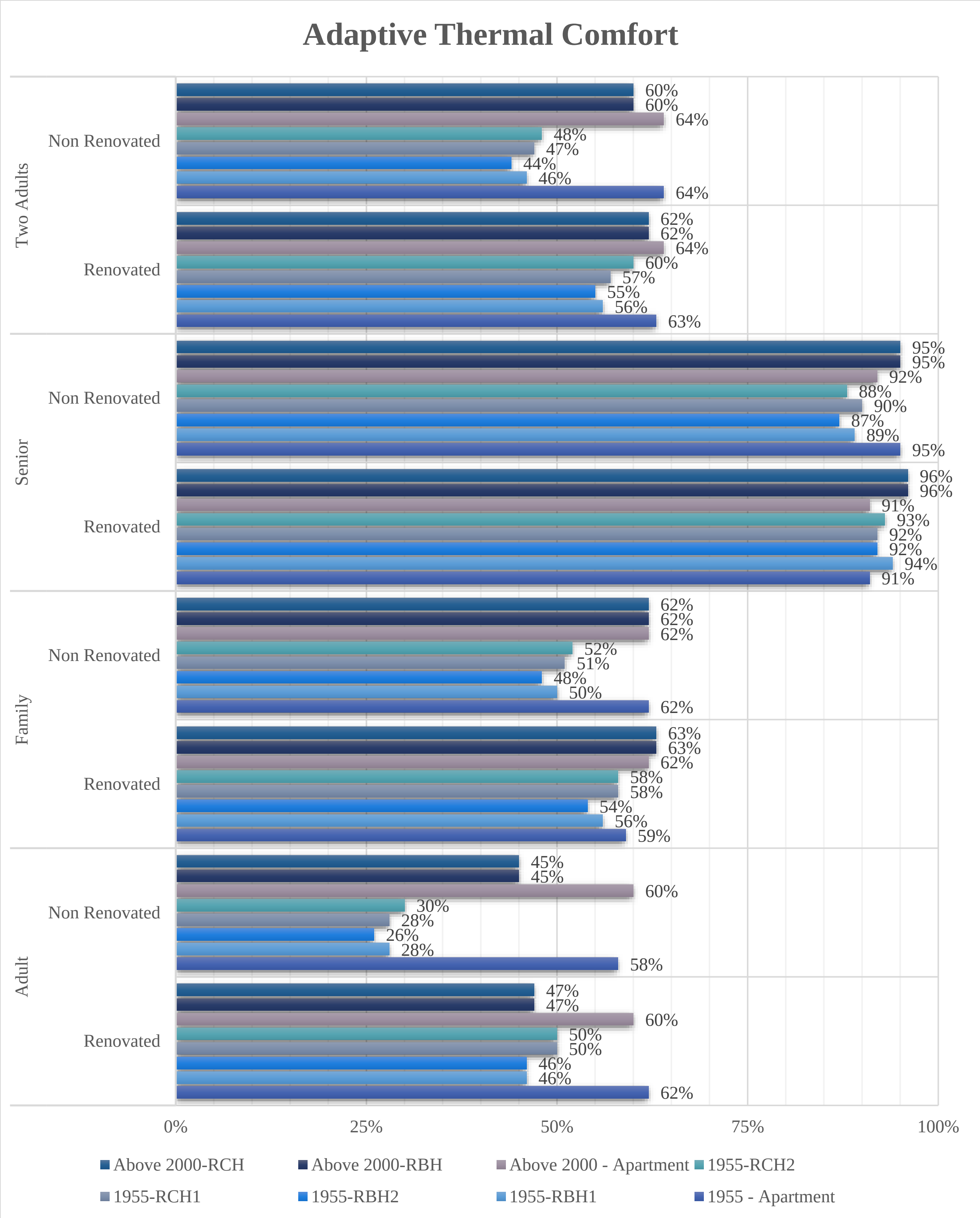

Figure 35 Adaptive Thermal Comfort for Neighbourhood Buildings

8 RESULTS OF THE SOCIOTECHNICAL SCENARIO STUDY

This section discusses the socio-technical scenarios, describing the adoption of natural gas alternatives. Firstly, the objective of the socio-technical scenarios is described. Then recent domain developments corresponding to landscape, regime and niche are analysed. Thirdly, potential linkages that can shape the transition along a particular direction are identified. Further, design choices and architecture for each scenario is outlined. Later, each scenario is elaborated in detail. Lastly, each scenario is evaluated against its objectives.

8.1 SPECIFICATION OF OBJECTIVE

The sociotechnical scenarios presented in this study are developed to explain the 'natural-gas-free' transition pathways, for the residential neighbourhood identified in the Case Study. The scenarios are developed for stakeholders from local planning and development, interested in the energy transition. Hence the scenarios are developed, based on the goal set by the Amsterdam metropolitan area for its neighbourhoods. It is expected that households become natural gas-free by 2035 and that the alternatives are attractive to households (Amsterdam Metropolitan Area, 2016). For this study, district heating, heat pumps (all-electric) and green gas have identified as potential alternatives to natural gas based on (Amsterdam Metropolitan Area, 2016). Thus, this study assesses the attractiveness of the identified alternatives to a household, based on their ability to provide low-temperature heat (space heating and district heating). The scope has been limited to low-temperature heat because it accounts for the 95% of the household's natural gas demand (for a household consuming 1400 Nm^3 of natural gas) (Garufi, 2015). Further, the time duration of transition has been set to 15-years, because all the households within Amsterdam must become natural gas-free by 2035. Thus, the developed socio-technical scenarios will elaborate on the transition possibilities for the households of a neighbourhood based on the above-listed goals and scope.

ANALYSIS OF RECENT AND ONGOING DYNAMICS

8.2 LANDSCAPE ANALYSIS

8.2.1 Response to Global Warming

Global warming is a key driver of 'Renewable Energy Transition'. To strengthen the global response to the threat from climate change and to promote sustainable development, the 'Paris Agreement 2015' was signed. The agreement aims to mitigate greenhouse gas emissions and to promote climate change adaptation measures. The Netherlands is one of the many counties that has agreed to abide by the agreement, thus it has created "Dutch Climate Policy" to reduce the carbon emissions. The goal of the climate policy is to reduce greenhouse gas emissions to the 1990 level and by 95% by 2050 (Government of Netherlands, 2018).

8.2.2 Earthquakes in Groningen

The Groningen gas field is the largest natural gas field of Europe, which is located in the province of Groningen, and it was first discovered in 1959. The gas field accounts for 50% of natural gas production in the Netherlands (Roggenkamp and Hammer, 2004). Since the late 1990s, the province has started to experience gas-induced earthquakes and their frequency has only increased in recent times (DutchNews.nl, 2018a). It is predicted that in 2025, there would be at least one earthquake event per day which is less than or equal to magnitude-5 on the Richter scale (van Putten, van Putten and van Putten, 2016). In 2016, the Dutch minister of the Department of Economic Affairs has limited natural gas production in Groningen to 27 bn Sm^3/year. After an earthquake measuring 3.2 on the Richter scale in January 2018, the government has announced to bring down production to 12 bn Sm^3/year (DutchNews.nl, 2018b). Further, the national government plans to stop extracting gas altogether in Groningen by 2030 (DutchNews.nl, 2018a).

8.2.3 Energy Security Concerns

Beyond energy agreement, energy security is crucial to the government of the Netherlands, as the economy is largely dependent on fossil fuels for its functioning. Fossil fuels account for 92% of primary energy supply in 2016 (only coal, natural gas and petroleum) (CBS Statline, 2019). Of which, the Netherlands has imported 53% of its fossil fuels from outside and the remaining 47% is indigenous production. The government considers these imports as a threat to national security, because of the conflicts happening in Ukraine and the Middle east (Ministry of Economic Affairs, 2016).

On the other hand, the government is facing another problem concerning the dwindling of natural gas resources. Though the natural gas obtained from its internal reserves account for 44% of primary energy supply, the reserves are dwindling. End of 2017, the natural gas reserves were only 45% of 1990's level. For the last ten years, the natural gas discovery was 3 bn Sm³/year and the extraction rate was 58 bn Sm³/year, on average. However, the respective discovery and extraction rates during the 1990s were 32 bn Sm³/year and 35 Sm³/year (CBS StatLine, 2018). By continuing with the current trend for discovery and extraction, the gas reserves might last for another 16 years or until 2033. Thus, it becomes a key priority to secure energy supply even before 2050 (CBS Statline, 2019).

8.2.4 Summary

Three major drivers steering the Netherland's energy transition are the Climate change, Earthquakes in the Groningen region and the energy security concerns. In this regard, it is expected that the present energy system's dependence on fossil fuels will be reduced by increasing the share of renewable energy sources. The low-temperature heat sector is largely dependent on Natural gas for meeting the household's heating needs. Here, the household's dependence on natural gas is expected to decrease, by enabling households to switch to alternative sources of low-temperature heat such as (district heating and green gas). Further, electricity is expected to play a critical role in providing low-temperature heat (Ministry of Infrastructure and Environment, 2017). According to the Ministry of Infrastructure and Environment (2017), renewable energies are expected to play a critical role in the transition of the electricity sector, primarily. Below presented image is a pictorial representation of Landscape forces and their influence on the current energy system.

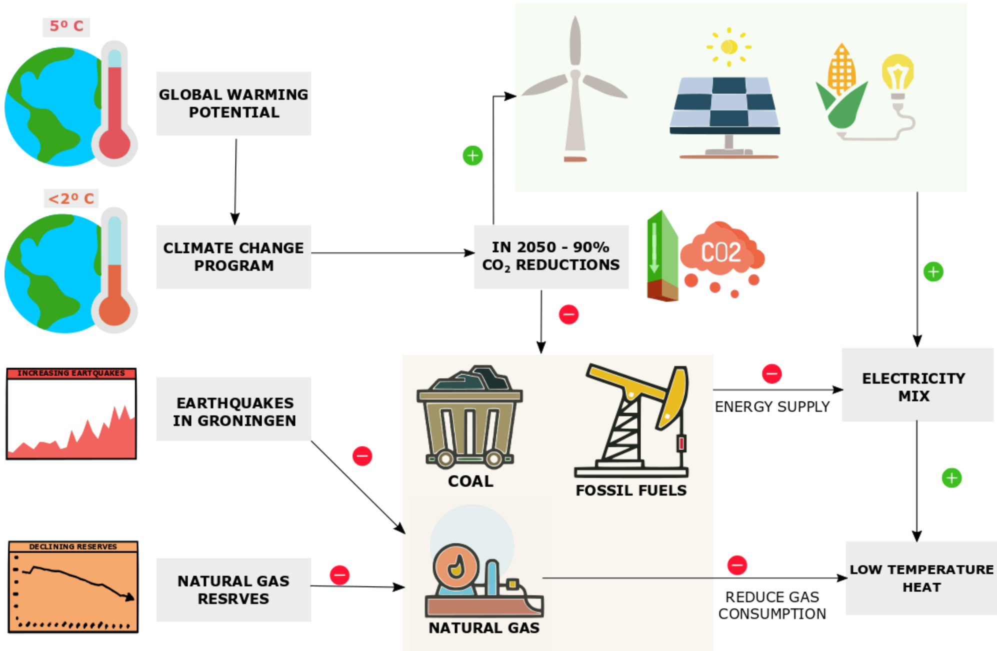

Figure 36 Landscape Forces and Influence on Energy Sources

8.3 Regime Analysis

A Sociotechnical regime can be primarily understood as rules or grammar structure which are used by different groups of actors from different regimes to coordinate activities between themselves (Geels, 2004). In this section, an ST-regime for energy supply is presented. Firstly, an overview of various actors, their roles and their interconnections are described, then the influential changes affecting the regime's fossil fuel dependence are presented.

8.3.1 Energy Supply System

In the Netherlands, the energy sector has six directly observable actors and these actors perform various roles. In the beginning, are the 'Suppliers' and they provide raw materials for energy production. A company that can be identified in this domain is 'NAM (Nederlandse Aardolie Maatschappij)'; core business of the company is exploration and production of oil and gas, within the Netherlands. The company supplies 75% of the natural gas required by households and businesses, in the Netherlands.

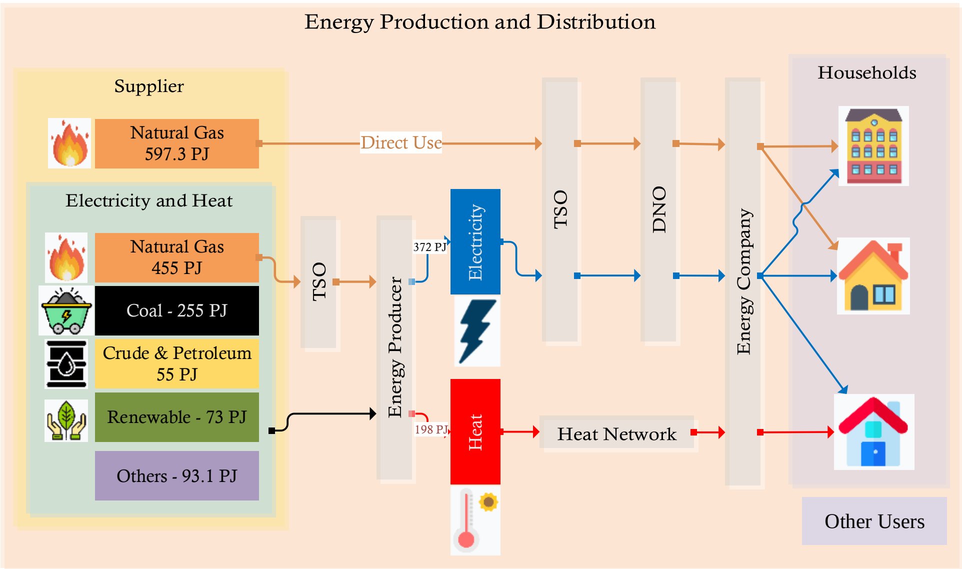

Figure 37 Energy production and Distribution in 2014 (Dallamaggiore *et al.*, 2016; Maurits Kreijkes, 2017; CBS, 2019b)

In the image presented above, the value chain connecting energy supplier to the household is presented. Various intermediate actors such as 'Service companies', 'Storage & terminals' and others are excluded for simplifying the value chain (van den Berg, Denys and Bos, 2012).

After 'Energy Suppliers' are 'Energy producers'; these actors transform primary fuels into the energy for final use. Companies under this category include 'AEB Amsterdam' from Amsterdam, the company processes waste into 'low-temperature heat'; Nuon is another company that transforms 'natural gas' into 'low-temperature district heat' and electricity. Other companies include Essent, Eneco, Engie, etc. (Gerdes, Marbus and Boelhouwer, 2014).

TSO refers to transport service operator, is primarily responsible for the operation, maintenance and development of the transmission system (Gasunie, 2019). Gasunie is a Dutch gas TSO, it is additionally responsible for developing interconnections with other systems and for ensuring the system's long-term ability to meet gas transportation demands (Gasunie, 2019). TenneT is the electricity TSO of the Netherlands, its core objective is to provide a secure and continuous supply of the electricity (TenneT, 2019).

DNO refers to the distribution network operator, it is the company responsible for the operation of the power line and the infrastructure that connects homes and commercial properties to the national transmission grid. Besides, DNO is directly responsible for rolling out smart meters to households (Mulder and Willems, 2019).

Active DNOs in MRA region are Enexix and Liander (Gerdes, Marbus and Boelhouwer, 2014). DNO has limited contact with customers and customers cannot choose DNO, unlike choosing an ‘Energy company’.

‘Energy company (energy retailer)’ provides energy to end-users; these companies are the only actors, to be in direct contact with households. ‘Households’ pay the retailers for the energy they use and the energy bill includes both retail and distributional charges (Mulder and Willems, 2019). It has to be noted that, in some cases, the roles of ‘Energy supplier’ and ‘Energy retailer’ are satisfied by a single company and it is evident with companies such as Eneco, Essent and Nuon (Mulder and Willems, 2019).

8.3.2 Low-Temperature Heat Sector

The above-mentioned landscape factors are exerting pressures on the existing ‘Low-Temperature Heat Sector’. As the sector is largely dependent on the natural gas for meeting the household heating needs; this dependence can be observed via an orange line in Figure 37. More than 90% of households in the Netherlands use natural gas for ‘low-temperature heat’ (Nuon Energy N.V, 2017). This dependence on the natural gas is creating an opportunity window for novelties (such as district heating, green gas and heat pumps) to emerge and replace the natural gas. Various trends affecting the sector are listed below:

8.3.2.1 Independence from Natural Gas

Changing Role of Natural Gas

It is planned that in 2030, there will be two million households that are gas-free. Further, within Amsterdam, two new residential districts are being built without gas (DutchNews.nl, 2018c). Gasunie (Dutch gas TSO) expects that, less gas will be used in the Netherlands by 2050 (Gasunie, 2016).

In this regard, Natural gas is no longer a fuel of choice, but it has become the fuel that will enable energy transition in the Netherlands. During the transition period, households are required to switch away from natural gas for heating homes and water.

- Gas-fired power plants are expected to become backup sources for renewables, especially wind.
- Natural gas will support residential sector until 2030 in the adoption of alternatives; later it is expected to undergo a rapid phaseout between 2030 and 2050 (Honoré, 2017).

No to New Gas Grids

Natural gas is dominantly used by households (95%) for heating purposes. To reduce natural gas usage, the government wants to build new residential districts without any connection to the gas, in principle. And it considers that it is necessary to have no new gas grids in new residential districts under construction as well (Ministry of Economic Affairs, 2017).

Price Change Mechanisms

The government is planning to reduce the dependence on natural gas by making it less attractive to the consumers. This step is achieved by increasing the taxes on Natural gas; in 2020 the government is planning to increase the natural gas tax by 0.04 €/m^3 (Klimaatakkoord, 2018) and then consecutively increase the tax on natural gas tax by 0.01 €/m^3 until 2026 (Government of the Netherlands, 2019a). This tax increase is an addition to previously existing ODE Tax ‘Opslag Duurzame Energie’ of 0.03/m^3 on gas (Bekhuis, 2018).

In future, it is planning to research about ‘effective allocation of costs’ and ‘financial incentives’ for influencing decisions towards a low-carbon energy system (Ministry of Economic Affairs, 2017).

8.3.2.2 Dependence on Electricity

In future, it is expected that the demand for electricity will increase as a result of ‘low-temperature heat’ sector becoming free from natural gas. This is evident from the expected role of electric heating in households from (Ministry of Infrastructure and Environment, 2017) and (Ministry of Economic Affairs, 2017). Also, the government is making electricity more attractive to consumers by reducing the taxes on electricity, as the government is planning to decrease tax on electricity by 0.027 €/kWh (Klimaatakkoord, 2018).

8.3.3 Electricity Sector

Electricity produced in the Netherlands is largely dependent on fossil fuels such as Natural gas (49%) (Maurits Kreijkes, 2017). In future, the system is expected to undergo a lot of changes. Firstly, electricity produced from natural gas and coal will decrease, as a result of mothballing natural gas and coal-based power plants (Honoré, 2017).

Increasing the Share of Renewables

It is expected that by 2023 the 41% of electricity will be renewable in nature. The government plans to achieve this using SDE+ policy and 'net-metering' schemes to support local energy production (Ministry of Infrastructure and Environment, 2017). In 2030, the share of renewable electricity is expected to reach 73.5%. The wind is expected to play a major in this development (Schoots, Hekkenberg and Hammingh, 2017). Further, the Metropolitan region of Amsterdam plans to make its electricity fully renewable by 2040 (Ministry of Infrastructure and Environment, 2017).

8.4 Niche Analysis

Here district heat, heat pump, green gas are considered to be niches in this study because these technologies are supported using subsidies and this support is similar to the niche nurturing process described (Geels, 2004). Households are provided subsidies for becoming natural gas-free, district heating, heat pump are strategic alternatives supported by this subsidy (Gemeente Amsterdam, 2019). In 2019 Amsterdam's district heating network has received a €400 million strategic investment for providing fossil-free heating and hot water (Shrestha, 2019). Similarly for green gas, the province of North-Holland has invested €1 million for developing biomass expertise centre and €0.5 million for developing a demonstration plant. Likewise, heat pumps are receiving ISDE+ subsidy from the national government for reducing the barriers to adoption (Heynen *et al.*, 2018).

8.4.1 District Heating

District heating (DH) is a system, where the heat for consumer needs is produced at a central location and then it is distributed to the consumer. DH can be used to meet the low-temperature needs of residential and commercial consumers and the high-temperature needs of the industrial sector. According to Lund et al. (2014), DH will play a crucial role in improving energy efficiency and in maximizing the renewable-energy utilization. In a DH system, there are three major components Heat source, Distribution network, and Consumer installation.

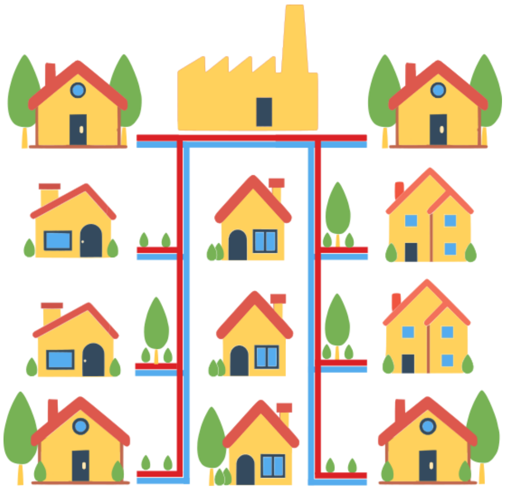

Figure 38 Schematic of a Neighbourhood Connected to a District Heating Network

8.4.1.1 Heat Source

Heat source powers the district heating system, they are multiple heat sources such as waste-incinerators, natural gas boilers, biomass boilers, industrial processes, large-scale heat pumps, solar thermal panels, etc. Based on the report by Metropoolregio Amsterdam (2018), residual heat from industrial processes and geothermal energy are expected to support the Amsterdam region. Currently, within the Amsterdam municipality, there are two major heat producers AEB and NUON. For the Nieuw-West region, AEB provides heat by incinerating waste; and for the regions surrounding Diemen, Nuon uses 'Gas-fired cogeneration power plants' (warmopweg.nl, 2016; Frithjof, 2015). In pursuit of sustainable heat, NUON has made it public that it would become a sustainable provider of heat within one generation (Nuon Energy N.V, 2017; Gemeente Amsterdam, 2018).

8.4.1.2 Distribution Network

The distribution network consists of the insulated pipeline network in which the heat transfer fluid flows from heat generation plat to residential or commercial spaces. The distribution network is often buried underground and water is used for transporting heat. The forward feed temperatures of water range between 70°C and 150°C, and while the return temperature of the water us between 35°C and 70°C (Gudmundsson, Thorsen and Zhang, 2013).

In Amsterdam, only a few neighbourhoods within Nieuw-West and Amsterdam-Zuid are connected to district heating. Within the connected neighbourhoods, the level of district heating penetration is varying from one neighbourhood to other (Klimaatmonitor, 2018b). The heating network within Amsterdam is owned and operated by Alliander N.V, but it has been leased to Nuon from mid-2008 to 2020 (Nuon Energy N.V, 2017).

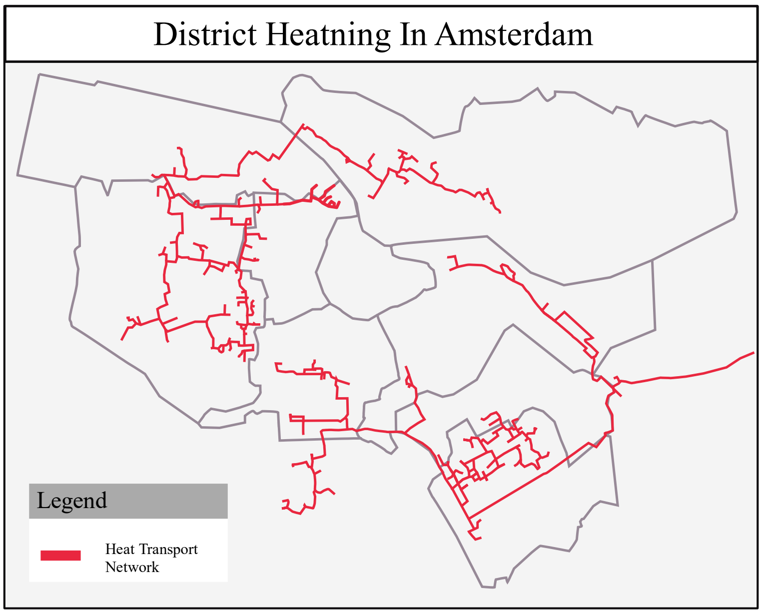

Figure 39 District Heating Network in Amsterdam (Vattenfall Warmte, 2019)

8.4.1.3 Customer Installation

Customer installation refers to a subscription interface that customers must have to access heat from the district heating network. Depending on the utility requirements, the subscription interface is directly or indirectly connected to the DH network. The table presented below lists the customer installation's rental costs for individual and collective delivery sets (Autoriteit Consument & Markt, 2019).

Table 18 Delivery Set Rental Costs determined by (Autoriteit Consument & Markt, 2019)

Type	Space Heating & Hot Water	Space Heating	Hot Water
Individual	126.19	103.99	114.66
Collective	2881.86	2585.33	2585.33

8.4.1.4 Status of the District Heating in the Netherlands

In the Netherlands, customers of District Heating are protected from high prices, through Heat Act. 'The Netherlands Authority for Consumers & Markets (ACM)' decides the maximum price for district heating on an annual basis. The cost of using heat is determined based on the average price of using natural gas (Authority Consumer & Market, 2020). The below-listed table identifies the maximum prices a customer can pay for using heat from a district heating system.

Table 19 Maximum Price for District Heating in the Netherlands (Authority Consumer & Market, 2020)

Type	Fixed amount	Price per GJ
Space Heating & Hot Water	469.17	26.06
Space Heating	234.58	26.06
Hot Water	234.58	26.06

Similar to energy prices, Autoriteit Consument & Markt also determines the cost for connecting a new household to district heating in the Netherlands, annually

Table 20 District Heating Connection Costs determined by (Authority Consumer & Market, 2020)

Type	Connection < 25m €	Connection >25m $\frac{€}{m}$
Connection Cost in 2020	4510.73	180.74

8.4.1.5 Technology Specific Attributes

Negative Attributes

The customers of district heat believe that they are paying more than they would for using natural gas. According to Osman (2017), lack of billing transparency is a major reason consumers perceive district heat as costly.

Positive Attributes

A major benefit of district heating is that homeowners can use cleaner heat sources, such as geothermal heat, waste heat, waste incineration etc (Osman, 2017). Further, the system is silent and vibrationless in comparison to the individual heating system. Using district heating, the user can directly access hot water, without delay (Yoon, Ma and Rhodes, 2015). Also, the system's maintenance care is performed by the heat supplier (Vattenfall, 2019).

Connecting to District Heating

To connect a household to district heating, the household has to be present near a heat network. According to Vattenfall (2019), Buurt 9 is an opportunity neighbourhood, thus households can be connected to the district heating. However, for a household to connect to district heating, it is required to form a group with other neighbourhood residents. In this case, the homeowners are either required to form groups either individually or through VVE (homeowner association) and discuss with Vattenfall for connection possibilities. Then Vattenfall will investigate the technical possibility for building the network (listing costs for installation etc.). Once the homeowner group agrees with the terms and conditions of the heating contract, Vattenfall will develop the heating network (Vattenfall, 2019).

Within Amsterdam, homeowners of any given neighbourhood are given an opportunity until 2035 for adopting alternative heating options. In the absence of a switching action, the municipality is planning to connect the private homeowners to the district heating (Gemeente Amsterdam, 2018). Further to reduce the cost burden, the municipality is providing reimbursements to homeowners for switching to alternative heating options (Gemeente Amsterdam, 2019).

8.4.1.6 Path forward for District Heating

To enable private homeowners into adopting DH, Bouw (2016) suggests that DH supplier must offer transparent products based on the homeowners' needs. Further Bouw (2016) expects that reducing the price of district-heating will have minor influence in altering the customer's perception. Thus Bouw (2016) suggests introducing 'Alternative price models' for increasing the customer choice and to add value to the final product. Also, increasing Third-party access (TPA) can positively influence customer-confidence in the district heating solutions, because customers can choose their retailers and the costs of district heating will be competitive (Bouw, 2016).

8.4.2 Air Source Heat Pump

Air source heat pump is a mechanical device that reverses the natural flow of heat by absorbing heat from a renewable source (e.g. ambient air) and delivers it to the warmer space (e.g. inside of a building). This is accomplished with the help of a refrigerant fluid circulating through evaporator, compressor, condenser and expansion valve continuously. In the evaporator, the fluid is at lower pressures, thus it can absorb heat from the outside air and converts to vapour. The hot vapour then enters the compressor, where the vapour is pressurised to a higher pressure. The compressor uses electricity for accomplishing the task. The high-pressure vapour then enters a condenser, hear the hot vapour undergoes phase change by emitting heat to the inside space. Later, refrigerant fluid enters an expansion vale, where the fluid undergoes expansion and reaches a lower pressure. This low-pressure fluid enters evaporator and the illustrated process continues cyclically.

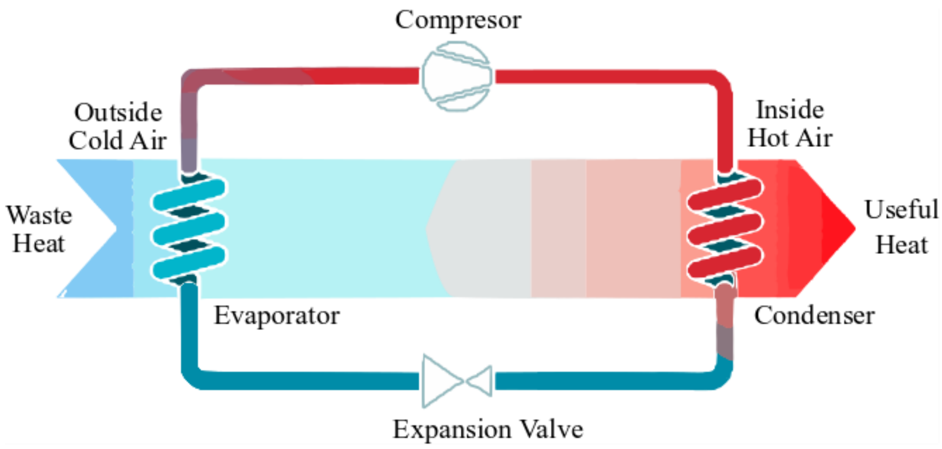

Figure 40 Working Schematic of Air Source Heat Pump (Heynen *et al.*, 2018)

There are different types of heat pumps, such as ‘air source’, ‘water source’ and ‘ground source’ heat pumps. For this study, the choice is limited to air-source heat pumps because they are widely adopted in the EU (David *et al.*, 2017) and the Netherlands (Heynen *et al.*, 2018). Air source heat pump is expected to meet household space heating needs and provide hot tap water.

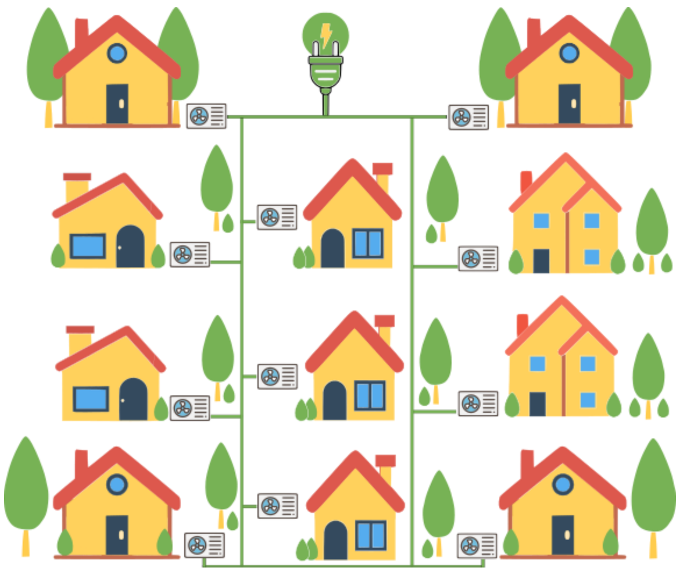

Figure 41 Fully Electrified Neighbourhood

8.4.2.1 *Performance of an Air Source Heat Pump*

The efficiency of a heat pump is measured in terms of coefficient of performance (COP), and it determines the amount of electricity required to deliver a certain volume of heat. Higher the COP of a heat pump, the lower energy it needs for running the heat pump. The electricity demand (ED) of a heat pump is calculated by dividing the heating demand (HD) of the building with the COP of a heat pump. ED is measured in Wh. COP of a heat pump (for heating purpose) is dependent on the ambient air temperature and it varies with air temperature. The below-presented graph shows the COP variation for a heat pump operating at a Carnot efficiency of 40%. The X-axis represents ambient air temperature in Celsius and the Y-axis represents the COP (dimensionless).

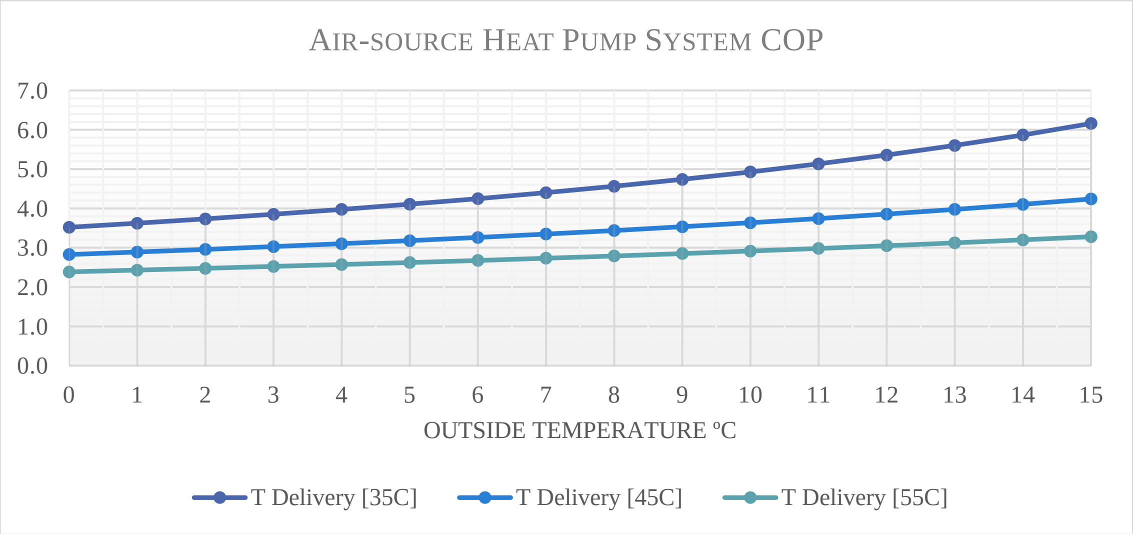

Figure 42 COP of Air Source Heat Pump (ASHP) with η_c =40%

8.4.2.2 *Status of Heat Pumps*

A heat pump is considered to be a disruptive technology by Heynen *et al.* (2018) because its introduction requires a different proposition, infrastructure and use. As the users must cook differently and the heat pump is relatively complex technology to understand and use (Owen, Mitchell and Unsworth, 2013). However, recently due to the introduction of ISDE subsidy, heat pumps have become a financially feasible alternative for the early adopter. The image presented below shows the total number of adoptions and prognosis for a heat pump in the Netherlands Heynen *et al.* (2018).

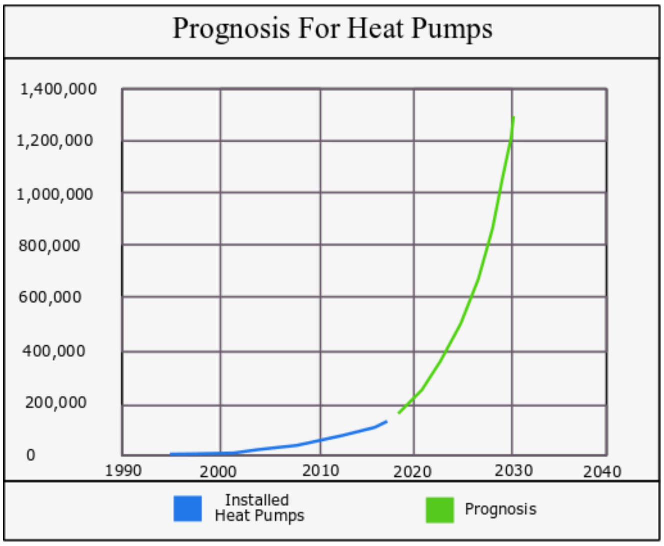

Figure 43 Prognosis for total installed capacity of Heat pumps in 2030 by (Heynen *et al.*, 2018)

As the heat pumps are entering the mass market, Heynen *et al.* (2018) interpret that the mass market is cost-sensitive in comparison to early adopters. In this regard, it is expected that tax shifts and subsidies provided by the government will heat pumps accessible to the mass market. As presented in the above picture, it is expected that between 2020-2030 the heat pump adoption is expected to take-off. Further, during this period the cost of heat pumps are expected to decrease by 30-50% by 2030 Heynen *et al.* (2018). A similar prognosis related to cost reduction has been made by Schepers *et al.* (2015) expecting the price of heat pumps to reduce by 25% in 2025 and by 40% in 2040. Despite subsidies, heat pumps are considered costly in comparison to gas boilers (CV Totaal, 2019a; CV Totaal, 2019b).

Table 21 Heat Pump Investment and Installation Costs (CV Totaal, 2019a; CV Totaal, 2019b)

Heat Pump (Capacity)		Cost (Including Tax)	Subsidy
Space Heating	5 kW	€5,000.00	€1,900.00
Space Heating	7 kW	€6,000.00	€1,900.00
Hot Water	90 L	€1,900.00	€1,250.00
Hot Water	200 L	€3,100.00	€1,250.00

8.4.2.3 Technology Specific Attributes

Negative Attributes

According to a study conducted by Caird, Roy and Potter (2020) 73% of users of (both ground and air source) heat pump are satisfied with the system. However, there is a significant minority of users experiencing discomfort. This section will elaborate on the problems experienced by the minority. Major problems experienced by the minority are “operational problems”, “poor technical support” and “high running costs”

According to Owen, Mitchell and Unsworth (2013), heat pumps are considered to have a high degree of complexity because the technology is not intuitive and users of technology find it baffling to understand. According to Caird, Roy and Potter (2020), almost 44% of surveyed users were uncertain about the know-hows for operating the system at optimum efficiency. Nearly 30% of users found it difficult to understand the operation-instructions and, in most cases, the users restricted their actions to temperature adjustments.

Almost a quarter of surveyed users complained that they were unable to heat their rooms to the required temperature. Particularly, users who lived in a low energy efficiency building experienced slow warm-up of rooms. Further, in some cases, users living in the smaller sized household experienced intrusive noise of fan (Caird, Roy and Potter, 2020).

For a significant minority, a heat pump is a sophisticated technology and this minority would like to receive more technical advice for operating efficiently. Due to lack of technical support, they feel dissatisfied in using heat pump (Caird, Roy and Potter, 2020).

Users experienced high running costs due to two primary reason 1. users supplement an undersized heat pump with an auxiliary electric heater; Since the electric heater is inefficient in comparison to a heat pump, it is likely to increase energy bills; 2. In some cases, users display a comfort-taking behaviour (rebound effect) 85% of users heated all the rooms (including unoccupied rooms) of their home and 59% of users had a setpoint temperature at 22ºC or greater. These user behavioural changes and inefficient-heating system adaptations are likely to increase energy bills (Caird, Roy and Potter, 2020).

“My family now are spoilt and go about in pyjamas and light clothing; whereas when we moved here we were wearing coats inside in the winter” - Private ASHP user from (Caird, Roy and Potter, 2020).

Positive Attributes

Though a few users complained about high operational costs, it has been identified that many users who were knowledgeable about heat pumps had high energy efficiencies. Further, 100% of users with higher-performing systems are satisfied with running costs. Almost 80% of surveyed users agreed that the system has enabled them to warm their houses and experience higher comfort. Further, for a heat pump to achieve cost-efficient performance the system has to be switched on all night and at 95% capacity when the household is unoccupied. Due to this requirement, all households continuously experience a warm indoors and they list it as their main advantage of adopting heat pump (Caird, Roy and Potter, 2020).

8.4.2.4 Path Forward for Heat Pumps

For heat pumps to be adopted, homeowners must initiate the adoption decision by investing in the technology. However, heat pumps are costly in comparison gas boilers and homeowners are unaware of the benefits of using a heat pump. Thus Owen, Mitchell and Unsworth (2013) suggest the local governments (/suppliers) to undertake the task of educating the households about benefits and to provide subsidies. Educating homeowners can be performed through public demonstration, because it improves the technology's visibility and people can experience and get accustomed to the technology (Owen, Mitchell and Unsworth, 2013). Financial barriers are overcome in the Netherlands through ISDE+ subsidies and this subsidy has contributed to the market's adoption of air-source heat pumps.

Beyond users' awareness and willingness, the supply side of the heat pump market (manufacturers, distributors and installers) must improve its knowledge, quality and communications skills (Heynen *et al.*, 2018). Further, suppliers must additionally invest in educating the homeowner about the operational aspects of the heat pump. If homeowners adopt heat pump without proper operational guidance, it can lead homeowners into the belief that heat pump is an inefficient technology. This perception can negatively affect the adoption of heat pumps (MacAdam, 2019).

Also, the electricity infrastructure must be adapted to accommodate the integration of heat pumps, thus 1-phase connection must be upgraded to 3-phase connections for accommodating the heat pumps. This connection upgrading process is undertaken by the network operator (Liander, 2020).

8.4.3 Green Gas

It refers to renewable gas produced from biomass with natural gas specifications, green gas contains methane 88% and carbon dioxide 12% (Himbergen and Lammers, 2011). Though green gas is chemically similar to methane, the differentiating aspect between both is the resulting net-CO_2 emissions. Combusting natural gas would result in net-positive CO_2 emissions while combusting natural gas would result in net neutral or negative CO_2 emissions (Mozaffarian *et al.*, 2004). According to Gasunie (Dutch natural gas infrastructure and transportation company) green gas is carbon-neutral and renewable, as the resources are used for producing the gas are constantly replenished (e.g. manure) by biological processes.

Primary using green gas is advantageous to both households and the regime actors. Since, Households can use green gas without the need for adopting a costly heating alternative (Miedema, van der Windt and Moll, 2018). For regime actors, it is advantageous because it does not incur major infrastructural change and the innovation is incremental in nature(Gasunie, 2016) (Miedema, van der Windt and Moll, 2018).

8.4.3.1 Production Routes

The green gas can be produced using two primary routes 1. Biological and 2 Thermochemical routes. Within the Netherlands the biogas is largely produced using the biological route, utilizing anaerobic digestion process (Miedema, van der Windt and Moll, 2018).

Anaerobic digestion (AD) process uses microorganisms (in the absence of oxygen) for decomposing complex organic matter into biomethane. The gas produced contains about 35-45% of CO_2 and the remaining is methane. For the gas to be injected into the grid, CO_2 must be removed and a methane purity of >95% can be achieved (Li *et al.*, 2017). However, AD is not feasible for producing large volumes of green gas, because of the cost concerns. Usually, the upgrading techniques are costly because they use energy (for producing energy, making the process less-efficient) and they consume chemicals as well (Li *et al.*, 2017).

In this regard, biomass gasification is expected to play a major role in large scale production of biomethane, because the costs are relatively low (Li *et al.*, 2017) (Miedema, van der Windt and Moll, 2018). The technique uses dry-biomass and gasifiers, for converting the biomass into syngas and the syngas constitutes CO, CO_2, H_2,

CH_4 and water vapour. The produced syngas can be directly used for generating power, heat, biofuels and biomethane. Since the gas contains methane in smaller quantities, it must undergo a methanation process, where CO and H_2 are converted into methane (Li *et al.*, 2017).

8.4.3.2 Current Situation for Green Gas

With the help of AD, a total of 13 PJ of biogas has been produced in 2016 and 2.6 PJ of it was used as green gas and it has been directly injected into the gas grid. According to Gas Terra, it possible to produce up to 3 bcm of green gas in 2030 (30% of 2017's natural gas demand or 95 PJ) (Miedema, van der Windt and Moll, 2018). However, the AD technique is hampered by scalability problems for larger production quantities. Thus, gasification is considered as a potential route for producing green gas by Miedema, van der Windt and Moll, (2018).

In this regard, ECN has successfully developed an 800-kW_{th} pilot gasifier in 2008, for producing 'Substitute Natural Gas (SNG)'. After the successful pilot demonstration, since 2010, ECN has goals for developing a 10 MW_{th} gasifier. Only, recently the plans for 10 MW_{th} gasifier are revived by the collaboration between ECN, the province of Noord Holland, ENGIE and other actors (NHN, 2016) (Gasunie, 2017). Further, there are other initiatives related to biomass gasification, that are happening within the Netherlands (van der drift, 2013). Many of these initiatives (except BioMCN) are considered to be small in comparison to ECN's initiative Miedema, van der Windt and Moll, (2018).

8.4.3.3 Barriers to Green Gas Development

According to (Miedema, van der Windt and Moll, 2018) the diffusion of Green gas as technology is hampered by its scalability problems. Though the knowledge to produce green gas is existing in the Netherlands, the know-how is limited to pilot production plants. To scale from pilots to demonstration projects and subsequently to commercial plants, there is a requirement of huge capital investments. However, the key players (from natural gas regime) that can invest in developing the green gas are reluctant to invest in the technology because of high investment risks, unpredictable biomass prices and there is no clear role for gasifying the biomass into green gas in the energy policy (Miedema, van der Windt and Moll, 2018).

8.4.3.4 Technology Specific Attributes

Natural gas is an odourless less compound. To detect leakage and prevent accidents, an odorizing substance is added to the natural gas. This artificial odorant added to natural gas helps a person with regular smelling abilities to detect any presence of natural gas (≥1%) in the ambient air. Similarly, before injecting green gas into the grid, the green gas injector is responsible for odorizing green gas (Tempelman and Butenko, 2020).

However, there are several risks associated with the odorization of green gas. As green gas is obtained from biogas; the source used for producing biogas determines the final composition of green gas. Thus, the injected green gas can occasionally have compounds that can mask the smell of odorant (usually THT). In such cases, when the gas reaches the consumers, then leakage cannot be detected because the gas is devoid of the odorant's distinctive smell. Such situations can lead to dangerous outcomes such as an exposition and death because the transported gas lacks the warning effects of natural gas (Tempelman and Butenko, 2020).

Until now, one such instance has happened in the Netherlands. Limonene is a volatile organic compound and it is present in green gas produced from citrus peels. Despite odorising the green gas to required THT concentrations, the compound limonene can mask the smell of odorant. The green gas producer who was unaware of the limonene's presence and its detrimental effects has unknowingly injected the green gas into the DSO network. However, the DSO was able to identify the presence of limonene and stopped the injection of green gas before it could reach consumers. As a result, the Dutch legislation has banned citrus peelings from the "positive list" of products that can be used for producing biogas (Tempelman and Butenko, 2020).

Similarly, the green gas produced via manure-co-digestion process has traces of cattle manure's odour and it can be uneasy to some end users (US EPA, 2020).

8.4.3.5 Path Forwards for Green Gas

To overcome the above-mentioned barriers, public-private partnerships or joint venture is prescribed as a potential solution by Miedema, van der Windt and Moll, (2018). Though the prescribed solution is already visible in the provincial government's involvement with ENGIE and ECN's for developing 10 MW_{th} gasifier, the authors specifically call for the national government's involvement in the development of green-gas (NHN, 2016) (ECN, 2017).

The primary reason Miedema, van der Windt and Moll, (2018) prescribe these solutions because the expected contribution of other renewable sources to support low-temperature-heat transition is low and the housing sector's dependence on the natural gas is substantial. Thus, for the Netherlands to become natural gas-free, it becomes important to increase the share of renewable sources. Green gas in this regard can play a significant role in reducing the dependence on other renewable sources. Further, the technology has been tested and the knowledge for producing is readily available (Van Der Meijden *et al.*, 2010) and it can potentially reduce the burden on natural gas. Thus, by collaborating with private parties from 'green gas' niche, the government is reducing the burden on the Groningen gas, while reducing the risks for private parties. Another advantage of public-private partnerships is - it can link the technology to the market, specifically the needs of the residential market (Fantozzi *et al.*, 2014). Aside from reducing risks, the government is also expected to play a guiding role by setting a clear vision for the green gas (Miedema, van der Windt and Moll, 2018). Authors believe that the Dutch government can play a guiding role in developing green gas because the government has played a similar role during the 1960s for natural gas (Roberts and Frank W Geels, 2019).

For green gas to replace natural gas in Amsterdam neighbourhoods, a minimum of 15 years is needed because the niche is in its nascent stages. Only recently, the province of North Holland has initiated the development of a demonstration plant (10 MW). According (Duijve, 2012) it takes at least three years to build a demonstration plant and gain knowledge and the required support for building a commercial plat. Later, it is expected that it would take a minimum of 10 years to build a commercial plant. Thus, it is expected that green gas can replace natural gas in Amsterdam in 2035 (15 years from 2020) (Miedema, van der Windt and Moll, 2018).

8.5 INVENTORY OF POTENTIAL LINKAGES

8.5.1 Scenario - District Heating for Space Heating and Domestic Hot Water

At the landscape level, the major factor's driving the transition along this direction is primarily the depletion of natural gas reserves, the earthquakes induced by natural gas production and the climate agreement (Warmopweg, 2016). Apart from landscape factors, the district heating is pursued by the local and regional government for supporting the regional energy transition (Simoës and Veldman, 2007)(Amsterdam Metropolitan Area, 2016). Also, Nuon an incumbent actor from the natural gas regime is extensively involved and interested in the development of district heat, in Amsterdam (Simoës and Veldman, 2007)(Nuon Energy N.V, 2017).

On the other hand, district heating has a negative perception among customers. However, Brande and Edler, (2017) expect that the customer's perception can be altered with the help of an effective marketing strategy, that informs customers about the actual benefits of district heat. According to (Yoon, Ma and Rhodes, 2015) district is convenient in comparison to individual heating technologies for various reasons. These reasons include 1. Unlike boilers or heat pumps, it neither needs a boiler room nor a special concrete plinth on the south side of building (Owen, Mitchell and Unsworth, 2013); 2. it does not produce noise or vibration while operating; 3. Heat pumps require more time to warm up and they do not produce hot water on demand (Owen, Mitchell and Unsworth, 2013); 4. Unlike heat pumps or boilers, maintenance responsibility of district heating is taken care of by the supplier (ACM ConsuWijzer, 2020); 5. In the event of break down, heat pumps can become an expensive investment (Brande and Edler, 2017), whereas the district heating supplier is responsible for providing heat and compensate customers for outages (ACM, 2020b).

As identified by (Burlinson, Giulietti and Battisti, 2018) the investment barriers to adopting district heating, can be overcome with the help of financial support (e.g. subsidies). In this regard, the local government is providing subsidies to households in the form of cost reimbursement (Gemeente Amsterdam, 2019). Thus, a household can effectively obtain all the costs incurred while becoming natural gas-free. According to (Gemeente Amsterdam, 2018) it is interesting for households to renovate the buildings before switching to district heating. In this regard, the local government and the national government are supporting households financially by providing low-interest loans (Gemeente Amsterdam, 2017)(Nationaal Energiebespaarfonds, 2018). However, there are some inefficiencies for accessing financial aid. In this regard, Ebrahimigharehbaghi, Qian, *et al.* (2019) is suggesting for various improvements to facilitate the adoption of renovation measures and in accessing the loans. Thus, it is expected that suggestions made by Ebrahimigharehbaghi, Qian, *et al.* (2019) (Ebrahimigharehbaghi, Qian, *et al.*, 2019) are successfully implemented over the course of the transition period. As a result, the new implementations are expected to positively influence the adoption of district heating.

Since it is clear that natural gas is phasing out and the neighbourhood is expected to switch to a natural gas alternative. In this case, district heating is preferred by the households of a neighbourhood because the homeowners view district heating as a convenient and reliable option, in comparison to heat pumps. Since the green gas is in the demonstration phase and there are many uncertainties about its development, the households are unlikely to wait until its maturity. As a result, the homeowners within a particular neighbourhood would adopt district heating because it is convenient.

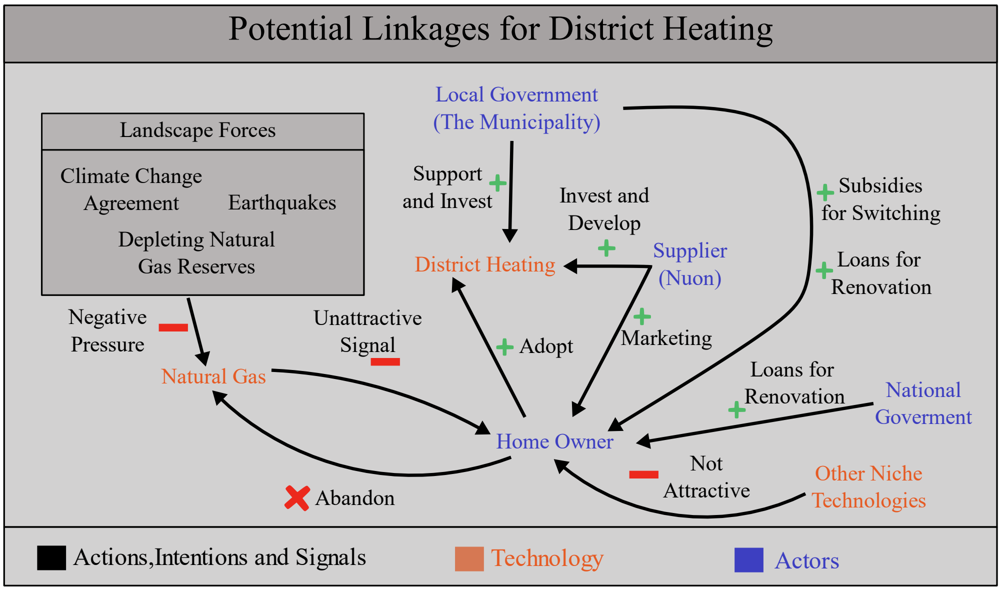

Figure 44 Potential Linkages for District Heating

8.5.2 Scenario - Heat Pumps for Space Heating and Domestic Hot Water

According to Heynen *et al.*, (2018) the landscape factors that have contributed to the recent adoption of heat pumps are - the earthquakes in the Groningen region and the climate agreement. Further, the adoption spike of heat pumps in 2016 and 2017 is a direct result of the support provided by the national government in the form of ISDE grant. Thus, it is expected that the existing landscape factor and the policy will continue to support the development of heat pump niche.

Despite the above-mentioned dynamics, for heat pumps to become widely adopted, various barriers limiting its development must be resolved. First, the households are concerned that heat pumps are investment intensive. In this regard, the national government is providing subsidies to buy heat pumps (Rijksdienst voor Ondernemend Nederland, 2019). Further, Heynen *et al.*, (2018) suggest households to insulate the building, before buying a sized heat pump, as it would reduce the capacity of the required heat pump. In this regard, both the local government and the national government are supporting households by providing low-interest loans (Gemeente Amsterdam, 2017)(Nationaal Energiebespaarfonds, 2018). However, there are some inefficiencies for building renovation and loan accessibility. In this regard, Ebrahimigharehbaghi, Qian, *et al.* (2019) is suggesting for various improvements to facilitate the adoption of renovation measures and in accessing the loans. Thus, it is expected that adopting suggestions made by Ebrahimigharehbaghi, Qian, *et al.* (2019) will positively influence the adoption of heat pumps.

Since it is clear that natural gas is phasing out and the neighbourhood is expected to switch to a natural gas alternative. In this case, the heat pump is preferred by the households because the financial barrier for adopting heat pump is eliminated and more households can easily adopt heat pumps. This development would increase the visibility of heat pumps, in the initial phase. As a result of increasing visibility, the remaining households of the neighbourhood would become confident about heat pump and adopt them as well (Owen, Mitchell and Unsworth, 2013).

Since there is a negative perception among households with respect to district heat being costly and the supplier's monopolistic position, it is expected that households would shy away from district heating (Osman, 2017). Since the green gas is in the demonstration phase and there are many uncertainties about its development, and the households are less likely to wait until its maturity. As a result, the homeowners within a particular neighbourhood would adopt heat pumps.

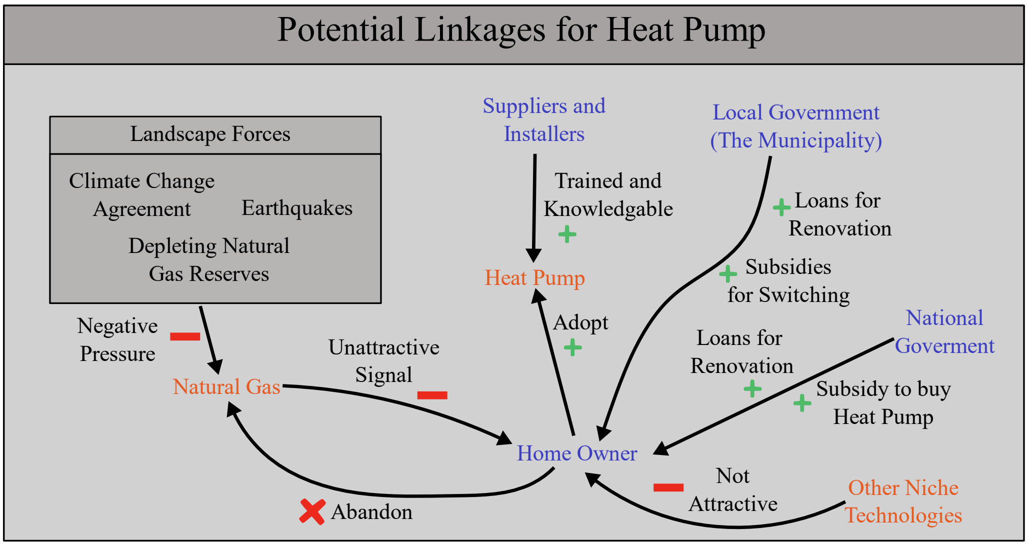

Figure 45 Potential Linkages for Heat Pump Adoption

8.5.3 Scenario - Green Gas for Space Heating and Domestic Hot Water

At the landscape level, the major factor's driving the transition along this direction is primarily the depletion of natural gas reserves, the earthquakes induced by natural gas production and climate agreement.

At the regime level, the residential sector is expected to become a captive customer of natural gas and it will continue to depend on it for meeting its space heating and hot water needs. Since the incumbents from the natural gas regime are forced to cast away their dependence on natural gas. It expected that the incumbents will collaborate with actors from green-gas niche to reinforce their waning position. Further, the national government is expected to promote the development of green gas by articulating goals for green gas and by steering the present policy towards public-private partnerships (Miedema, van der Windt and Moll, 2018).

As a result of the above-mentioned factors, with the backing of the national government, the green gas niche can work with incumbent players to exploit the opportunity created by the landscape factors and by the housing sector's dependence on natural gas, to replace natural gas.

Concerning competition between the niches, the green gas is expected to dominate at the neighbourhood level. In this scenario, it is expected that both district heating and heat pumps are undermined by the '*household's dependence on natural gas*' and their unwillingness to change.

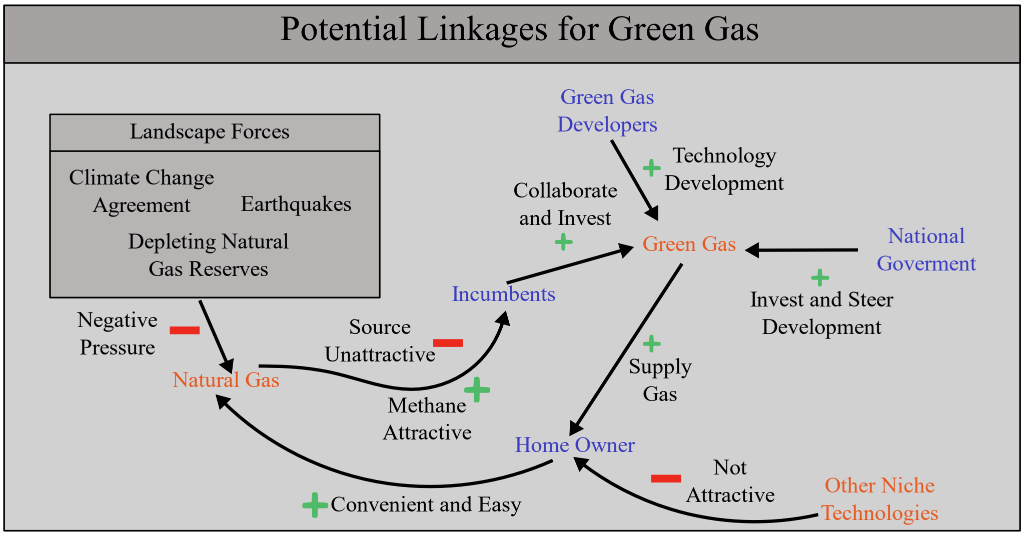

Figure 46 Potential Linkages for Green Gas Supply

8.6 Design Specification and Scenario Architecture

Table 22 Scenario Architecture

Scenario	Transition Pathway	Main driving Force	Technology	Actor Networks	Rules & Institutions
District Heating Period: (2020-2035)	Technological Substitution	In the Beginning: Proactive Homeowners During the Ending: Enforcement by Municipality Landscape pressures, discouraging the usage of natural gas	1.Development of new hot water transportation 2. Replace gas boiler with district-heat delivery setup	Bottom-up transition: Carried by proactive homeowners and DH supplier	Institutional Change: Displacement Regulative Rules: 1. Economic instrument 2. Ban on the usage of natural gas and(or) gas boilers Normative Rules: 1. Natural gas has a negative image 2. Environmental sustainability
Heat Pump Period: (2020-2035)	Technological Substitution	In the Beginning: Proactive Homeowners In the Ending: Enforcement by Municipality Landscape pressures, discouraging the usage of natural gas	1.Reinforcement of electricity grid 2. Replace gas boiler with air source heat pump	Bottom-up transition: Carried by proactive homeowners and new entrants	Institutional Change: Displacement Regulative Rules: 1. Economic instrument 2. Ban on the usage of natural gas and(or) gas boilers Normative Rules: 1. Natural gas has a negative image 2. Environmental sustainability
Green Gas Period: (2020-2035)	Transformation trajectory	Household's captivity to natural gas Landscape pressure, discouraging the usage of natural gas	1.No infrastructural changes 2.Replacement of old gas boiler with a new one	Top-down transition: 1. Incumbents (suppliers/producers) and the National government supports the development of green gas niche	Institutional Change: conversion Regulative Rules: 1. Economic instrument 2. Ban on the usage of natural gas. Normative Rules: 1. habituated to using natural gas, as a result of its convenience.

8.7 ELABORATION OF SCENARIOS

8.7.1 Adoption of District Heating

In this scenario, the main driving force within the neighbourhood to adopt district heating is the consensus among the residents (primarily homeowners) to proactively shift away from the natural gas and the landscape pressures created by Groningen gas.

Before 2035, homeowners are driving the transition within the neighbourhood, because the municipality wants homeowners to choose a suitable natural gas alternative by themselves, before the end of the transition (Gemeente Amsterdam, 2018). In this case, homeowners of the neighbourhood collectively opt for district heating, because it is a convenient, maintenance-free alternative and it can lead to significant emission reductions.

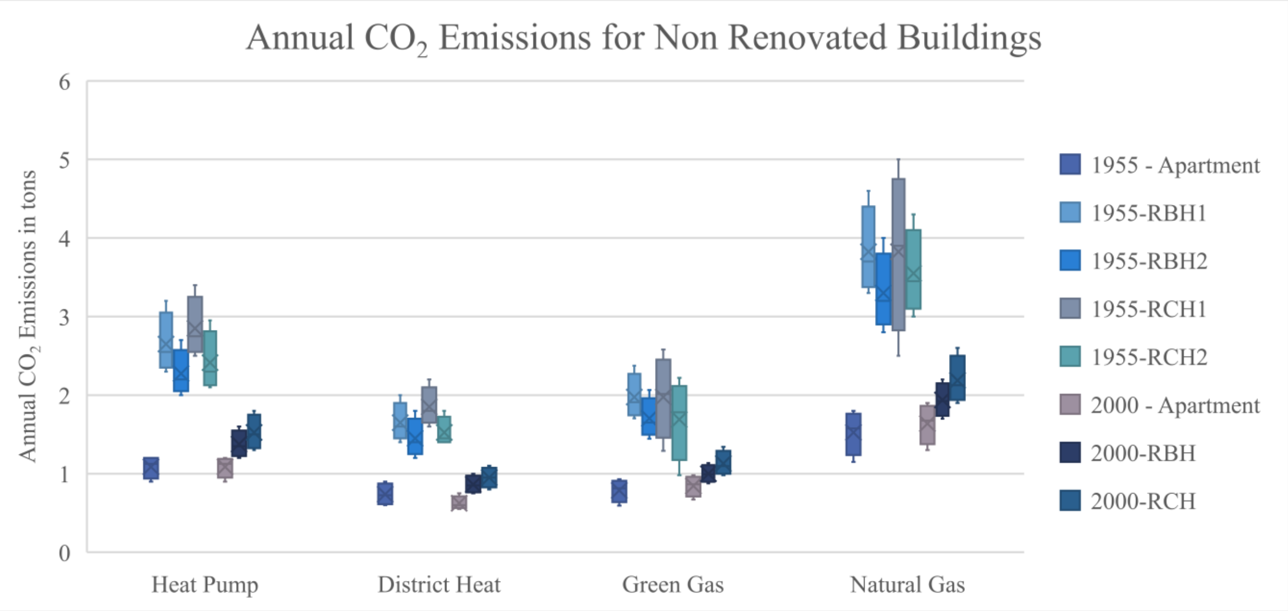

Figure 47 CO_2 Emissions of Various Heating Options

Various possibilities that lead homeowners to adopt district heating are

1. Majority of households are environmentally friendly, and the households are primarily interested in reducing CO_2 emissions. Since district heat leads to lowest emissions for all buildings, all homeowners adopt district heat.
2. Majority of households view district heating as a comfortable option in comparison to heat pumps because there are no delays in room heating, the system is simple to use, noiseless and the building doesn't require any insulation adjustments.
3. Homeowners interested in financial benefit adopt district heat, despite its higher $\frac{€}{kWh}$ because they are undereducated about heat pumps and they are uncertain about its economic benefits or they have renovated their building significantly and experience cost savings despite using district heat.

Note: As homeowners are proactive, they do not wait until 2035 for the green gas to mature. Thus, green gas is not a competition to district heat. For the situation, when homeowners are not proactive in shifting to other natural gas alternatives, the municipality can enforce homeowners into adopting district heating (Gemeente Amsterdam, 2018). As it is a top priority for the Amsterdam municipality to expand the district heat.

The adoption of district heat can happen immediately or gradually until 2035, during this transition period the homeowners are expected to become morally and environmentally conscious because of the listed reasons:

1. Natural gas extraction is affecting civilians in the Groningen region; thus, homeowners collectively want to alleviate the impact on Groningen residents by adopting other alternatives.
2. Increasingly, homeowners start to witness and experience the effects of climate change (around the globe) such as recent wildfires in Australia (Fountain, 2020), 2019's heatwave (Carrington, 2019) the spread of new diseases and droughts (Ligtvoet *et al.*, 2015)

The above-identified reasons set the normative rule for the homeowners of Buurt 9 and enable the adoption of district heating because it is an option that can alleviate the burden on the natural gas and also lead to highest CO_2 reductions (refer to figure 47).

During the transition period, the local government is expected to play a major role in supporting the transition and improving the efficiency of the neighbourhood. As district heating is the least emitting option (among considered), the local government needs to support its diffusion for achieving higher CO_2 emission savings.

Based on the findings from economic and environment impact, it can be identified that for households living in 1955-Apartment and Above 2000 buildings, district heat is (near) economically neutral. However, subsidy is required for other households to experience district heating as economically neutral (refer to section 8.7.1.1). So, subsidy provision is expected to reduce any economic resistance, experienced by the environment conscious homeowner (refer to section 8.7.2.1).

For households living in 1955 Between Row houses, it is economically interesting to renovate the building first and consecutively adopt district heating. Thus, it will lead to win-win situation for homeowners and the governments. In this regard, local government can play a significant role in assisting homeowners to renovate and to adopt district heating by providing renovation loans and subsidies.

According to Ebrahimigharehbaghi, Qian, *et al.* (2019) primary barriers to renovation and adoption of NGA are "*time and effort required to obtain loan or subsidy*"; "*Reliable experts"*; "*Knowledge and Skills*". Thus it is suggested by Ebrahimigharehbaghi, Qian, *et al.* (2019) that the focus of the present policy must aim to reduce the complexity of loan and subsidy procurement. Then to eliminate the uncertainty surrounding energy renovations, it is important to homeowners receive tailor made solutions and are guided through the renovation process (explaining the impact of renovation, proving loan assistance, connecting to reliable contractors, etc.). In this regard local government can play a significant role in assisting homeowners, because government agencies are the most trusted by homeowners (Ebrahimigharehbaghi, Qian, *et al.*, 2019). According Broers *et al.* (2019) home owners appreciate the energy audits performed by municipally governments and feel comfortable and confident in the information provided by the government-agents. Energy desk is public-private-initiative supporting homeowners through the energy-renovation process by providing tailor made solutions (Energieloket Amsterdam, no date). Thus, with help of such similar initiative, the homeowners can be nudged into renovating their buildings.

Also, energy-popup shops are an interesting option for supporting local initiatives because they can be used to create awareness and support homeowners at a neighbourhood level by addressing the specific needs and wishes of the homeowners. Initial experience with popup shops, show that they could have a positive and influential impact on energy renovation decisions (Ebrahimigharehbaghi, Qian, *et al.*, 2019).

Further, it is important to note that when households switch to energy-intensive behaviours (higher setpoint temperatures) then household is expected to spend more on energy costs. Thus, it is required to raise awareness for households to consume less energy. In this regard, local government can play a significant role in rising the awareness of households by creating and experimenting new policies to reduce energy consumption (Dahlbom *et al.*, 2009).

During the transition period, incumbents are expected to play a passive/reactive role by supporting the requests of homeowners. Incumbents are expected to stop supplying natural gas and provide electricity to their customers. Concerning grid adaptations, it is expected that a new network for supplying district heat will be established in the neighbourhood and the gas connection will be removed, on the request of homeowners

(Liander, 2020). Niche actor, Vattenfall is expected to play an active role during the transition by supporting the district heating development, and by actively reaching out to the homeowners (VVE) and inform homeowners about the benefits of using district heat.

In terms of major regulative changes - a ban on natural gas and(or) gas boilers can be expected nearing the end of the transition. Concerning economic instruments, it is expected that the local government will continue to encourage homeowners to make transition adaptations by providing subsidies and low-interest loans to support the NGA shift and to renovate inefficient buildings (Gemeente Amsterdam, 2017; Gemeente Amsterdam, 2019). Further, it is expected that the national government will continue to use existing economic instruments, such as taxing natural gas for discouraging the usage of natural gas (Government of the Netherlands, 2019a).

Concerning institutional changes – ‘displacement’ of the existing institution with new institutions is expected for providing low-temperature heat. This is expected because district heating is a natural monopoly. Thus, permit-requirements for becoming a heat supplier is different from the permit-requirements for becoming a natural gas supplier (ACM, 2020a). Also, customers’ monopoly concerns can be appeased by enabling TPA (third party access) (Bouw, 2016). In this regard, Amsterdam is planning to have an open network, where multiple producers can feed heat into the grid (Decentralized Energy, 2017). This enables competition among heat producers to produce heat in a cost-efficient way. This new arrangement can lead to the creation of new conditions for accessing the network by producers and it must be negotiated with existing district heating company (Bouw, 2016). As a result, new rules and local institutions are expected to be created for supporting the smooth operation of a district heating network. Thus, ‘displacement’ of institutions is expected.

The dynamics for the district heating adoption can be viewed as a technological substitution because the district heating is replacing the usage of natural gas as well as its distribution network by creating a new infrastructure for providing low-temperature heat. The power struggle can be expected among the homeowners to choose a suitable heating alternative. In this case, the local government can stimulate discussion among households by using formal instruments such as ‘resident association’ to enable participation (Tumber, 2012). Further, through household participation, it is possible for the local government to identify an attractive option, easily.

8.7.1.1 *Economic and Environment Impact Assessment*

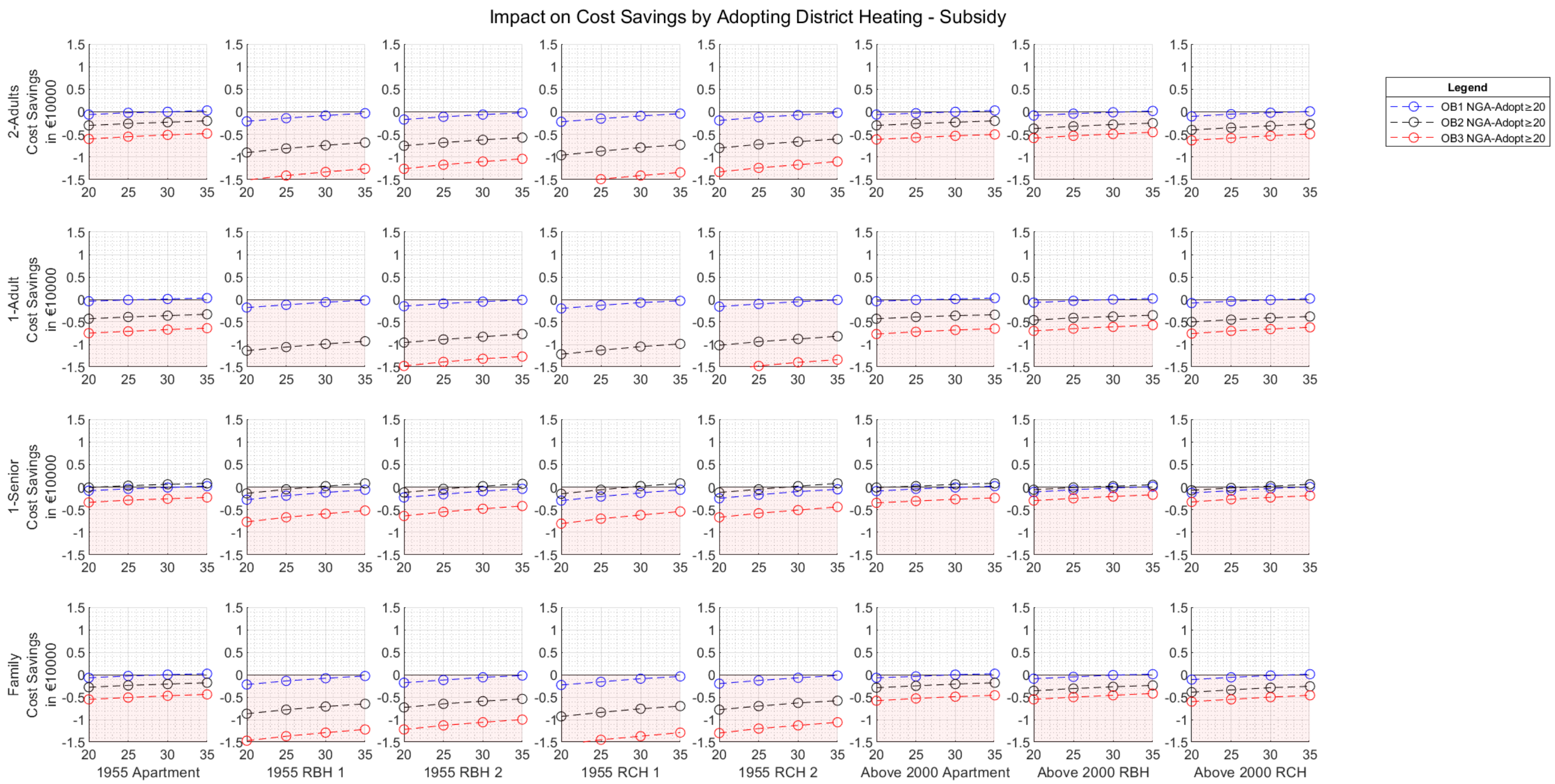

Figure 48 Economic Impact of Adopting District Heating by Non-Renovated House – District Heating Adoption Delayed

For the above image, red region represents economically unattractive options. It can be observed that in spite of subsidy provision, for household living in Row houses constructed in 1955, using district heating (from 2020-2050) is costly in comparison to natural gas (from 2020-2050). Only from 2035, district heating becomes economically neutral for households living in Row houses from 1955. Whereas for households living in 1955-Apartment and Above 2000 buildings, district heat is (near) economically neutral. Thus, subsidy provision is crucial for achieving economic neutrality.

Further, it has to be noted that, when a household switches to energy intensive behaviours or rebound behaviour (OB2-Setpoint 20ºC – black line; OB3-Setpoint 22ºC – red line) the costs are increasing. Thus, it is necessary to raise the awareness of consumers about their energy consumption patterns for reducing energy costs.

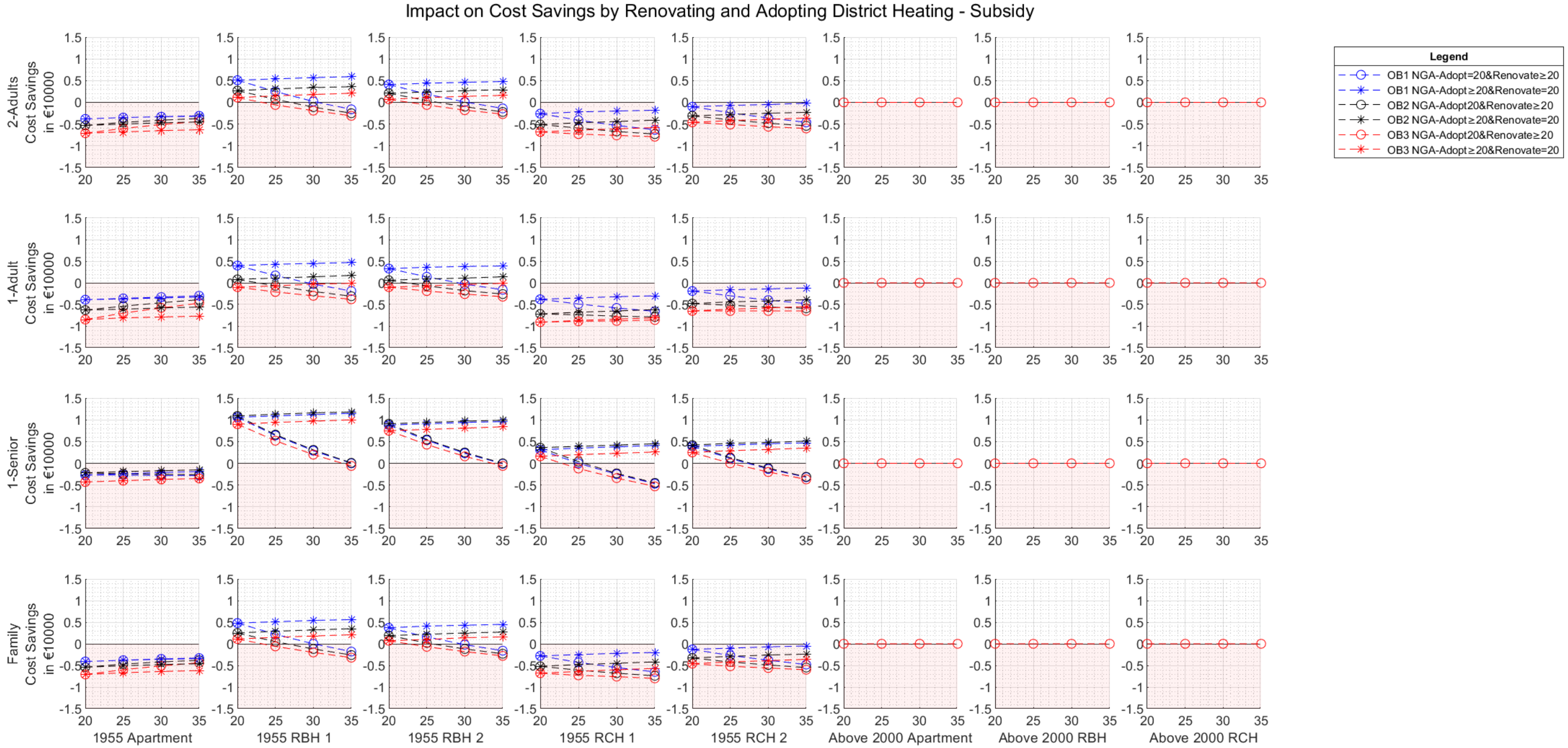

Figure 49 Economic Impact of Adopting District Heating and Renovating Household – District Heating Adoption & Renovation Delayed – Building Renovated to Comprehensive Basic

The above image presents the impact of delaying renovation after adopting NGA in 2020 (circle marker) and delaying NGA adoption after renovating in 2020 (asterisk marker). It can be observed that for all households living in 1955-Between Row House (76% of Row Houses), district heating becomes economically interesting.

Further, it can be noted that adopting NGA in 2020 and delaying renovation to 2025 or 2030 or 2035 – is economically attractive but the economic savings fall significantly as the renovation is pushed further towards 2035. Whereas renovating the building in 2020 and delaying the adoption of NGA to 2025 or 2030 or 2035 – is economically attractive, additionally the economic savings are increasing as the NGA adoption is pushed towards 2035. Thus, it is necessary to renovate various buildings that are positively influenced by renovation. Further, it can be noted that when households switch to energy intensive behaviour such as setpoint 20ºC, they are still able to achieve cost savings.

Note: In the above image, for Above 2000 buildings the economic impact is not calculated because the buildings are already meeting the insulation requirements for comprehensive basic. Thus, economic impact is not presented.

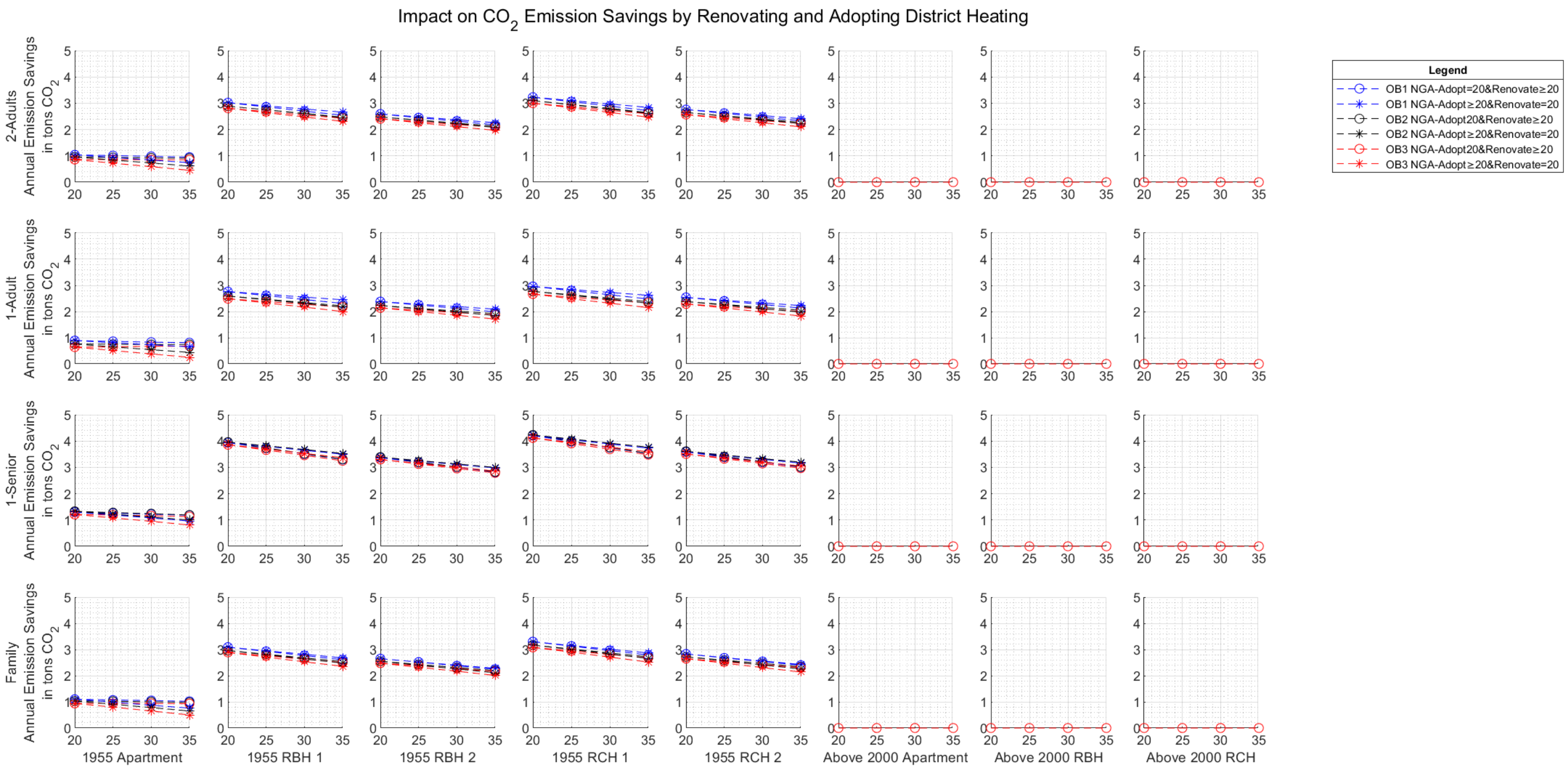

Figure 50 Environment Impact of Adopting District Heating and Renovating Household – District Heating Adoption & Renovation Delayed – Building Renovated to Comprehensive Basic

From the above figure – the saving on CO_2 emissions is similar for both options (to renovate first or to adopt NGA first). However, either delaying the adoption of NGA or renovation leads to decrease in savings on CO_2 emission. Thus, for households interested in maximizing CO_2 emission savings, it required to renovate the house or adopt NGA as early as possible.

8.7.2 Adoption of Heat pump

In this scenario, the main driving force within the neighbourhood to adopt heat pumps is the consensus among the residents (primarily homeowners) to proactively shift away from the natural gas and the landscape pressure created by Groningen gas and climate change.

Before 2035, homeowners are driving the transition within the neighbourhood, because the municipality wants homeowners to choose a suitable natural gas alternative by themselves, before the end of the transition (Gemeente Amsterdam, 2018). In this case, homeowners of the neighbourhood increasingly adopt heat pump, because it is cost-efficient, and it leads to higher thermal comfort.

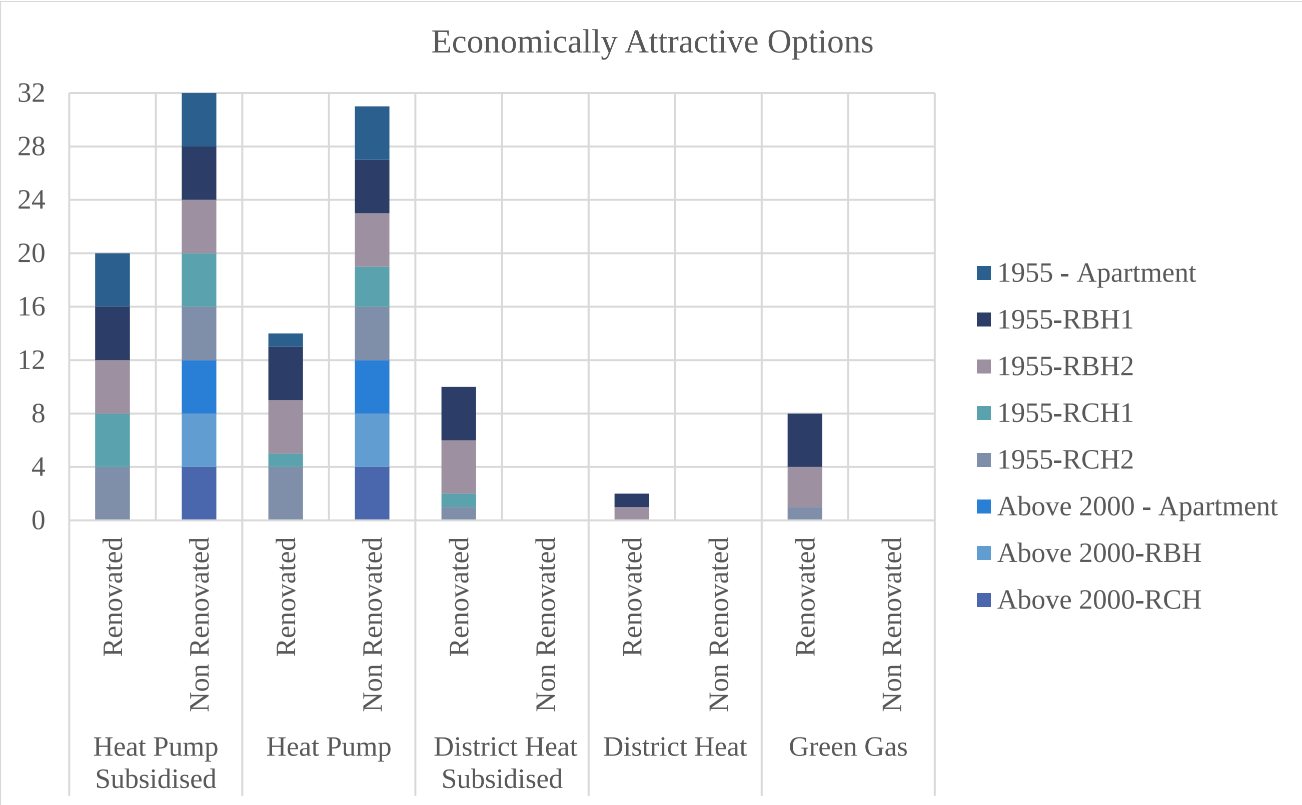

Figure 51 Economically Attractive Options

Various possibilities that lead homeowners to adopt heat pump are

1. Households in Buurt-9 are primarily interested in saving on energy expenditures and then on CO_2 emissions. Since the heat pump is economically interesting to all of the assessed households (32 types), it creates a possibility for all homeowners to adopt it (refer to figure 48).
2. Sceptical homeowners in the neighbourhood can be enabled into adoption by education and through public demonstration of the heat pump. These actions are expected to improve the technology's visibility among the neighbourhood residents and enable homeowners to get accustomed to the technology.
3. Though district heating is a comfortable, maintenance-free and noiseless option, homeowners adopt heat pump because they value economic savings and they are less bothered about slow warm-up of rooms and noise produced by fans.

Note: As homeowners are proactive, they do not wait until 2035 for green gas to mature. Thus, green gas is not a competition for the heat pump.

The adoption of the heat pump can happen immediately or gradually until 2035, during this transition period the homeowners are expected to become morally and environmentally (to a lesser degree) conscious because of the listed reasons:

1. Natural gas extraction is affecting civilians in the Groningen region; thus, homeowners collectively want to alleviate the impact on Groningen residents by adopting other alternatives.
2. Increasingly, homeowners start to witness and experience the effects of climate change (around the globe) such as recent wildfires in Australia (Fountain, 2020), 2019's heatwave (Carrington, 2019) the spread of new diseases and droughts (Ligtvoet *et al.*, 2015).

Despite becoming morally and environmentally conscious, the primary objective of homeowners is to minimize costs. Thus, the homeowners of Buurt 9 are expected to adopt a heat pump for reducing their energy expenditure and to a certain degree reduce the dependence on natural gas and to reduce CO_2 emissions. Hence normative rules for heat pump adoption are "cost savings", "reducing dependence on Groningen gas", and "reducing CO_2 emissions".

During the transition period, the local government is expected to play a major role in supporting the transition and improving the efficiency of the neighbourhood.

Based on the findings from economic and environment impact, it can be identified that for all types of neighbourhood households, heat pump is an economically attractive. However, subsidy is required for all households to experience heat pump as economically attractive (refer to section 8.7.2.1).

For households living in 1955 Row house, it is economically interesting to renovate the building first and consecutively adopt heat pump. For households living in 1955 Apartment, it is economically interesting to adopt heat pump first and consecutively renovate. Whereas for households living in Above 2000 buildings, it is interesting adopt heat pump directly, without renovating the building (refer to section 8.7.2.1).

In this regard, local government can play a significant role in assisting homeowners to renovate the building by providing renovation loans. According to Ebrahimigharehbaghi, Qian, *et al.* (2019) primary barriers to renovation and adoption of NGA are "*time and effort required to obtain loan or subsidy*"; "*Reliable experts"*; "*Knowledge and Skills*". Thus it is suggested by Ebrahimigharehbaghi, Qian, *et al.* (2019) that the focus of the present policy must aim to reduce the complexity of loan and subsidy procurement. As a result of easing, homeowners can easily access renovation loans and subsidies for renovating the building and adopting heat pump.

Then to eliminate the uncertainty surrounding energy renovations, it is important that homeowners receive tailor made solutions and guidance through the renovation process (explaining the impact of renovation, proving loan assistance, connecting to reliable contractors, etc.). In this regard local government can play a significant role in assisting homeowners, because government agencies are the most trusted by homeowners (Ebrahimigharehbaghi, Qian, *et al.*, 2019). According Broers *et al.* (2019) home owners appreciate the energy audits performed by municipally governments and feel comfortable and confident in the information provided by the government-agents. Energy desk is public-private-initiative supporting homeowners through the energy-renovation process by providing tailor made solutions (Energieloket Amsterdam, no date). Thus, with help of such similar initiative, the homeowners can be nudged into renovating their buildings.

Also, energy-popup shops are an interesting development for supporting local initiatives because they can be used to create awareness and support homeowners at a neighbourhood level by addressing the specific needs and wishes of the homeowners. Initial experience with popup shops, show that they could have a positive and influential impact on energy renovation decisions (Ebrahimigharehbaghi, Qian, *et al.*, 2019).

Further, from economic analysis (refer to section 8.7.2.1). it can be found that when household switches to energy-intensive behaviours (higher setpoint temperatures) without renovation, then household is expected to spend more on energy costs. Thus, it is required to raise awareness of households to consume less energy. In this regard, local government can play a significant role in rising the awareness of households by creating and experimenting new policies to reduce energy consumption (Dahlbom *et al.*, 2009).

Further, it is expected that incumbents actors will play a passive role by only providing electricity to households. The DNO is expected to play a reactive role, as it will upgrade the electricity connection from single-phase to three-phase; and remove the gas connection, only on the request of homeowners (Liander, 2020). For niche actors supporting the development of heat pumps, it is expected that installers and suppliers will become knowledgeable about heat pumps and develop their communications skills to assist their customers to operate heat pumps efficiently (Heynen *et al.*, 2018).

In terms of major regulative changes, a ban on natural gas and(or) gas boilers can be expected. Concerning economic instruments, it is expected that the local government will continue to encourage homeowners to make transition adaptations by providing subsidies and low-interest loans to support the shift (Gemeente Amsterdam, 2017; Gemeente Amsterdam, 2019). Further, it is expected that the national government will continue to use existing economic instruments (increasing tax on natural gas and decreasing tax on electricity) for discouraging the usage of natural gas and encouraging electric alternatives (Klimaatakkoord, 2018; Government of the Netherlands, 2019a).

Concerning institutional change – 'displacement' of existing institutions is expected. According to Heynen *et al.* (2018), heat pumps will be widely adopted in the coming decade, and this widespread adoption could lead to grid load-problems. Due to the development of new problems, new rules are expected to be created. E.g. a household is more likely to install a heat pump and rooftop solar, because both products are complementary and they can reduce household's dependence on the grid (Costa, 2017; Cetin-Öztürk, 2018). Since the electricity load and electricity supply have seasonal variations, it is expected that the grid can experience a surge in supply during summers. This surge can lead to peak situations, that can destabilize the grid. Thus, new institutions and rules are expected to be created for addressing problems arising from the adoption of heat pumps and their complementary products.

The dynamics for the heat pump adoption can be viewed as a technological substitution because the heat pump is replacing natural gas boiler to provide low-temperature heat. However, this dynamic also shares similarities with the transformation pathway because the households are migrating their energy needs from 'natural gas' to 'electricity'. Since the incumbents (suppliers/network operators) from the natural gas regime are actively involved in electricity sectors, they are expected to contribute to this transition. The role of incumbents is 'reactive', as they are waiting for the market to act (e.g. A DSO will reinforce the grid, only on the request of households (Liander, 2020)). Further, power struggles within the neighbourhood are highly possible, particularly among households (homeowners), while choosing an alternative niche. In this case, the local government can stimulate discussion among households by using formal instruments such as 'resident association' to enable participation (Tumber, 2012). Further, through household participation, it is possible for the local government to identify an attractive option, easily.

8.7.2.1 *Economic and Environment Impact*

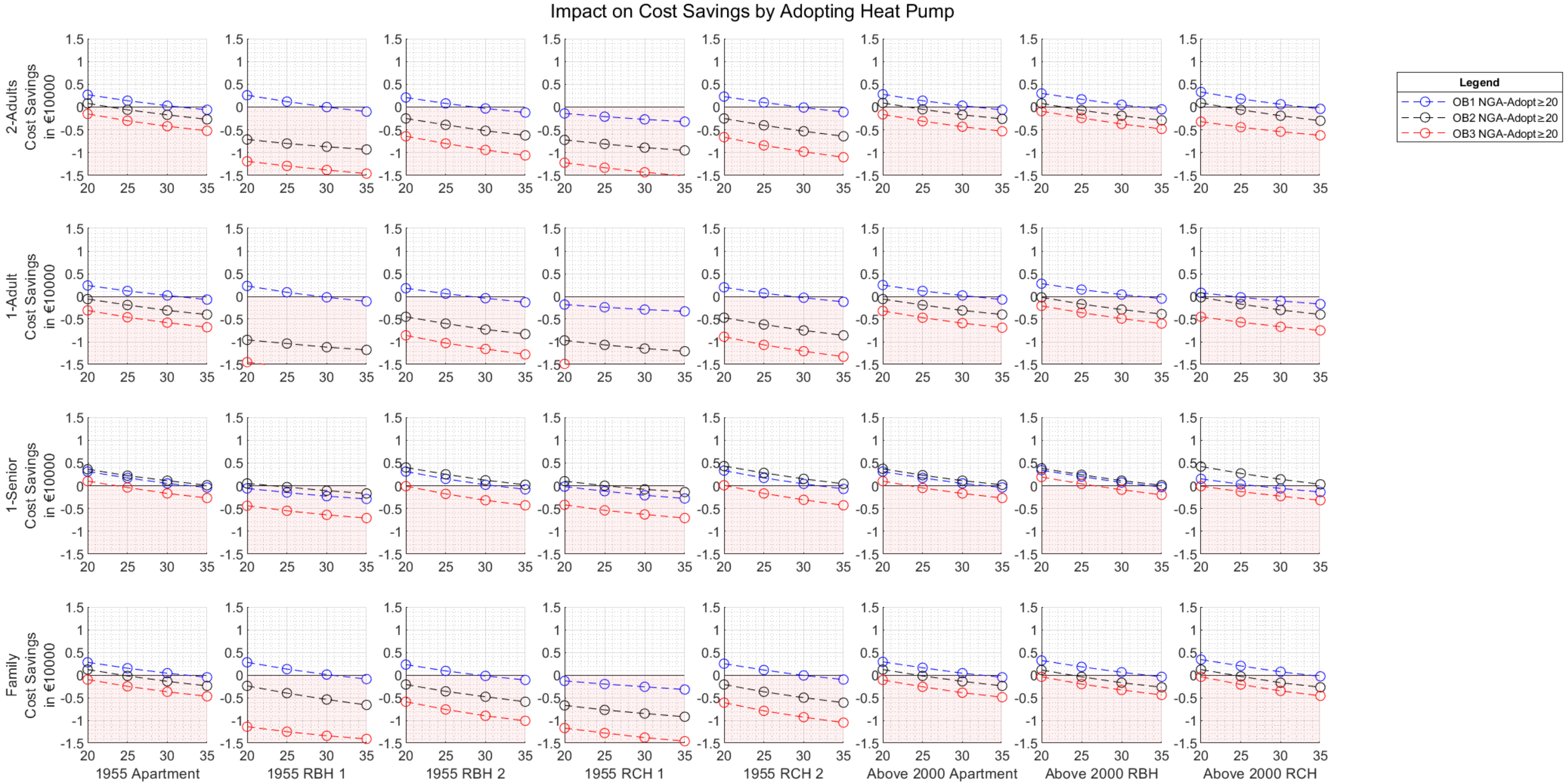

Figure 52 Economic Impact of Adopting Heat Pump by Non-Renovated House – Heat Pump Adoption Delayed

For the above image, red region represents economically unattractive options. It can be observed that even without subsidy provision, for 31 of 32 considered households, heat pump is an economically interesting alternative. However, in this case households must adopt heat pump before 2020, otherwise it will become economically unattractive to adopt heat pumps after 2020.

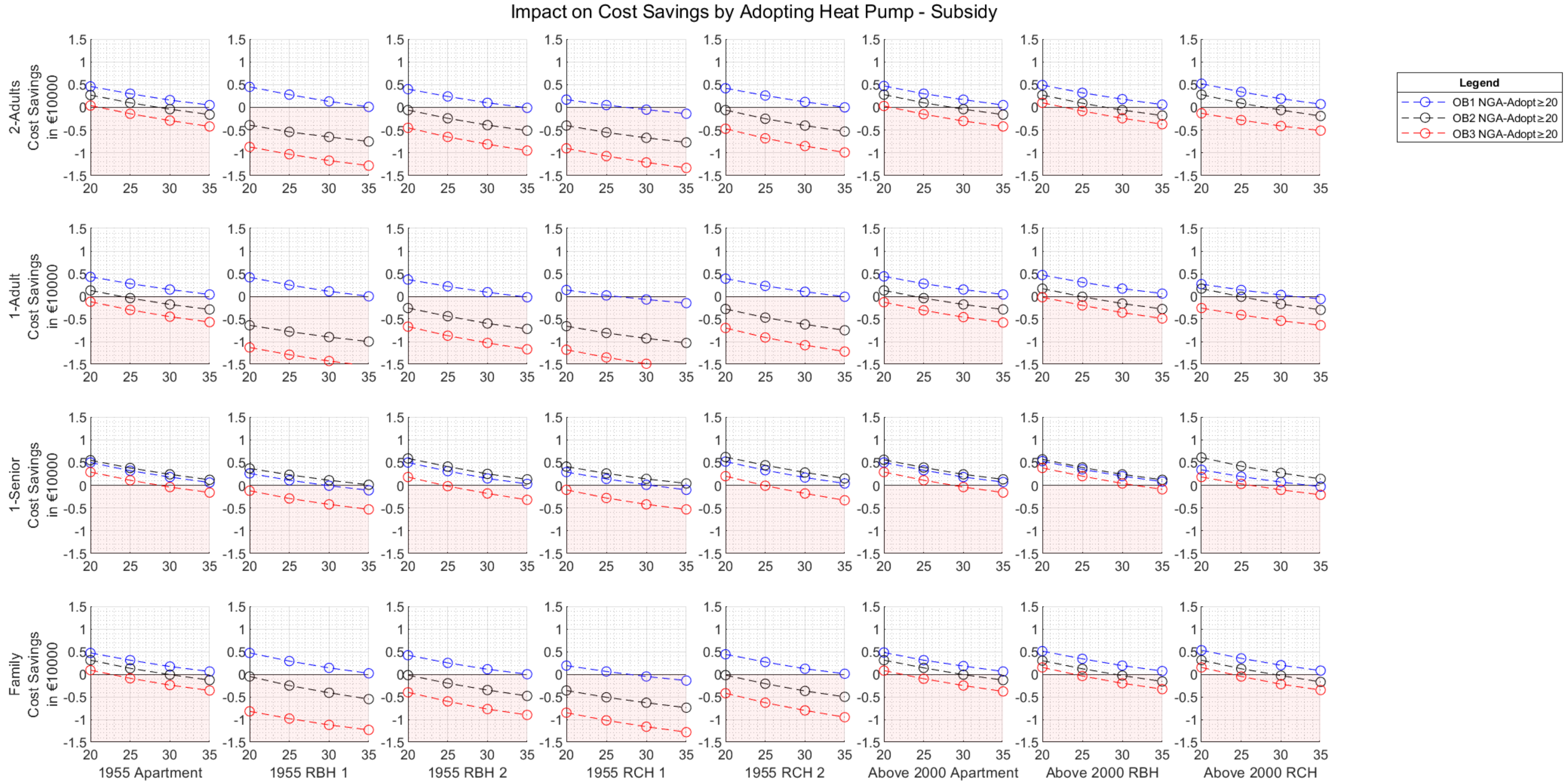

Figure 53 Economic Impact of Adopting Subsidised Heat Pump by Non-Renovated House – Heat Pump Adoption Delayed

It can be observed that with subsidy provision, for all of the considered households, heat pump is an economically interesting alternative. However, the impact of subsidy is minimal, overall.

Further, it has to be noted that, when a household switches to energy intensive behaviours or rebound behaviour (OB2-Setpoint 20ºC – black line; OB3-Setpoint 22ºC – red line) the costs are increasing. Thus, it is necessary to raise the awareness of consumers about their energy consumption patterns for reducing energy costs.

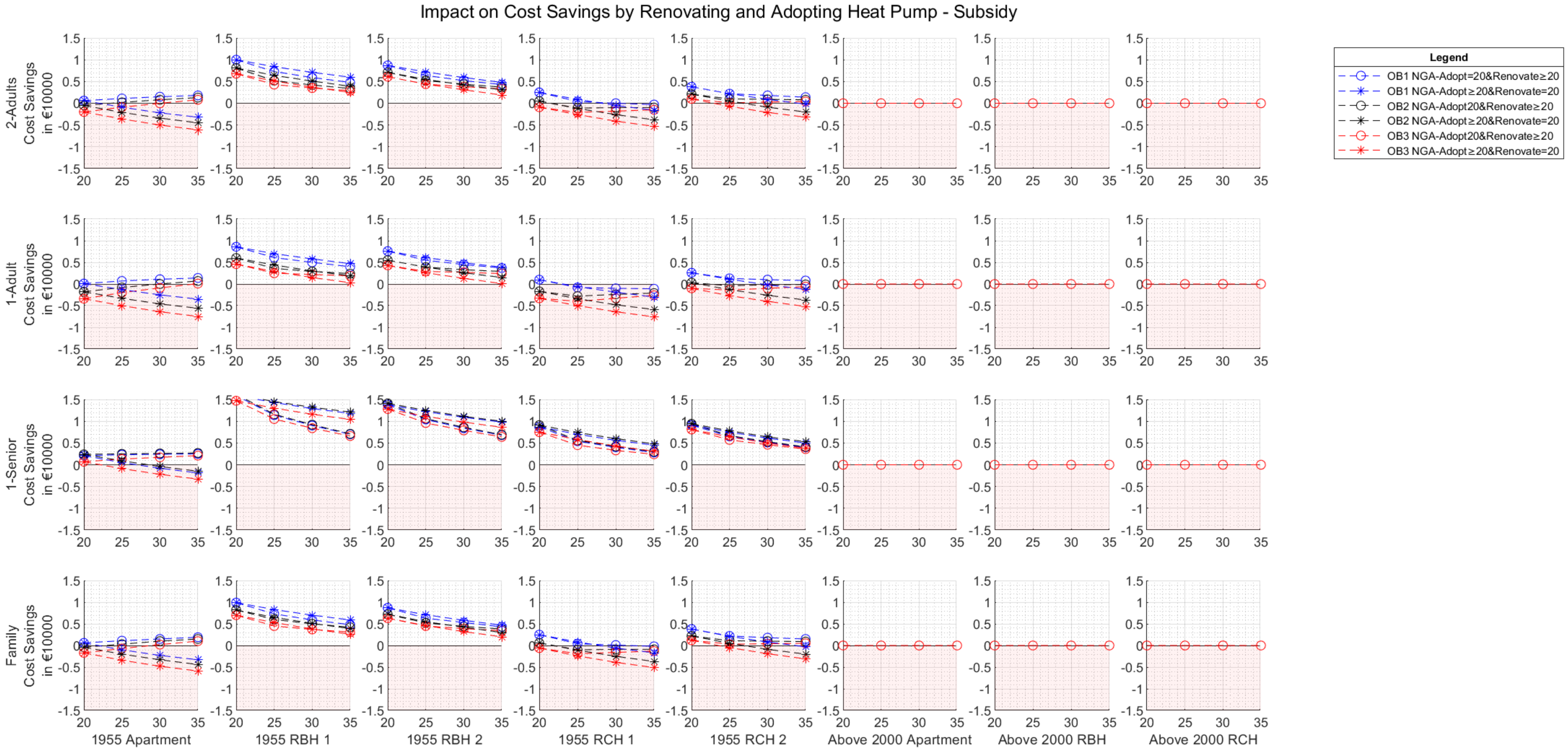

Figure 54 Economic Impact of Adopting Subsidised Heat Pump and Renovating - Heat Pump Adoption Delayed – Building Renovated to Comprehensive Basic

It can be noted from the above image that, renovating and adopting heat pump is interesting for all households living in 1955 Row houses. With the help of renovation, households can easily switch to energy intensive behaviours (OB2-Setpoint 20ºC – black line; OB3-Setpoint 22ºC – red line) while also saving on costs. For households living in 1955-Apartment, it is interesting to adopt heat pump first and then renovate the building.

Note: In the above image, for Above 2000 buildings the economic impact is not calculated because the buildings are already meeting the insulation requirements for comprehensive basic. Thus, it is not possible to calculate economic impact.

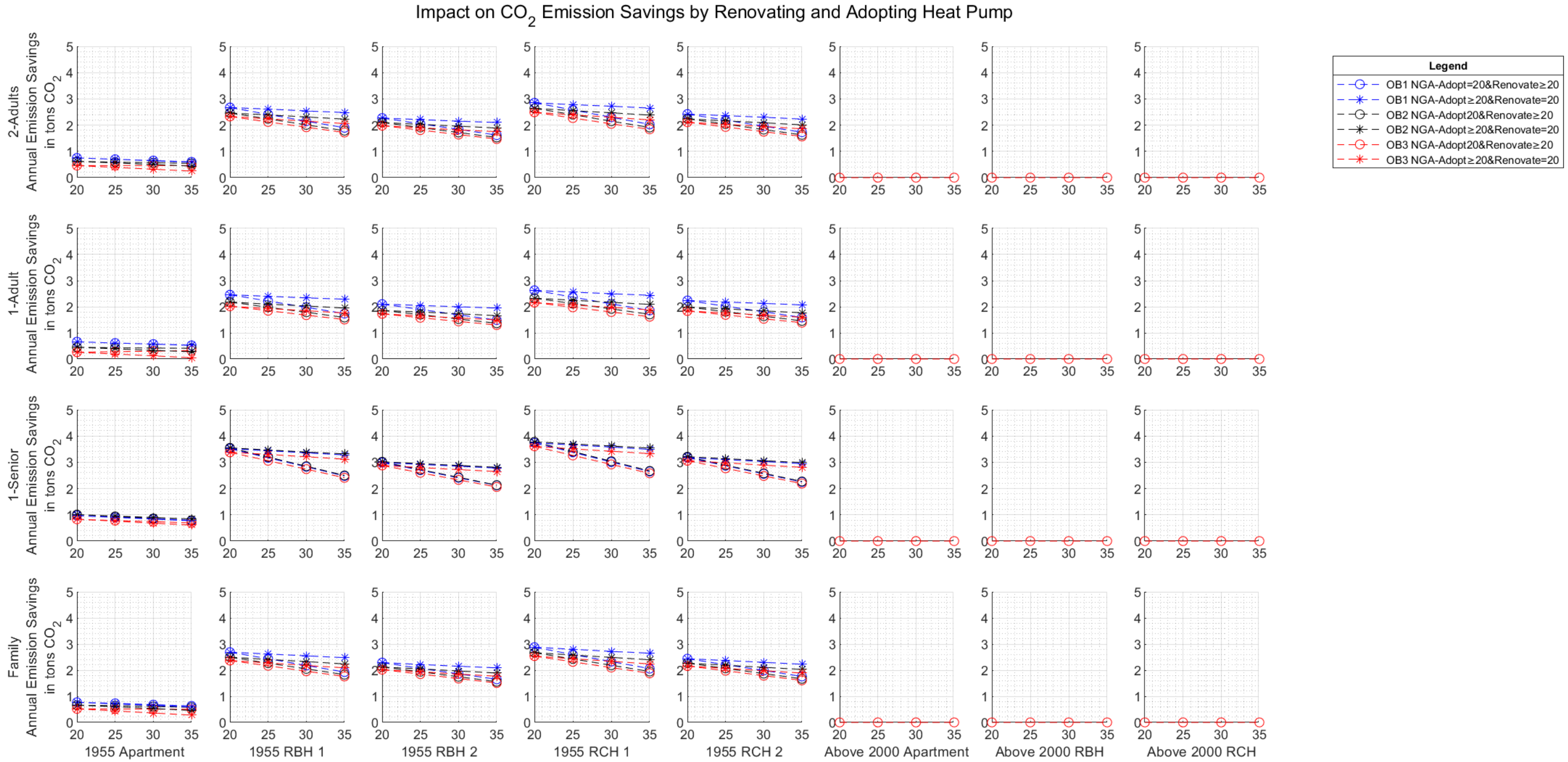

Figure 55 Environment Impact of Adopting Heat Pump and Renovating Household - NGA Adoption & Renovation Delayed – Building Renovated to Comprehensive Basic

From the above figure – it can be noted that adopting Heat pump in 2020 and delaying renovation to 2025 or 2030 or 2035 – is environmentally attractive but the CO_2 emission savings fall significantly as the renovation is pushed further towards 2035. Whereas renovating the building in 2020 and delaying the adoption of NGA to 2025 or 2030 or 2035 – is also environmentally attractive. In the second case, the CO_2 emission savings are marginally falling, as the heat pump adoption is pushed towards 2035. Thus, it is necessary to renovate various buildings that are positively influenced by renovation in saving CO_2 emissions. Further, it can be noted that when households switch to energy intensive behaviour such as setpoint 20ºC and 22ºC, they are still able to achieve CO_2 emission savings.

8.7.3 Adoption of Green Gas

In this scenario, the green gas is expected to relieve the neighbourhood from using natural gas, because of two major factors 1. the households are captivated to using natural gas; and 2. the landscape pressures, complemented with the inadequacy of the other alternative, has supported the development of the green gas niche. As a result, green gas is expected to grow substantially and replace natural gas. Adopting green gas significantly increases the energy costs and other concerns include smell and safety issues. The foul-smell is dependent on the source used for producing green gas. However, due to homeowner's captivity to natural gas, other factors are expected to be less significant in enabling or disabling the adoption of green gas

During the transition period, the local government is expected to play a major role in supporting the transition and improving the efficiency of the neighbourhood.

Based on the findings from economic and environment impact, it can be identified that for households living in 1955-Row Between Houses, green gas is economically attractive only when the building is renovated. For other energy inefficient households, renovating the building can reduce costs incurred by using green gas (refer to section 8.7.3.1).

In this regard, local government can play a significant role in assisting homeowners to renovate the building by providing renovation loans. According to Ebrahimigharehbaghi, Qian, *et al.* (2019) primary barriers to renovation and adoption of NGA are "*time and effort required to obtain loan or subsidy*"; "*Reliable experts"*; "*Knowledge and Skills*". Thus it is suggested by Ebrahimigharehbaghi, Qian, *et al.* (2019) that the focus of the present policy must aim to reduce the complexity of loan and subsidy procurement. As a result of easing, homeowners can easily access renovation loans for renovating their building and incur less costs.

Then to eliminate the uncertainty surrounding energy renovations, it is important that homeowners receive tailor made solutions and are guided through the renovation process (explaining the impact of renovation, proving loan assistance, connecting to reliable contractors, etc.). In this regard local government can play a significant role in assisting homeowners, because government agencies are the most trusted by homeowners (Ebrahimigharehbaghi, Qian, *et al.*, 2019). According Broers *et al.* (2019) home owners appreciate the energy audits performed by municipally governments and feel comfortable and confident in the information provided by the government-agents. Energy desk is public-private-initiative supporting homeowners through the energy-renovation process by providing tailor made solutions (Energieloket Amsterdam, no date). Thus, with help of such similar initiative, the homeowners can be nudged into renovating their buildings.

Also, energy-popup shops are an interesting development for supporting local initiatives because they can be used to create awareness and support homeowners at a neighbourhood level by addressing the specific needs and wishes of the homeowners. Initial experience with popup shops, show that they could have a positive and influential impact on energy renovation decisions (Ebrahimigharehbaghi, Qian, *et al.,* 2019).

Here, the technology developers from green gas niche are at the centre of green gas development with the incumbents from the natural gas regime. Incumbents are expected to cast away their dependence on natural gas and support the development of green gas niche. During the transition period, the local government is expected to play a major role in improving the efficiency of the neighbourhood because the goal of the government is to reduce CO_2 emissions. Based on the findings from the techno-economic analysis it can be identified that delaying building renovation lead to higher emissions than delaying the adoption of NGAs. Further, building renovations have a positive impact on cost savings for households. Thus, it is a win-win situation for both government and homeowners. In this regard, local government can play a significant role in assisting homeowners to renovate, because government agencies are the most trusted by homeowners (Ebrahimigharehbaghi, Qian, *et al.*, 2019). According to Broers *et al.* (2019), homeowners appreciate the energy audits performed by municipal governments and feel comfortable and confident in the information provided by the government agents. Energy desk is public-private-initiative supporting homeowners through the energy-renovation process by providing tailor-made solutions (Energieloket Amsterdam, no date). Thus, with the help of such similar initiative, the homeowners can be nudged into renovating their buildings. Further, it is expected that incumbents actors will play an active role in the development of the green gas niche by collaborating with niche technology developers.

As identified by Miedema, van der Windt and Moll (2018) despite performing energy conservation measures, other renewable alternatives are insufficient to support the energy transition. As a result, it is expected that the national government will play a pivotal role in steering the development of green gas, similar to its past role in natural gas development. Since ECN has already developed the technology for producing green gas at a smaller scale, it is expected that incumbents will reorient themselves by collaborating with ECN and invest in the development of green gas. Incumbents (e.g. Engine) are supportive of green gas because the required infrastructure for transporting the green gas is present and the households are creating the future demand for green gas (methane) by being captivated to natural gas. It is expected that the municipality will play a passive role in this scenario by supporting the development of energy conservation measures. Concerning boiler installers, no competency training or skills development is expected.

Concerning institutional and rule changes – ‘conversion’ of existing institutions and rules is expected. Over the course of the transition, it is expected that policy will change from using less natural gas by conserving energy to using no natural gas. As a result, the natural gas will gradually phaseout, while bridging the households to green gas. Further, the regulative rules in this scenario will be aimed at reducing the dependence on natural gas by encouraging energy-saving measures. By the end of the transition period, it can be expected that a full ban on natural gas is possible. This ban will be gradual, where the ratio of green gas will keep increasing until it replaces natural gas. Concerning economic instruments, it is expected that the local government will continue to encourage homeowners to make transition adaptations (to become natural gas-free) by providing subsidies and low-interest loans to perform home renovations (Gemeente Amsterdam, 2017)(Gemeente Amsterdam, 2019). Further, it is expected that the national government will continue to use existing economic instruments, for discouraging the usage of natural gas (Government of the Netherlands, 2019a). Normative rules for the scenario are centred around the convenience offered by the natural and the households are habitual dependence to using gas (natural gas) for heating and cooking purposes.

The identified dynamics for the green gas adoption at neighbourhood level fits the transformation trajectory, described by (Geels et al., 2016). Since the incumbents are likely to re-orienting themselves in this scenario to ‘green gas’ by collaborating with niche actors. This path would concurrently guide incumbent to carry their innovation activities in the green gas niche.

8.7.3.1 Economic and Environment Impact

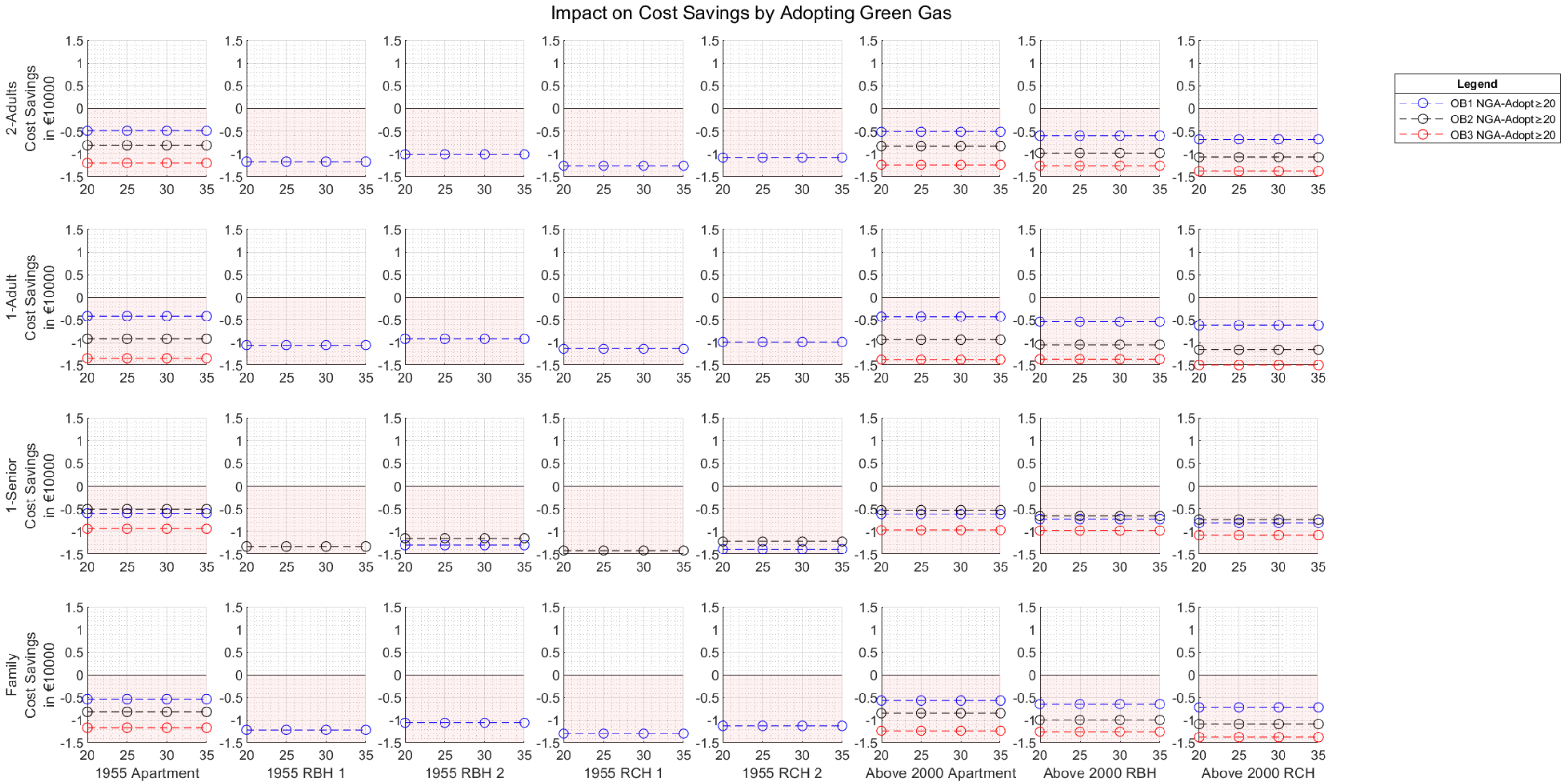

Figure 56 Economic Impact of Adopting Green Gas by Non-Renovated House – Green Gas Adopted in 2035

From the above figure it can be observed that for households living in 1955-Apartment and Above 2000 Buildings, on average all the identified households are expected to spend €5000 for energy costs. Whereas households living in 1955-Row houses are expected to spend €10000 in addition on energy costs.

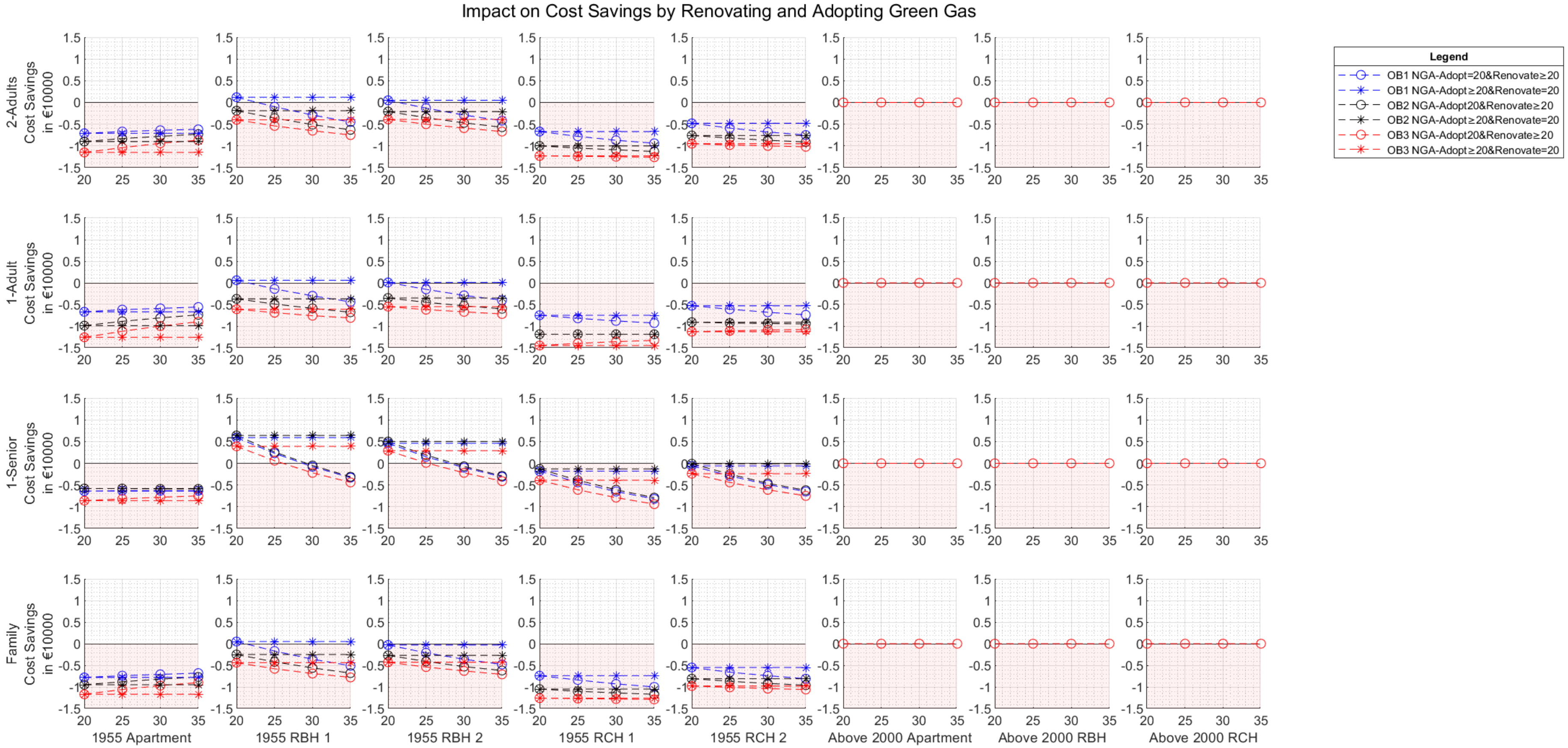

Figure 57 Economic Impact of Adopting Green Gas and Renovating – Green Gas Adoption Delayed – Building Renovated to Comprehensive Basic

From the above figure it can be observed that for households living in 1955-Row Between House, by renovating the building, significant cost savings can be achieved. For households living in other buildings, renovating the building will not result in any cost savings, however energy costs will decrease compared to non-renovated building. Further, to achieve cost saving, it is required that 1955-Row Between House buildings are renovated before 2025.

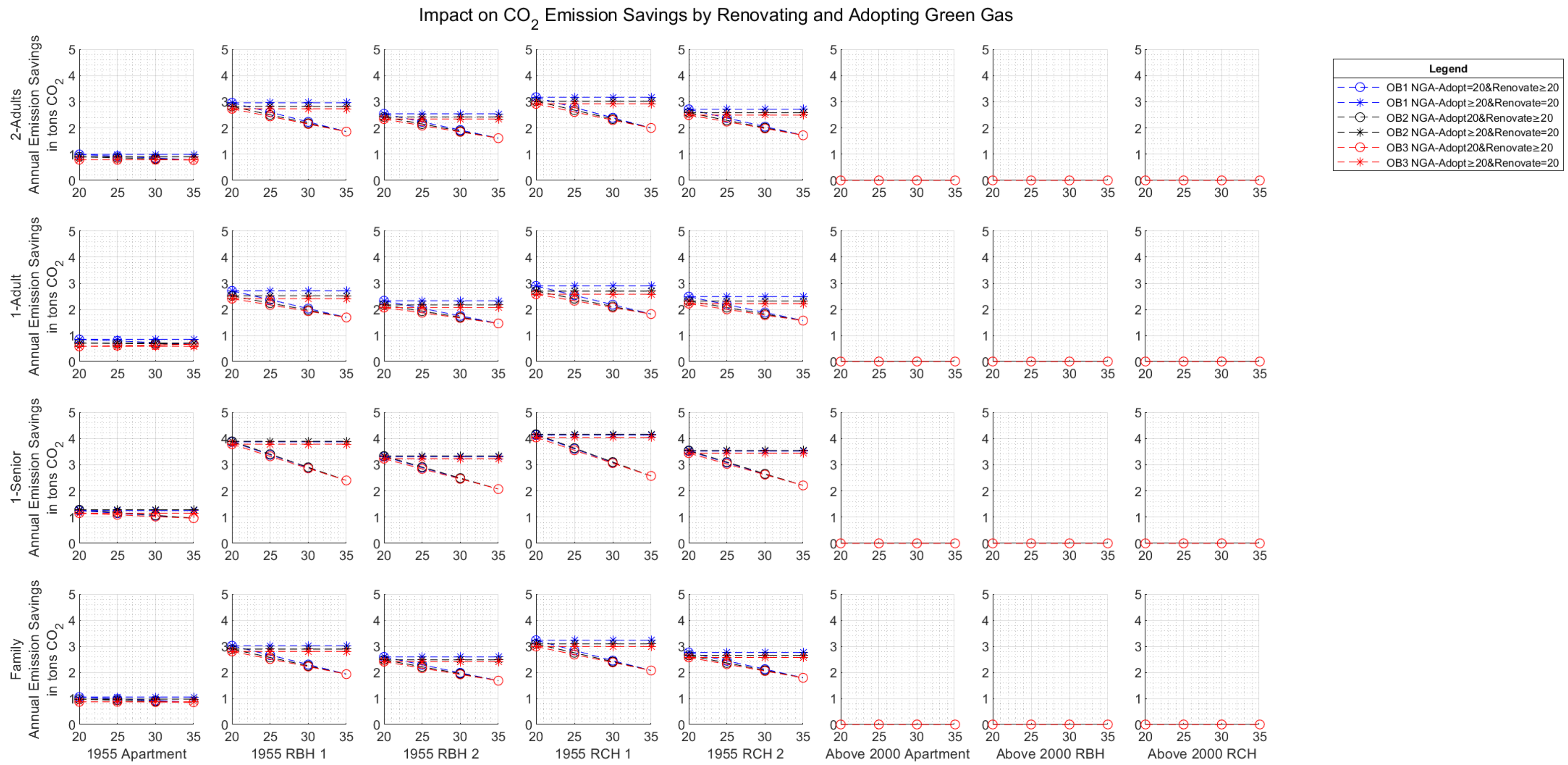

Figure 58 Environment Impact of Adopting Green Gas and Renovating – Green Gas Adoption Delayed – Building Renovated to Comprehensive Basic

To maximize CO_2 emission savings, it is required that buildings are renovated early. Delaying renovation will on lead to smaller CO_2 emissions savings.

8.8 REFLECTION AND RECOMMENDATIONS

In the scenario for district heating, the district heat network is expected to supply the low-temperature heat to the households (homeowners) of the existing neighbourhood. Here the households are expected to rent (/use an existing) deliver set, with the help of delivery the supplier can supply heat to households. Further, it is the responsibility of the niche actors to install the distribution network and supply heat without any interruption (with a leeway one major outage per year)(ACM, 2020b). To eliminate financial barriers constraining households from adopting district heat, the local government is providing subsidies. Thus, with the help of district heat, by the end of 2035, all the households can meet their low-temperature needs (space heating and domestic hot water), conveniently.

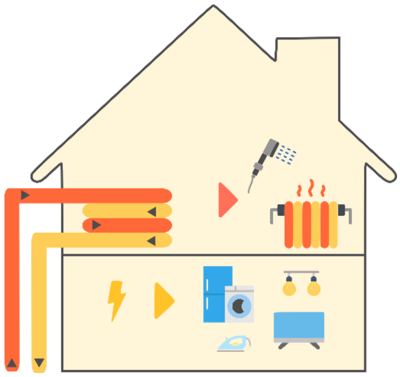

Figure 59 District Heat for Space Heating and Domestic Hot Water Purpose

In the scenario for heat pumps, it is expected that households will use heat pumps to meet all their space heating and domestic hot water needs. Further, it is expected that households will buy the heat pumps based on the heat requirements and maintain the heat pump regularly to prevent any failures or malfunction. It is expected that DNO will reinforce the electricity grid to support the demand created by heat pumps. To eliminate financial barriers constraining households from adopting heat pumps, the national government is providing subsidies. The local government is also providing subsidies, in the form of reimbursements to various cost incurred while becoming natural gas-free. Also, it is expected that energy-intensive households would perform renovations to reduce their heating demand for saving on energy and investment costs. For financially constrained households, they are expected to use these loans to improve their building insulation levels. In this regard, both local and national government are providing low-interest loans. By the end of 2035, all the households in the neighbourhood are expected to meet their low-temperature needs (space heating and domestic hot water), using heat pumps.

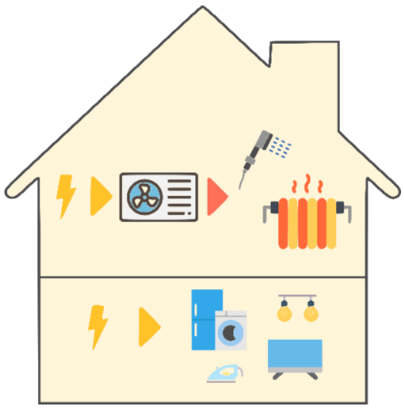

Figure 60 Heat Pump for Space Heating and Domestic Hot Water Purpose

In the scenario for green gas, it is expected that households will use green gas and a gas boiler to meet their space heating and domestic hot water needs. Further, it is expected that households will use green gas, primarily because of the reliance on natural gas and their unwillingness to switch to other alternatives. Since there green gas is underdeveloped, it is expected that the local government will support households during the transition period by providing low-interest loans to improve the building insulation. As it would reduce the natural gas consumption, once the green gas becomes commercially available, by 2035. It is expected that households will continue to use green gas for meeting their low-temperature heat needs. In the event of green gas failing to meet commercial expectations, it is assumed that the municipality will decide district heat as the suitable choice for the neighbourhood.

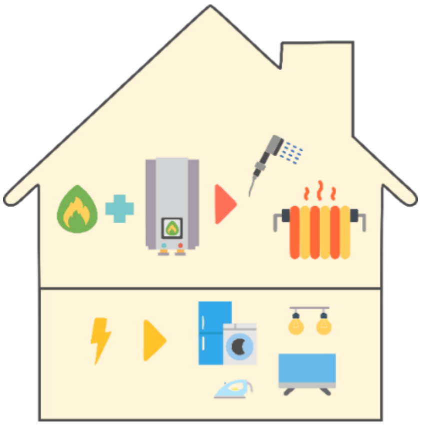

Figure 61 Green Gas Based Heating in Households - using a gas boiler

Note: Further for all scenarios, it is assumed that household's demand for electricity, arising from the usage of electric appliances will remain unchanged and all the households will extend their current practices to 2035.

9 CONCLUSION

In the context of dwindling natural gas reserves and increasing earthquakes in the Groningen region, the national government has set to become natural gas-free by 2050 (RVO, no date; Exel, Geus and Zeinstra, 2017). In this regard, the metropolitan region of Amsterdam is working towards becoming natural gas-free by 2035. To enable the natural-gas free transition, the local municipalities are expected to identify a desirable heating method for each neighbourhood within MRA (Amsterdam Metropolitan Area, 2016). In the context of global warming, the government of the Netherlands is fighting climate change by focusing on strategies to reduce CO_2 emissions. In this regard, the government is promoting energy conservation in the housing sector by providing 'low-interest loans' for energy renovations and subsidies for sustainable heating alternatives (Ministry of Economic Affairs, 2017) (Government of the Netherlands, 2019a).

Considering the above-mentioned policy initiatives, the study aims to understand the implications of energy transition options (natural gas-free options and energy conservation) on a single neighbourhood within the MRA from the perspective of homeowners. The first research question for the study is listed below:

1. *What is the attractiveness of alternatives to the natural-gas and energy-renovation options to the households of an existing neighbourhood from the perspective of 'homeowners'?*

To answer the question, the study has used techno-economic analysis for assessing the attractiveness of natural-gas-alternatives (NGAs) and energy-renovation-options (EROs) from a homeowner's perspective. As techo-economic analysis is insufficient for explaining the adoption of an NGA by a neighbourhood, the study has used sociotechnical scenarios (aided by MLP) for narrating the adoption of an NGA. Thus following the research question is phrased to narrate the adoption of an NGA.

2. *What is the narrative offered by the MLP for explaining the adoption of District Heating or Heat Pumps or Green Gas by the neighbourhood?*

In the consecutive subsections, the impact of energy transition options is elaborated from techno-economic perspective and sociotechnical perspective.

9.1 DISTRICT HEATING

9.1.1 Technoeconomic Impact Assessment

District heating is marginally expensive for many households, when compared against natural gas. District heating is directly attractive to households that are able to renovate the building and save significantly on energy savings. While using district heating, through building renovation households can achieve cost savings, despite switching to energy intensive behaviours (refer to figure 49). Further, it has been found that district heating is financially feasible, only if the households are able to procure subsidies (Gemeente Amsterdam, 2017)(Nationaal Energiebespaarfonds, 2018). For households, that are interested in reducing CO_2 emission, district heating is the most attractive option.

9.1.2 Sociotechnical Impact Assessment

In this scenario, the main driving force within the neighbourhood to adopt district heating is the consensus among the residents (primarily homeowners) to proactively shift away from the natural gas and the landscape pressures created by Groningen gas and climate change.

Homeowners are driving the transition within the neighbourhood. Here homeowners of the neighbourhood collectively opt for district heating, because it is a convenient, maintenance-free alternative and it can lead to significant emission reductions. On the request of homeowner, the district heat supplier develops the heating network, the DNO operator disconnects the household from gas grid.

Primary normative rule for the homeowners of Buurt 9 to adopt district heating is environmental protection and emissions reduction. Major regulative change - a ban on natural gas and(or) gas boilers can be expected nearing the end of the transition. Concerning economic instruments, it is expected that the local government will continue to encourage homeowners to make transition adaptations by providing subsidies and low-interest loans for supporting the NGA shift and to renovate inefficient buildings. Further, it is expected that the national government will continue to use existing economic instruments, such as taxing natural gas for discouraging the usage of natural gas.

During the transition, the local government is expected to play a significant role in assisting homeowners to renovate, because government agencies are the most trusted by homeowners. Incumbents are expected to play a passive/reactive role by supporting the requests of homeowners. Incumbents are expected to stop supplying natural gas and provide electricity to their customers. Concerning grid adaptations, it is expected that a new network for supplying district heat will be established in the neighbourhood and the gas connection will be removed, on the request of homeowners. Niche actor, Vattenfall is expected to play an active role during the transition by supporting the district heating development.

Concerning institutional changes – 'displacement' of the existing institution with new institutions is expected for providing low-temperature heat. The dynamics for the district heating adoption can be viewed as a technological substitution because the district heating is replacing the usage of natural gas as well as its distribution network by creating a new infrastructure for providing low-temperature heat.

9.2 HEAT PUMP

9.2.1 Technoeconomic Assessment

Heat pump is the most attractive option (financially) for many households. In few cases, adopting heat pump without building renovation is more financially attractive to a household than adopting heat pump with renovation. Specifically, for older building, it is interesting to renovate the building and adopt heat pump because it allows the household to switch to higher set point temperatures, without increasing costs (refer to figure 54). Whereas by adopting heat pump in a non-renovated house, the household cannot switch to higher set-point temperatures. Otherwise the switch will result in increased costs. For households, that are interested in reducing CO_2 emission, heat pump is not the most attractive option. However, it can lead to significant CO_2 emission reductions.

9.2.2 Sociotechnical Impact Assessment

In this scenario, the main driving force within the neighbourhood to adopt heat pumps is the consensus among the residents (primarily homeowners) to proactively shift away from the natural gas and the landscape pressure created by Groningen gas and climate change.

Homeowners are driving the transition within the neighbourhood. Here, homeowners of the neighbourhood increasingly adopt heat pump, because it is cost-efficient, and it leads to higher thermal comfort. Homeowner are expected to buy heat pump from suppliers and install the heat pump with help of installers.

Primary normative rule for the homeowners of Buurt 9 to adopt district heating is cost saving. Major regulative change - a ban on natural gas and (or) gas boilers can be expected nearing the end of the transition. Concerning economic instruments, it is expected that the local government will continue to encourage homeowners to make transition adaptations by providing subsidies and low-interest loans for supporting the NGA shift and to renovate inefficient buildings. Further, it is expected that the national government will continue to use existing economic instruments, such as taxing natural gas for discouraging the usage of natural gas.

During the transition, the local government is expected to play a significant role in assisting homeowners to renovate, because government agencies are the most trusted by homeowners. Incumbents are expected to play a passive/reactive role by supporting the requests of homeowners. Incumbents are expected to stop supplying natural gas and provide electricity to their customers. Concerning grid adaptations, it is expected that electricity grid will be reinforced to three phase and the gas connection will be removed, on the request of homeowners. Niche actor, Vattenfall is expected to play an active role during the transition by supporting the district heating development.

Concerning institutional changes – 'displacement' of the existing institution with new institutions is expected for providing low-temperature heat. The dynamics for the heat pump adoption can be viewed as a technological substitution because the heat pump is replacing natural gas boiler to provide low-temperature heat.

9.3 GREEN GAS

9.3.1 Technoeconomic Assessment

From techno economic assessment study, it has been found that green gas is financially attractive to households, only when households are able to renovate the building and reduce their energy demand significantly. If the households are not able to either renovate the building or reduce their energy demand significantly, then green gas is not financially attractive. For buildings that are not able to achieve cost savings, renovation is still interesting because it can reduce expenditure. On the other hand, the CO_2 emissions resulting from using green gas is comparable to emissions resulting from district heating (refer to figure 33).

9.3.2 Sociotechnical Impact Assessment

In this scenario, the green gas is expected to relieve the neighbourhood from using natural gas, because of two major factors 1. the households are captivated to using natural gas; and 2. the landscape pressures, complemented with the inadequacy of the other alternative, is enabling green gas to develop. As a result, green gas is expected to grow substantially and replace natural gas. Here, the technology developers from green gas niche are at the centre of green gas development with the incumbents from the natural gas regime. Incumbents are expected to cast away their dependence on natural gas and support the development of green gas niche. Also the national government is expected to play a pivotal role in steering the development of green gas, similar to its past role in natural gas development. During the transition period, the local government is expected to play a major role in improving the efficiency of the neighbourhood because the goal of the government is to reduce CO_2 emissions.

The regulative rules in this scenario will be aimed at reducing the dependence on natural gas by encouraging energy-saving measures. The normative rule for is scenario is driven by the homeowners extensive reliance on natural gas boiler and unwillingness to change.

Concerning economic instruments, it is expected that the local government will continue to encourage homeowners to make transition adaptations by providing subsidies and low-interest loans for supporting the NGA shift and to renovate inefficient buildings. Further, it is expected that the national government will continue to use existing economic instruments, such as taxing natural gas for discouraging the usage of natural gas.

Concerning institutional and rule changes – 'conversion' of existing institutions and rules is expected. The identified dynamics for the green gas adoption at neighbourhood level fits the transformation trajectory, because Since the incumbents are re-orienting themselves in this scenario to 'green gas' by collaborating with niche actors.

9.4 ENERGY RENOVATION

At a neighbourhood level, it is first important to renovate the old buildings (1955 buildings) because it can reduce energy costs for the household significantly. As a households delays renovation, the economic potential to save money over 30 years diminishes gradually. This trend is visible in the below presented figure 51. The red triangle shows the cost saving potential for building renovation operating on natural gas. As the renovation is delayed to 2035, the renovation becomes financially unattractive by 2035.

Also, it is visible from figure 62 that delaying the adoption of NGA has minimum impact on CO_2 emissions compared to delaying the renovation measures (for 1955 between house Type 1 – occupied by family). Thus, it is important for the neighbourhood to adopt energy conservation measures in the beginning years of the transition.

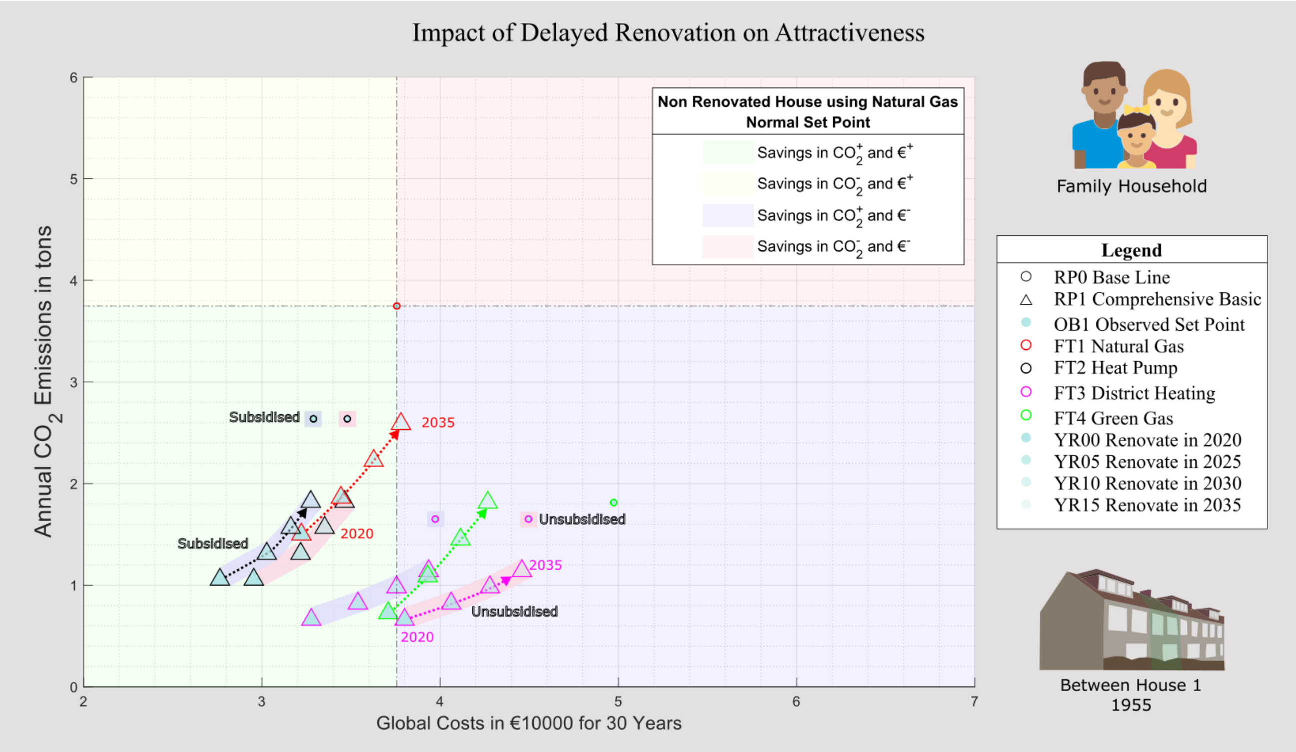

Figure 62 Delaying Renovation for Type1 1955 Between House

9.4.1 Barrier to Energy Renovation

According to Ebrahimigharehbaghi, Qian, *et al.*(2019) 'Lack of reliable information', 'Complexity in carrying out the renovations' and 'monetary cost' as primary barrier to energy renovation in the Netherlands.

The most important barrier to energy conservation is monetary costs. Lack of subsidies or loans is cited as the reason for not performing energy renovations by home-owners (Baginski and Weber, 2017; Broers *et al.*, 2019; Ebrahimigharehbaghi, Qian, *et al.*, 2019). Second barrier to renovations is – the time and effort required to apply for subsidies or loan. Thus, the authors conclude that financial factors as the most important barriers to energy conservation. Besides monetary cots, another most important barrier to energy efficiency is the difficulty in finding reliable information, the time and the effort required to obtain the information (Ebrahimigharehbaghi, Qian, *et al.*, 2019).

9.4.2 Path forward

Thus it is suggested by Ebrahimigharehbaghi, Qian, *et al.* (2019) that the focus of the present policy must aim to reduce the complexity of loan procurement. Then to eliminate the uncertainty surrounding energy renovations, it is important to homeowners receive tailor made solutions and are guided through the renovation process (explaining the impact of renovation, proving loan assistance, connecting to reliable contractors and etc.). In this regard local government can play a significant role in assisting homeowners, because government agencies are the most trusted by homeowners (Ebrahimigharehbaghi, Qian, *et al.*, 2019). According Broers *et al.* (2019) home owners appreciate the energy audits performed by municipally governments and feel comfortable and confident in the information provided by the government-agents. Energy desk is public-private-initiative supporting homeowners through the energy-renovation process by providing tailor made solutions (Energieloket Amsterdam, no date). Thus, with help of such similar initiative, the homeowners can be nudged into renovating their buildings.

Also, energy-popup shops are an interesting development in regard to support local initiatives because they can be used to create awareness and support homeowners at a neighbourhood level by addressing the specific needs and wishes of the homeowners. Initial experience with popup shops, show that they could have a positive and influential impact on energy renovation decisions (Ebrahimigharehbaghi, Qian, *et al.*, 2019).

10 DISCUSSION AND FUTURE WORK

- There are various other alternatives that can be used for producing low-temperature heat in the households, such as hybrid heat pump, micro CHP, pellet stoves, infra-red panels. All these potential technologies are left unaddressed in this study. Thus, a future work can aim to bring together various space heating and domestic hot water technologies and holistically identify the ideal performing solutions.
- In this research, there has been an extensive focus on energy saving measure for space heating. As a result, the potential for renewable electricity generation and solar heat technologies are not evaluated. As households are increasingly adopting solar technologies, it is optimal to investigate the self-generation and self-consumption potential for the whole neighbourhood. The insight can be used for building renewable energy generation scenarios and inevstigating the role of homeowners.
- Though the conducted case study is based on an actual neighbourhood, due to lack of information about neighbourhood households, key assumptions such as set point temperature, occupancy, electricity consumption profiles, and insulation values were assumed based on data. Further it is only known that the neighbourhood has 40% owner occupied houses, but it not clear from the GIS which household is occupied by owners and which isn't. To increase the reliability of results, the study can be made more neighbourhood specific by interviewing various households and by knowing more about the physical and social context, ownership details, preferences of the users, etc. A similar research in future can use insights from household and key stakeholders via interviews as a starting point for identifying key assumptions, motivations and user behaviours.
- In this study, overheating has been identified as major problem for family households, thus it makes renovation an unattractive option for family household. However, a future research can investigate the cooling potential and calculate the resulting economic performance and influence on thermal comfort.
- A future research can investigate the impact of renovation for a variety of insulation levels, ranging from simple wall insulation to NetZero building standards, on multiple types of buildings. Through such study, it is possible to identify what are the economical options for each building type. The government can use the insights for defining optimum standards for each building type to procure energy loan provision. This is suggested becasue the current standard for procuring loan is fixed and it is not always economical for poorly insulated buildings to upgrade to current loan standard.
- Climate change has a significant impact on the weather, thus simulating the buildings for warmer weather conditions will help in identifying the impact of renovations on thermal comfort and cost performance, when the global temperatures increases by 2ºC . Thus, a future research can implement the effects of 2º C increase in climatic conditions and check the performance of renovation packages.
- The study has assessed the impact of district heating, heat pumps and green gas options. For this assessment, the fuel price was assumed to a constant. However, it can be observed the prices of all the fuel options are changing annually. Primarily the tax shifts on natural gas and electricity is diverging the gap between electricity and natural gas prices. Additionally, the district heat's price is coupled with the price of natural gas. Thus, the gap between electricity and district heat is also diverging (ACM, 2018). Thus, a future study can include yearly fuel prices variations for identifying the impact.
- Similarly, a future study can also investigate the impact of decreasing the emissions factor of electricity and district heat. This needs to be considered because the emissions factor for electricity and district heat are expected to reach zero by 2040 for the MRA region (Ministry of Infrastructure and Environment, 2017).
- Within the study, the prices for green gas was assumed to be constant. However, with development of technology the price of green gas can decrease significantly. Thus, a future research can address a sensitivity of the price developments.
- While developing socio-technical scenarios, the research has an extensive focus on the technology under investigation, as result the impact of other technological developments on the natural gas

alternative are insufficiently investigated. A future research can dive into the interrelations between the technologies and illustrate the adoption of a new alternatives.

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APPENDIX

APPENDIX A – NEIGHBOURHOOD BUILDINGS

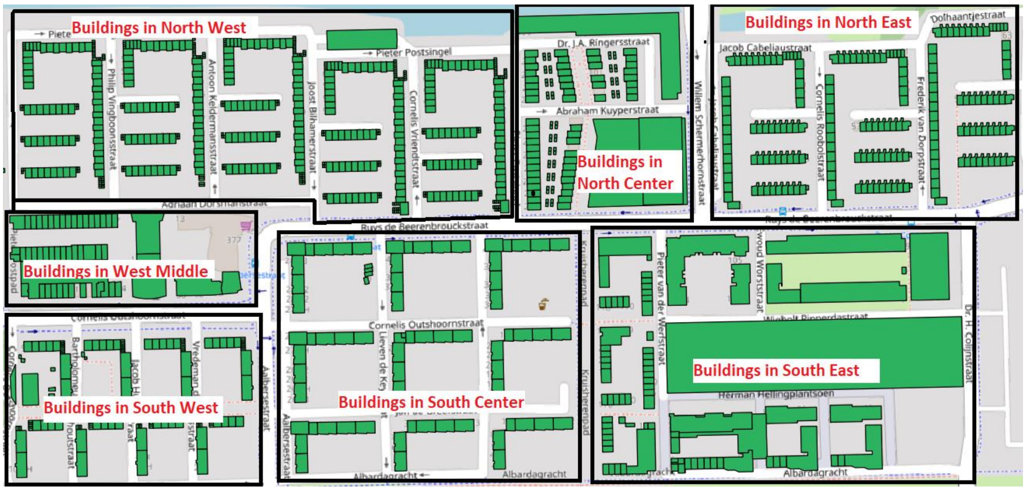

Figure 63 Buurt 9 buildings from QGIS - divided into various regions

Figure 64 Buildings in North West - Yellow is Row Houses Type 1 from 1960

Figure 65 Buildings in North Center – Yellow is Row houses from 2000 and > ; White is Apartment Blocks from 2000 and >

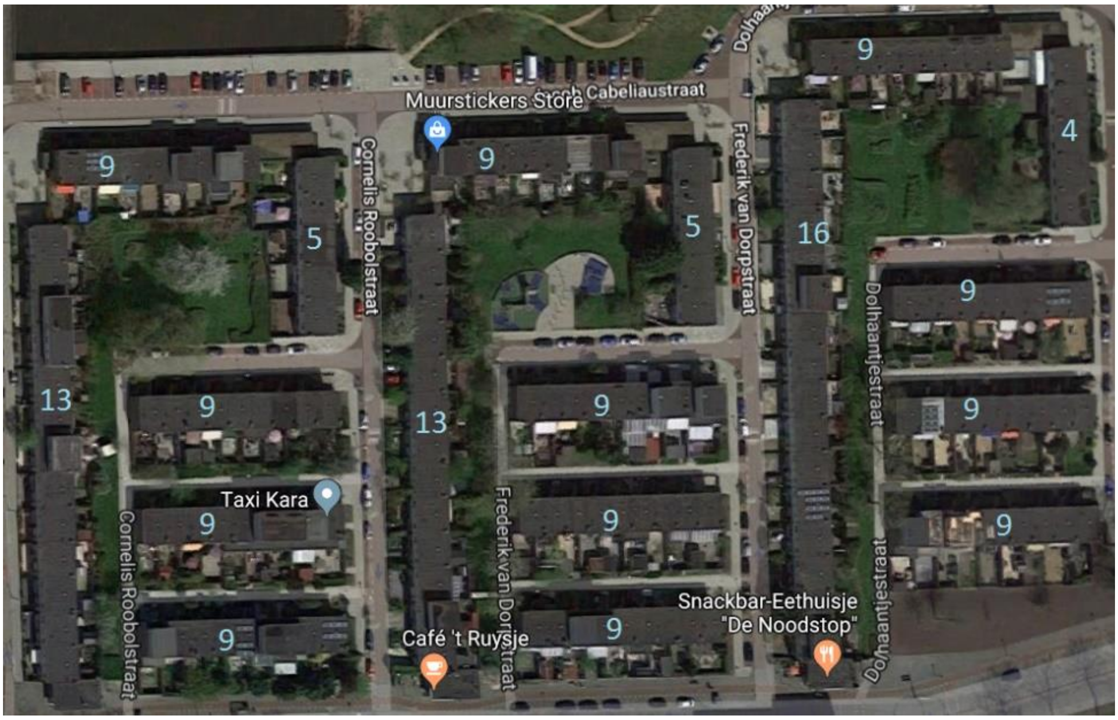

Figure 66 Buildings in North East – Blue is Row houses Type 2 from 1960

Figure 67 Buildings in South West – Yellow is Row Houses Type1 from 1960

Figure 68 Buildings in South Center - Pink is Apartment Blocks of 1960 Apartment

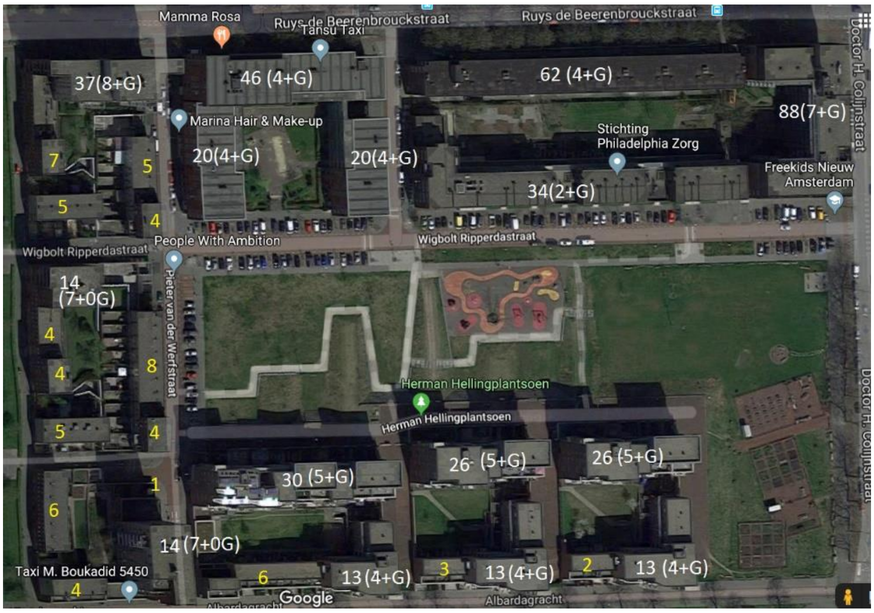

Figure 69 Buildings in South East - Yellow is Row houses from 2000 and > ; White is Apartment Blocks from 2000 and >

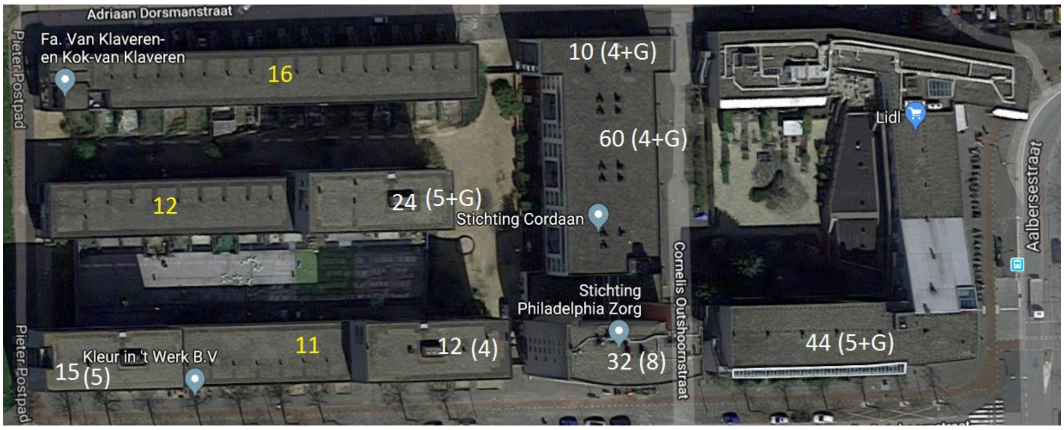

Figure 70 Buildings in West Middle - Yellow is Row Houses from 2000 and > and White is Apartment Buildings 2000 and >

APPENDIX B – EXAMPLE FOR FINDING BUILDING PROPERTIES

In the example illustrated below a random building (refer Figure 71) from Buurt 9 neighbourhood is selected. Then it is identified that the building is constructed in the year 1955 and it's energy is identified to label 'D' (National Energy Atlas, no date). Further, it's ground floor area is identified to be 43 m^2 with help of OpenStreetMap data (OpenStreetMap Contributors, 2018) and it is classified as "Between – Row house" based on the photographic information provided by (Google Maps, no date). A similar approach is followed for other building in the neighbourhood, to identify their 'building envelope' and gas consumption behaviour using WooN Onderzoek data set.

Figure 71 Building Energy Label and Construction Period from (National Energy Atlas, no date)

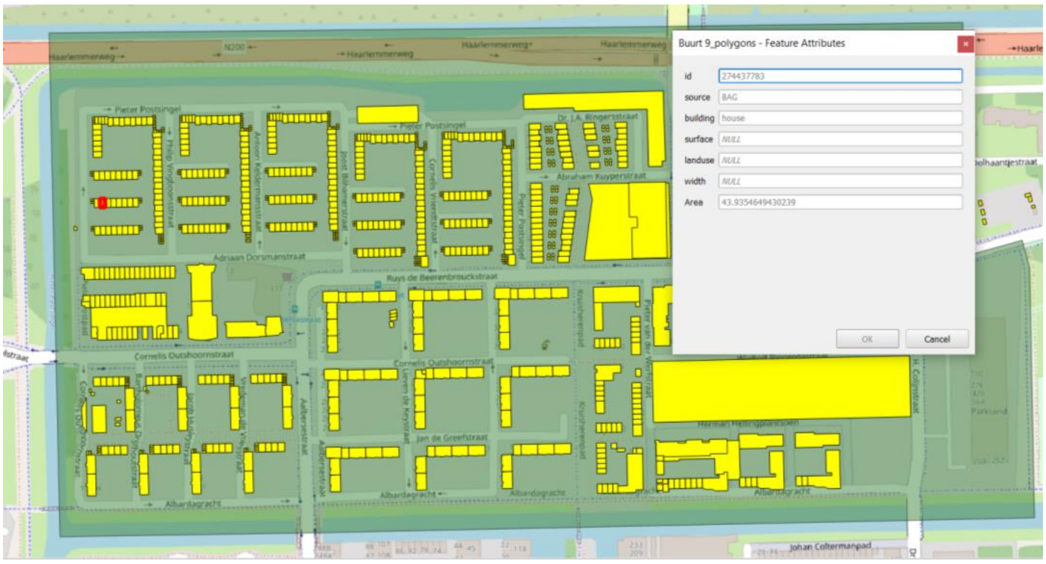

Figure 72 Building Ground Floor Area based on (OpenStreetMap Contributors, 2018)

Figure 73 Build Type - Between Row House from (Google Maps, no date)

In order to define the building envelope of the buildings present in Buurt-9, the data provided by (Government of the Netherlands, 2012) on the residential buildings is used. This data is used because of the lack of availability of building envelope data and building specific energy demand from Buurt 9 neighbourhood.

The data is selected because, certified inspectors have collected the data by conducting an extensive physical home survey. The inspectors note among many things the insulation levels, type of windows, gas and electricity demand of the household and the other physical properties of buildings. As the data contains necessary information about different types of houses from different time periods, the data is used for defining building envelope properties.

Building Property Definition: In order to identify building relevant information, the following process described below is used. Inputs parameters such as 'building period' and 'energy label' of the building is obtained from (National Energy Atlas, no date), the 'building floor area' is obtained from (OpenStreetMap Contributors, 2018) and 'building type' is obtained by scanning the neighbourhood in (Google Maps, 2019)

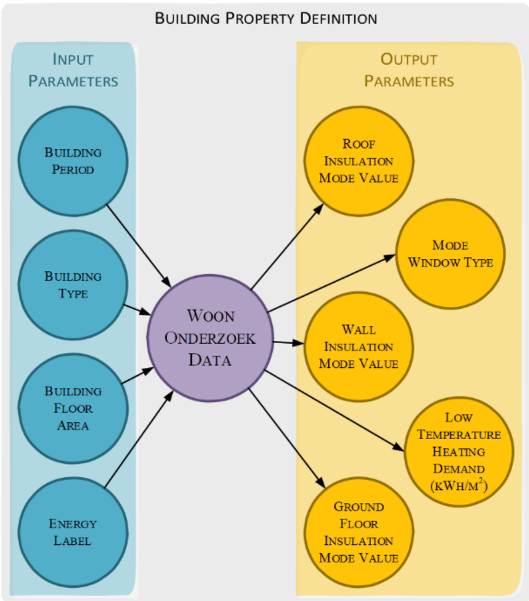

Figure 74 – Process for Identifying Building Insulation Property

Output Variables

Building Envelope Properties

	1955 Row House Type 1	1955 Row House Type 1	1955 Apartment	Above 2000 Row House	Above 2000 Apartment
Ground Floor Insulation Probability (GWP)	0 *($0.16 < 0.5$)*	0 *($0.14 < 0.5$)*	1	1	1
Ground Floor Insulation Thickness	-	-	50 mm	230 mm	130mm
External Wall Insulation Probability (EWP)	1 *($0.54 > 0.5$)*	1 *($0.55 > 0.5$)*	1 *($0.56 > 0.5$)*	1	1
External Wall Insulation Thickness	50 mm	50 mm	60 mm	120 mm	100mm
Roof Insulation Probability (EWP)	1 *($0.54 > 0.5$)*	1	1	1	1
Roof Insulation Thickness	50 mm	50 mm (From Type 1)	100 mm	90 mm	100 mm (From 1955 Apartment)
Window Type	Double Glazing	Double Glazing	Double Glazing	Double HR	Double HR

The insulation thicknesses

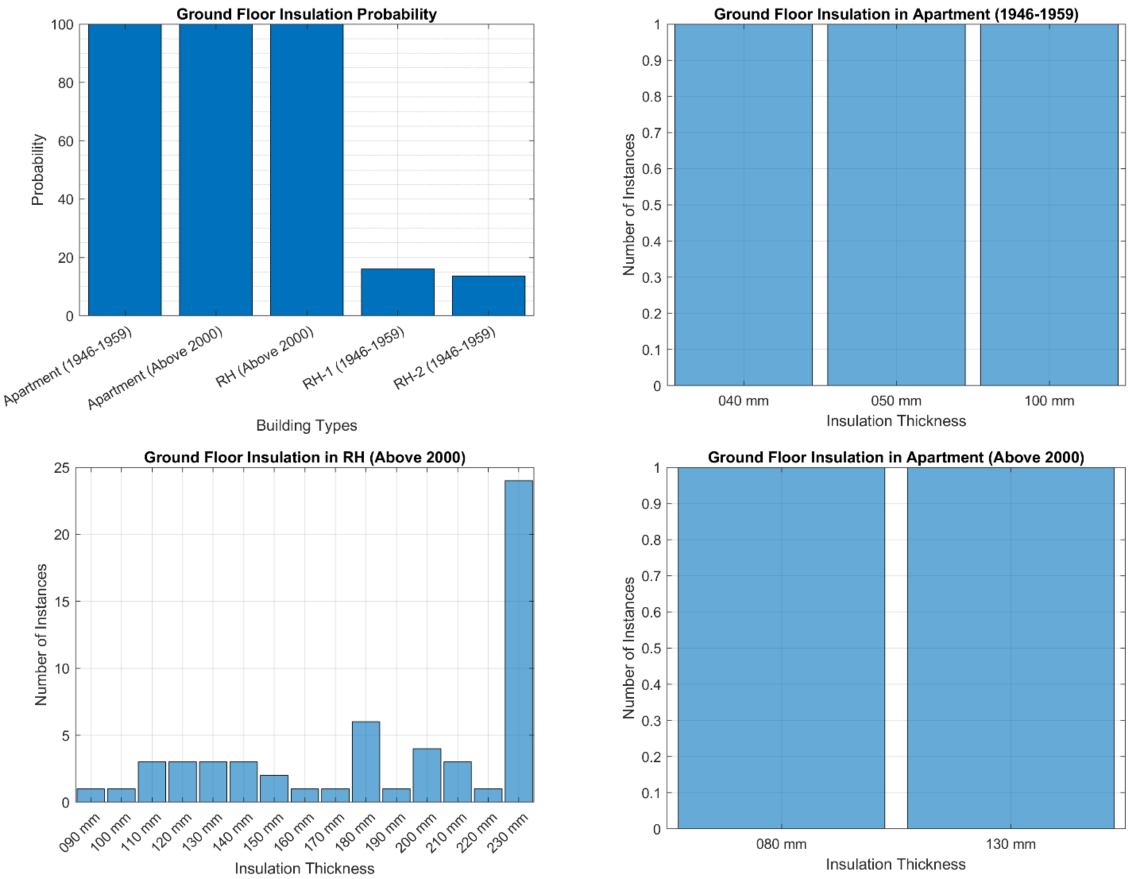

Figure 75 Ground Floor Insulation – Histogram Plots from WooN Data Set

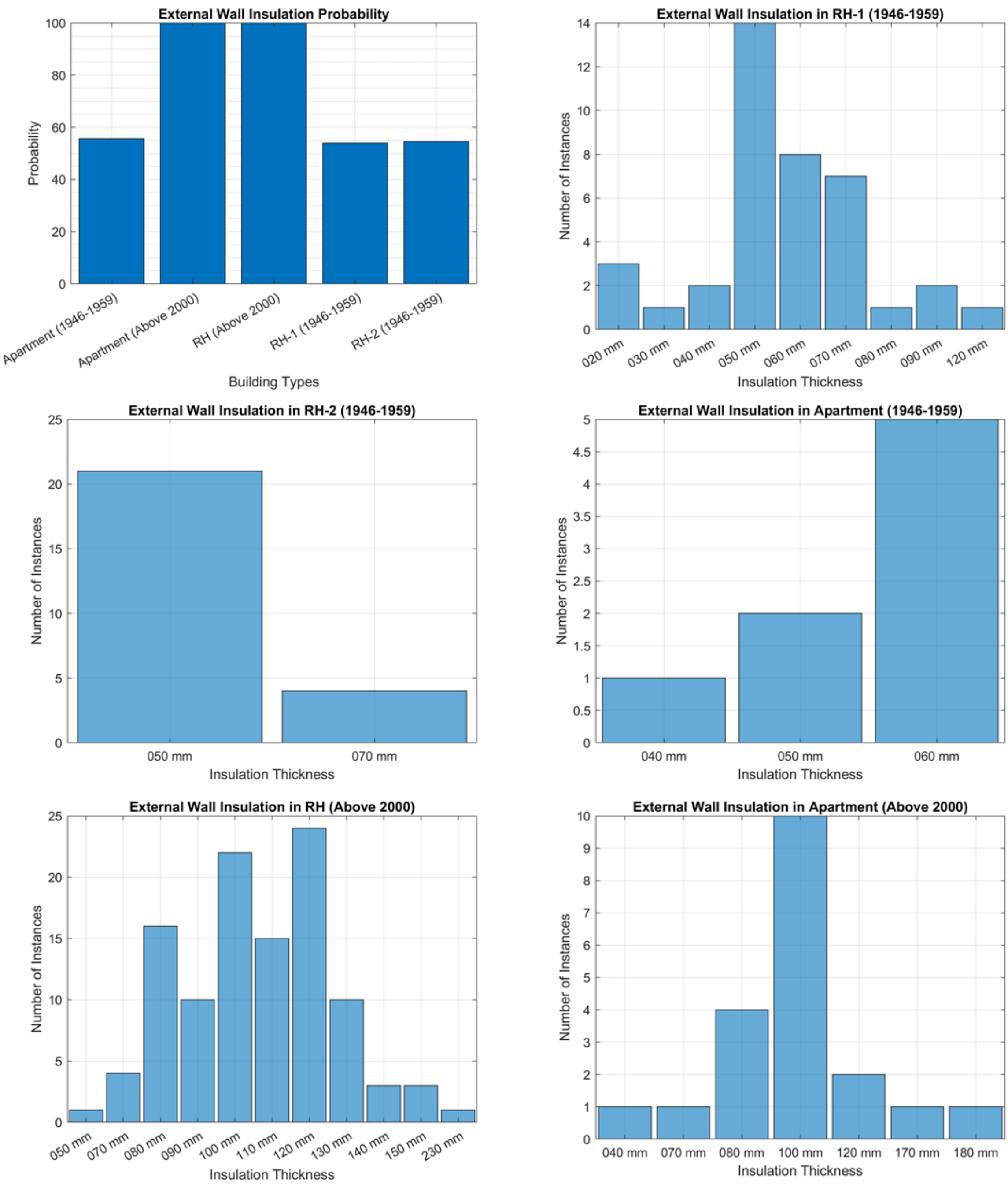

Figure 76 External Wall Insulation – Histogram Plots from WooN Data Set

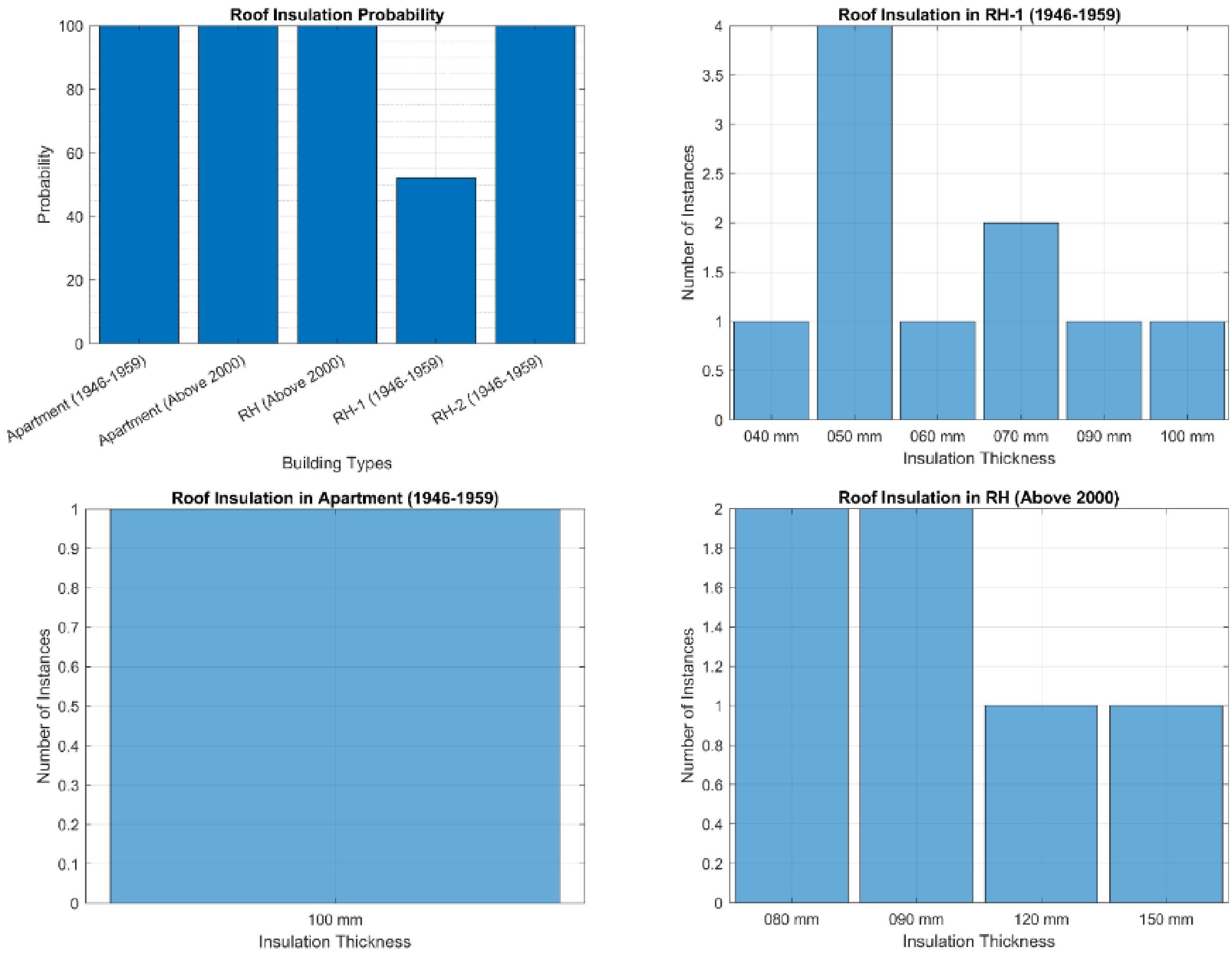

Figure 77 Roof Insulation – Histogram Plots from WooN Data Set

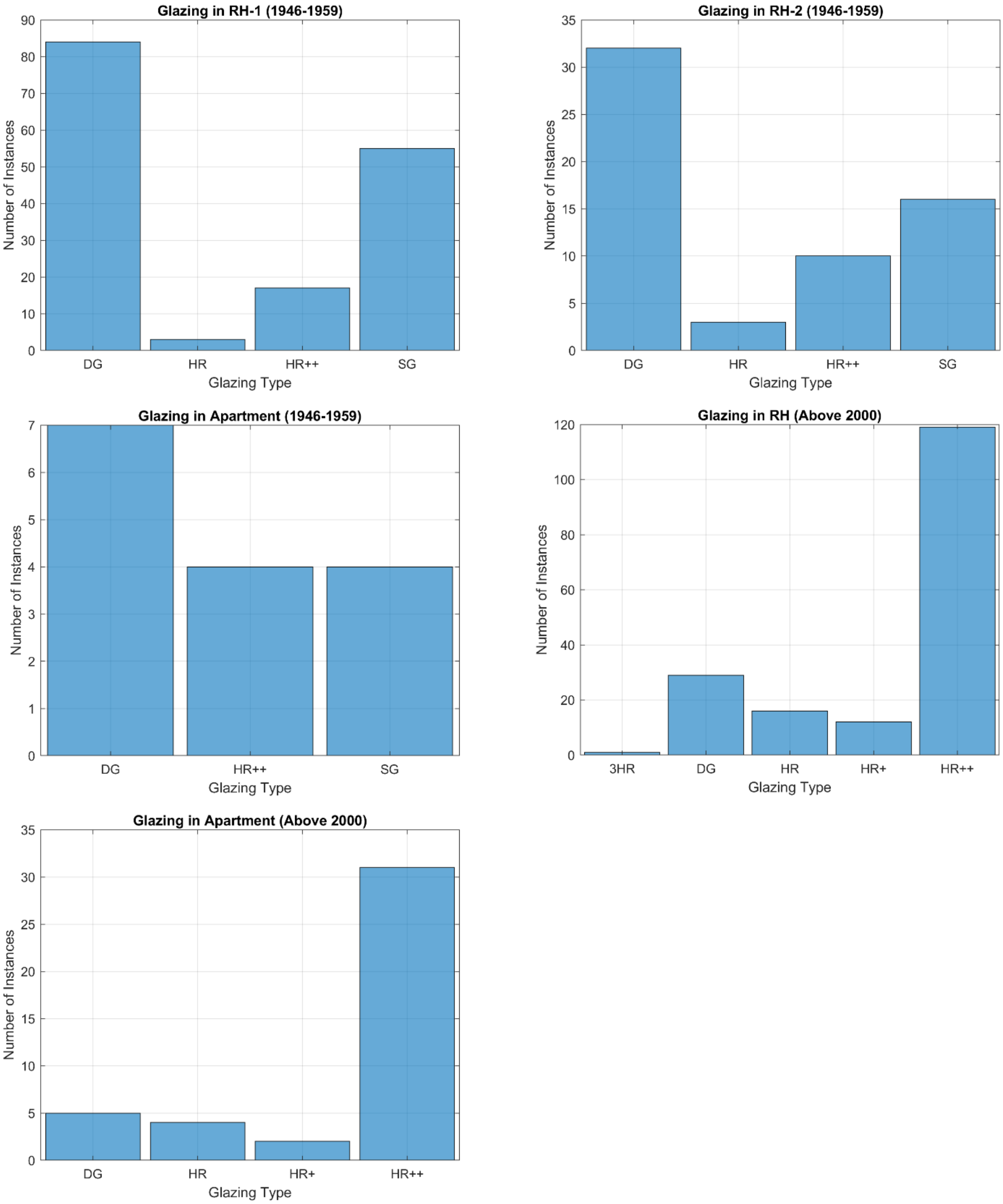

Figure 78 Window Type – Histogram Plots from WooN Data Set

Appendix C - Occupant Behaviour

Set point

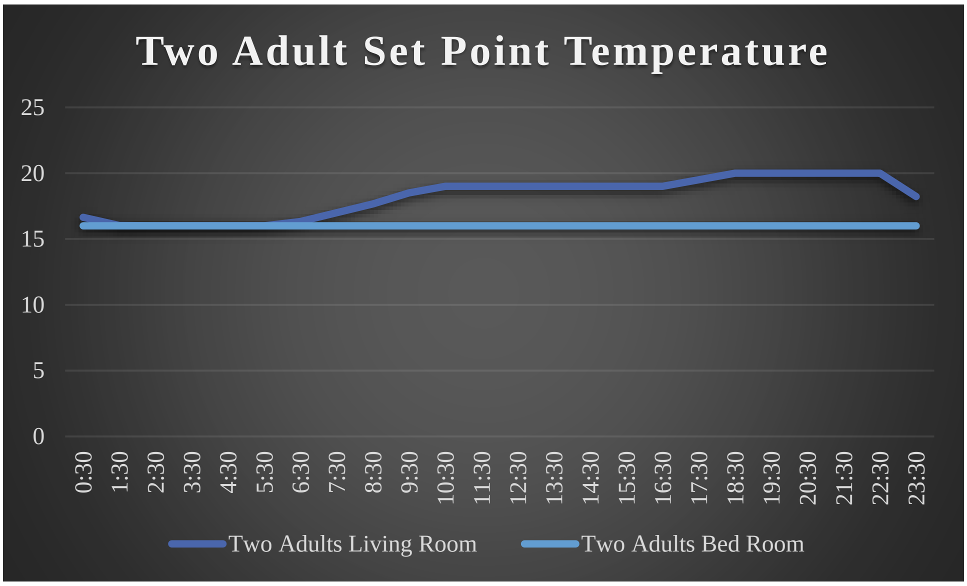

Figure 79 Two Adult Set Point Temperature

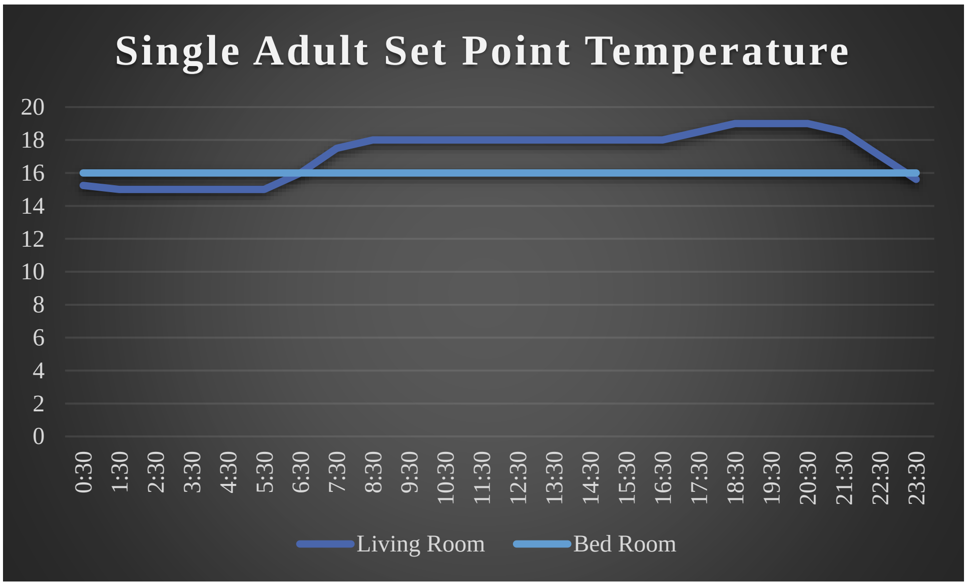

Figure 80 Single Adult Set Point Temperature

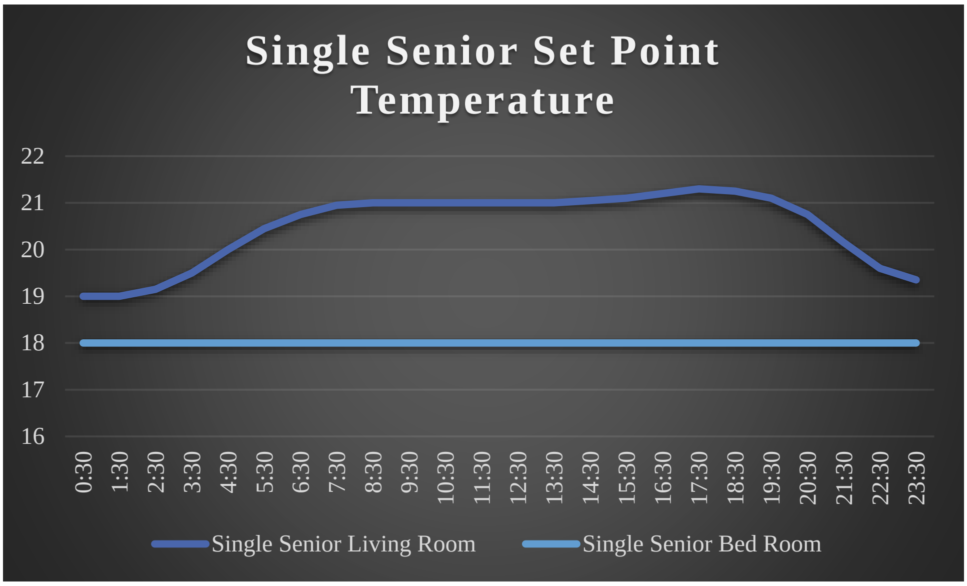

Figure 81 Single Senior Set Point Temperature

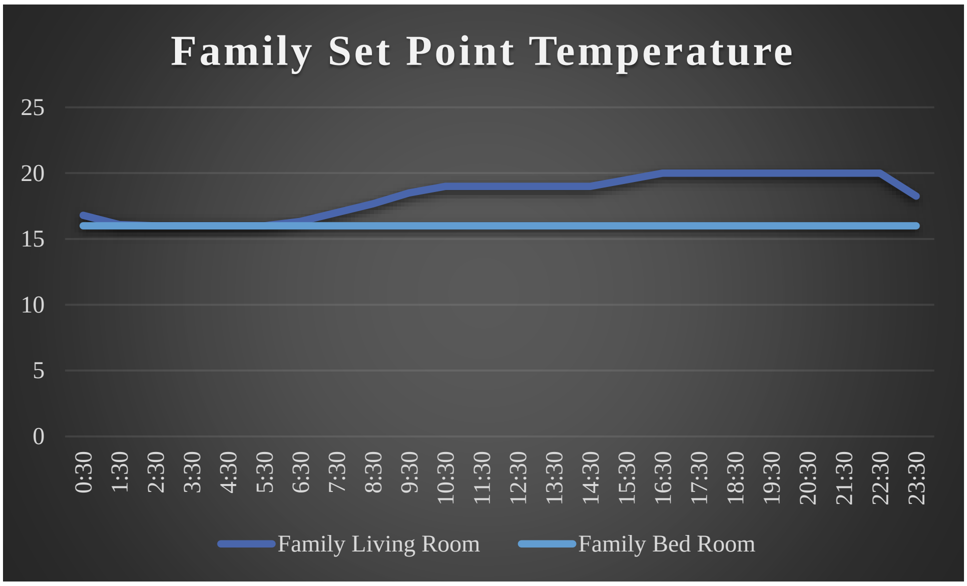

Figure 82 Family Set Point Temperature

Occupancy

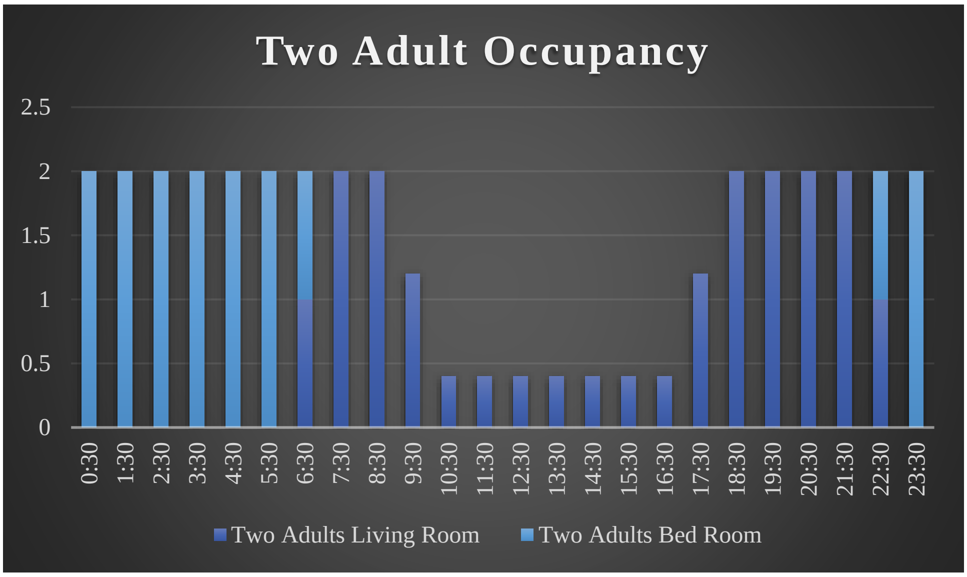

Figure 83 Two Adult Occupancy

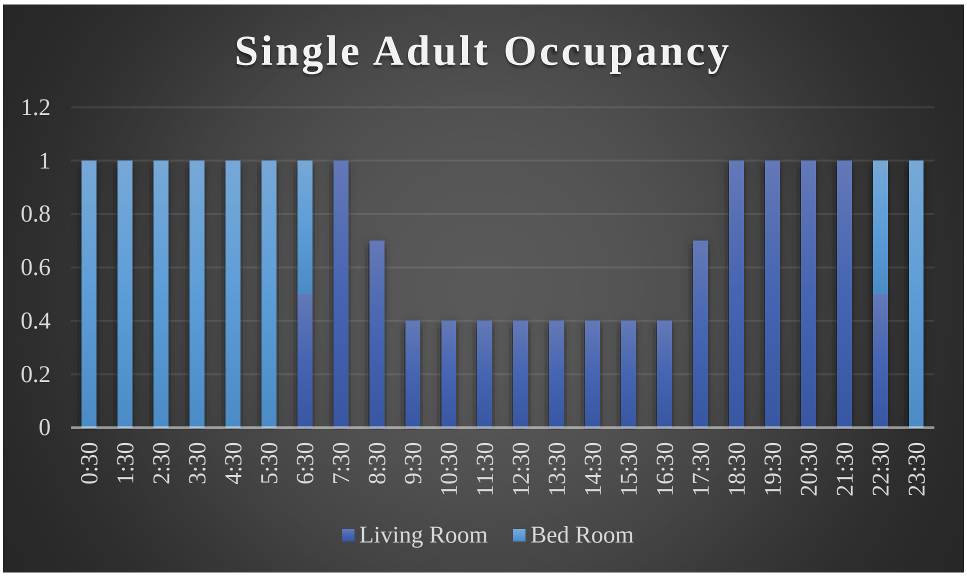

Figure 84 Single Adult Occupancy

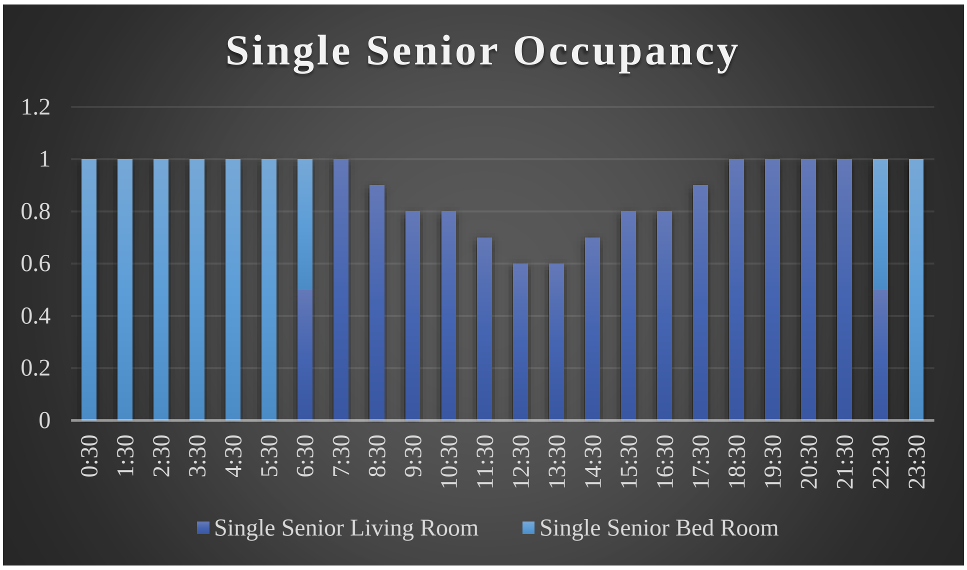

Figure 85 Single Senior Occupancy

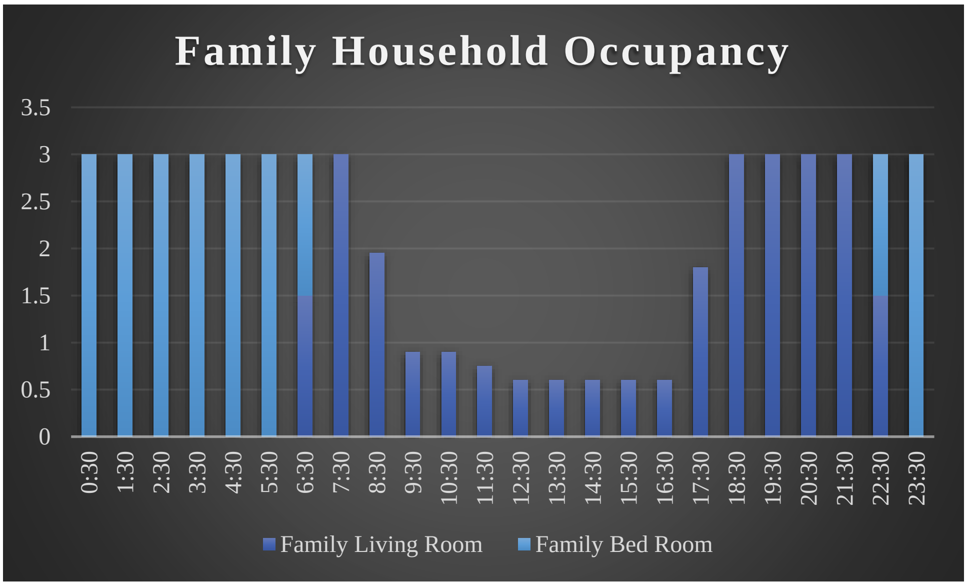

Figure 86 Family Occupancy