An agent-based exploration of complex heat transitions in the Netherlands

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Dissertation

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by

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Keywords: built environment; residential; households; thermal; insulation; complex adaptive systems; socio-technical systems; ABM; group decisions; investment, homeowner associations.

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Contents

Summary

The complex challenge of the heat transition in the Netherlands

In the Netherlands, a heat transition is taking place. Currently, the country's built environment largely relies on natural gas for heating. However, the use of this fuel is to be reduced over the coming decades. The national government has limited gas extraction from the Groningen field, which is located in the north of the country and is the largest in Europe. Moreover, it has set the goal to organise heating without natural gas. By 2050, the residential built environment should, in principle, be free of this fuel. To this aim, changes in laws, policies, regulations, and technical solutions are being discussed and implemented.

In the housing sector, building owners are currently responsible for deciding and implementing energy-related changes. These changes often require coordination and even cooperation between building owners for at least two reasons. Firstly, the business cases of projects such as heat networks are calculated for certain densities of demand or numbers of users. Secondly, the residential built environment is composed of single- and multi-family buildings or strata buildings, such as buildings with apartments. In strata buildings, which may have more than one owner, owners are required to organise in homeowner associations (HOAs). Changes in the building that concern more than one owner must first be approved by the HOA.

Moreover, in the owner-occupied share of the housing sector, decisions by households are not straightforward. Households can hardly be considered to have perfect financial rationality; instead, their rationality may be bounded by imperfect information and heuristics. Further, households consider various factors in their decision-making, and their preferences may be heterogeneous.

It follows that the heat transition is complex and uncertain. Collective projects require group decisions. Households consider multiple criteria in their decisions. Households are heterogeneous and their investment preferences and decisions may vary. Changes in formal institutions introduce additional uncertainties.

Research question and approach

To guide our exploration of a complex and uncertain heat transition, we formulated the following main research question: *How could the heat transition in the Netherlands be influenced by homeowners' individual and group decisions regarding investment in heating systems and insulation measures?*

We used agent-based modelling and simulation to explore this question. This method builds on the perspective of complex adaptive systems to represent individual agents that shape the behaviour of the overarching system with their decisions and interactions. We take a socio-technical perspective by describing the system in terms of actors (individuals or organizations), technology (heating systems and insulation in buildings), and institutions (regulations within and between building owners, and policies). Our modelling and simulation work was informed by recent policy developments and

scientific literature. We used the resulting models to explore scenarios of change in the system.

We modelled illustrative neighbourhoods as groups of households living in owner-occupied dwellings connected to the natural gas network. Dwellings were either single-family buildings or were part of multi-family buildings, and had an insulation level and a heating system with corresponding appliances. Households in the models had the option to replace their heating system, their insulation level, or both; their decisions were based on single or multiple criteria, and their financial rationality could be perfect or bounded.

Agent-based modelling for heat transitions

The focus of our first study was to demonstrate how to explore the heat transition with agent-based models (ABMs). From the factors that we explored, we found that specific value orientations or combinations of value orientations and institutional factors were needed to enable a heat transition. The transition took place when all households were environmentally oriented. Otherwise, natural gas tax had to increase; electricity tax had to decrease; time horizons that households used for comparing their investment options had to be 5 or 10 years, and either all households had to be financially oriented, or the population had to have a certain ratio of financially oriented households to environmentally oriented households.

The effect of group decisions

In our second study, which is an extension of the first one, we also represented an illustrative neighbourhood. We represented group decisions within and between HOAs in our ABM by modelling both individual preferences of households and group constraints. Individual preferences were represented as outcomes of a lifetime cost calculation with either a market discount rate or an implicit discount rate (IDR). In the literature, IDRs are described as the discount rates that, when used in a net present value calculation, would explain a choice that is not made with perfect financial rationality. They represent financial as well as non-financial factors. Therefore, we used IDRs to account for the non-financial factors that lead households to overestimate upfront costs and underestimate future cash-flows. In our ABM, IDRs were higher than market rates. Group constraints were represented in two levels. Firstly, as a percentage of households in an HOA that need to agree for a collective heating system to be implemented by all households, which we conceptualised as a *winner-takes-all* voting system. Secondly, as a percentage of households in the neighbourhood that need to agree on a collective heating system, such as a heat network, in order for this system to be implemented. In our conceptualization, votes from households in strata buildings count towards the total number of positive votes in the neighbourhood only if the project was first chosen by the HOA via the HOA's voting system.

We also conceptualised policy interventions. We explored financial policies and a disconnection policy that would require all households in the neighbourhood to phase out natural gas. We selected these policies because they represent potential developments in the Netherlands. The financial policies consisted of natural gas tax increasing and electricity tax decreasing beyond 2026, and changes in the regulated price of heat from networks. The disconnection policy required households to replace their heating systems that use natural gas; however, according to experts in the Netherlands, a top-down approach, specifically for heat networks, could prove problematic.

We explored the socio-technical conditions under which a heat transition would be possible, and our results were as follows. No combination of financial policies was sufficient for households to disconnect from natural gas. When the disconnection policy was not in place, households using a market discount rate preferred to maintain natural gas with high insulation, and households using an IDR preferred to maintain natural gas without changing their insulation. When the disconnection policy was in place, households determined their preferred option over the options without natural gas. Households using market discount rate preferred the most cost-efficient alternative to natural gas. Households with IDRs preferred an option with lower upfront costs because the discount rate that they used in their calculation was higher than the market discount rate; in other words, they undervalued future savings. Our results show that group decisions by homeowners could enable or block the heat transition by leading to a different outcome than if there were only individual decisions. Group decisions also influenced which alternatives to natural gas were implemented and the costs of phasing out natural gas.

The effect of multi-criteria decisions

In our third study, we built on our previous representation of group decisions and modelled individual preferences of households as outcomes of a multi-criteria calculation with four factors: finances, environment, duration of the works in the dwelling, and space that the new heating system would occupy. The last two factors represent inconveniences that households would experience if they were to change their dwelling's insulation or heating system. Households had a preference profile that specified the relative importance that the household assigned to each of those four factors when comparing combinations of heating systems and insulation levels. We explored three policies from our previous work (natural gas tax, electricity tax, and a cap on the price of heat from networks), and subsidies for insulation and for heat pumps.

Our findings were as follows. No combination of policies was on its own sufficient for households to disconnect. Instead, the preference profiles of households were the most influential conditions for the disconnection from natural gas. The preference profiles under which the entire neighbourhood disconnected from natural gas were not exclusively financial. In these profiles, both finances and environment had a nonzero weight, and environment was weighted at least as high as finances. Moreover, if the profile had a zero weight for space and a weight of 50% for duration, the profile had to be combined with additional policies: an increasing natural gas tax and a cap on the price of heat from networks. Partial transitions, in which only some households in the neighbourhood disconnected, also occurred. In most partial transitions, households adopted heating systems that they could implement individually or within their own building, instead of heating systems that require adoption by most of the neighbourhood. In terms of collective CO_2 emissions from operation, which were computed in the model, there was only a small difference in medians between partial transitions and simulations in which all households remained connected to natural gas but some households improved their insulation.

Conclusions

Our agent-based studies illustrate that group decisions and multi-criteria decisions could

influence the heat transition in the Netherlands as follows. Group decisions can enable or block collective projects such as heat networks or other decisions at the level of buildings or neighbourhoods; they can lead to a different outcome than when only individual decisions are made. This can affect which alternatives to natural gas are implemented, and as a result, the costs of the heat transition. Based on our modelling results, we would expect the phasing out of natural gas to be more expensive for households than remaining connected to natural gas. Although financial policies could be used to shift this balance, given that decisions by households are also influenced by non-financial factors, we expect that stimulating the transition with financial policies alone would not be effective. Moreover, there is a risk that some financial policies could lead to increased energy prices that are unaffordable for some households.

In addition to the complexity introduced by group decisions and multi-criteria decisions, our work highlights the relevance of two challenges. Firstly, that policies can have different effects on heterogeneous households. Secondly, that combinations of policies can change the attractiveness of different alternatives to natural gas.

The implementation of heat transition projects in the Netherlands is challenging. Robust techno-economic assessments of combinations of heating systems and insulation measures in the built environment are indispensable for heat transition projects. In addition to these assessments, actor analyses with a focus on heterogeneity as well as institutional analysis, both from a socio-technical perspective, are also indispensable.

Agent-based modelling and simulation is a well-suited method to explore the complexities of the heat transition. As shown in our studies, with an agent-based model it is possible to integrate techno-economic descriptions with institutional context, with decentralised decisions, and with actor heterogeneity in order to explore their influence on the heat transition. This dissertation takes the application of this method to explore the heat transition one step further.

SAMENVATTING

De complexe uitdaging van de warmtetransitie in Nederland

Een warmtetransitie vindt plaats in Nederland. Momenteel gebruikt de gebouwde omgeving van het land aardgas voor verwarming, maar in de komende tientallen jaren moet het aardgasverbruik afnemen. De Rijksoverheid heeft aardgaswinning uit het Groningen veld beperkt; het Groningen veld ligt in het noorden van Nederland en is het grootste aardgasveld van Europa. De Rijksoverheid heeft ook het doel gesteld om aardgasvrije verwarming te realiseren. Tegen 2050 moeten woningen in principe geen aardgas meer gebruiken. Om dit doel te bereiken worden wijzigingen in wetten, beleid, regulaties en technische oplossingen besproken en uitgevoerd.

In de sector woningbouw zijn gebouweigenaren momenteel verantwoordelijk voor beslissingen en uitvoering van energie gerelateerde wijzigingen. Deze wijzigingen vereisen vaak coördinatie en zelfs samenwerking tussen gebouweigenaren vanwege tenminste twee redenen. Ten eerste, de business cases van projecten zoals warmtenetten zijn berekend voor een bepaalde dichtheid van warmtevraag of aantal gebruikers. Ten tweede, de sector woningbouw bestaat uit zowel eengezinswoningen als meergezinswoningen (zoals appartementsgebouwen). Een pand met meergezinswoningen kan meer dan één eigenaar hebben en eigenaars zijn georganiseerd in een Vereniging van Eigenaars (VVE). Wijzigingen in het pand die van belang zijn voor meer dan een eigenaar moeten worden goedgekeurd door de VVE.

Verder zijn beslissingen door huishoudens in koopwoningen niet eenvoudig. Wij kunnen niet stellen dat huishoudens doorgaans beslissingen nemen met perfecte financiële rationaliteit. In plaats daarvan kan hun rationaliteit beperkt zijn door onvolledige informatie en heuristieken. Daarnaast gebruiken huishoudens meerdere factoren in hun beslissingen en hun voorkeuren kunnen heterogeen zijn.

Om deze redenen is de warmtetransitie complex en onzeker. Collectieve projecten vereisen groepsbeslissingen. Huishoudens gebruiken meerdere criteria om beslissingen te nemen. Huishoudens zijn heterogeen en hun investeringsvoorkeuren en beslissingen kunnen variëren. Wijzigingen in formele instituties voegen onzekerheden toe.

Onderzoeksvraag en aanpak

Wij gebruikten de volgende hoofdonderzoeksvraag om onze verkenning van een complexe en onzekere warmtetransitie te begeleiden: *Hoe zou de warmtetransitie in Nederland beïnvloed kunnen worden door de individuele en groepsbeslissingen van huiseigenaren met betrekking tot investeringen in verwarmingssystemen en isolatiemaatregelen?*

Wij verkenden deze vraag met agent-gebaseerd modelering en simulatie. Deze methode baseert zich op het perspectief van *complex adaptive systems.* Vanuit dit perspectief wordt het gedrag van een overkoepelend systeem vertegenwoordigd in termen van individuele agenten. De beslissingen en interacties van deze agenten vormen het gedrag van het overkoepelende systeem. Verder nemen wij een socio-technisch perspectief om het system te beschrijven in termen van actoren (individuen en organisaties), technologie (warmtesystemen en isolatie in gebouwen) en instituties (beleid en regelgeving binnen en tussen gebouwen). Wij gebruikten recente beleidsontwikkelingen en wetenschappelijke literatuur in ons modellerings- en simulatiewerk. Wij verkenden veranderingsscenario's in het systeem met de resulterende modellen.

Wij modelleerden fictieve buurten als groepen van huishoudens die wonen in koopwoningen met aardgasaansluitingen. Woningen waren eengezins- of meergezinswoningen en hadden een isolatieniveau en een warmtesysteem met bijbehorende huishoudelijke apparaten. Huishoudens in de modellen hadden de optie om hun verwarmingssysteem, isolatieniveau of beide te vervangen. Beslissingen door huishoudens waren gebaseerd op enkelvoudige of meervoudige criteria. De financiële rationaliteit van huishoudens was perfect of beperkt.

Agent-gebaseerde modellering voor warmtetransities

De focus van onze eerste studie was om te demonstreren hoe de warmtetransitie kan worden verkend met agent-gebaseerde modellen (ABMs). Vanuit de verkende factoren vonden wij dat specifieke waarde oriëntaties of combinaties van waarde oriëntaties en institutionele factoren noodzakelijk waren om de warmtetransitie te realiseren. De transitie vond plaats wanneer alle huishoudens milieu-georiënteerd waren. Anders was de combinatie van de volgende condities noodzakelijk: stijging in de aardgasbelasting; daling in de elektriciteitsbelasting; de tijdshorizon die huishoudens gebruikten om hun investeringsopties te vergelijken moest 5 of 10 jaar zijn; alle huishoudens moesten financieel-georiënteerd zijn of een bepaald aandeel van financieel-georiënteerde huishoudens in relatie tot milieu-georiënteerde huishoudens was nodig.

Het effect van groepsbeslissingen

Onze tweede studie was een uitbreiding van de eerste. Hier gebruikten wij ook een fictieve buurt. In onze ABMs namen we groepsbeslissingen binnen en tussen VVEs mee. Wij modelleerden zowel de individuele voorkeuren van huishoudens als de groepsbeperkingen zoals hierna beschreven. Individuele voorkeuren waren uitkomsten van een levensduur kostenberekening gedaan met een marktsdiscontovoet of een impliciete discontovoet (IDR). IDRs waren hoger dan marktsdiscontovoeten en vertegenwoordigden niet-financiële factoren waardoor huishoudens aanloopkosten overschatten en toekomstige geldstromen onderschatten. Groepsbeperkingen waren vertegenwoordigd op twee niveaus. Ten eerste, als een aantal huishoudens binnen een VVE die een collectief warmtesysteem voor een gebouw moeten goedkeuren; wij namen deze groepsbeperking als een *alles-of-niets* stemmingssysteem mee. Ten tweede, als een aantal huishoudens in een buurt die een collectief warmtesysteem zoals een warmtenet moeten goedkeuren. In onze conceptualisatie telden stemmen uit gebouwen met meergezinswoningen alleen mee als de uitkomst van hun *alles-of-niets* stemmingssysteem was om een warmtenet te kiezen.

Wij conceptualiseerden beleidsinterventies. Wij verkenden financiële beleidsmaatregelen en een aardgasafsluiting beleidsmaatregel. De aardgasafsluiting was geconceptualiseerd als een verplichting voor alle woningen in de buurt om van het aardgasnetwerk af te gaan. Wij kozen deze beleidsmaatregelen omdat ze potentiële beleidsontwikkelingen in Nederland vertegenwoordigen. De financiële beleidsmaatregelen bestonden uit een stijging van de aardgasbelasting en een daling van de elektriciteitsbelasting na 2026 en wijzigingen in de gereguleerde prijs van warmte uit warmtenetwerken. De aardgasafsluiting beleidsmaatregelen vereisten huishoudens om hun aardgaswarmtesystemen te vervangen door aardgasvrije warmtesystemen.

Wij verkenden de socio-technische condities waaronder de warmtetransitie mogelijk zou zijn. Geen verkende combinatie van de financiële beleidsmaatregelen was voldoende om huishoudens te stimuleren om van het aardgasnetwerk af te gaan. Wanneer de aardgasafsluiting beleidsmaatregel niet aan de orde was prefereerden huishoudens met marktdiscontovoet om aardgas te houden met een hoog isolatieniveau; huishoudens met IDR prefereerden om aardgas te houden zonder veranderingen in hun isolatieniveau. Wanneer de aardgasafsluiting beleidsmaatregel aan de orde was bepaalden huishoudens hun voorkeur tussen de opties zonder aardgas. Huishoudens met marktdiscontovoet prefereerden het meest kosten-efficiënte alternatief voor aardgas. Huishoudens met IDRs prefereerden een alternatief met lagere aanloopkosten omdat de discontovoet die ze gebruikten in hun berekening hoger dan de marktdiscontovoet was; met andere woorden: ze onderschatten toekomstige besparingen. Onze resultaten laten zien dat groepsbeslissingen door woningeigenaren de warmtetransitie mogelijk of onmogelijk kunnen maken omdat groepsbeslissingen kunnen leiden tot een andere uitkomst dan alleen individuele beslissingen. Groepsbeslissingen hadden ook een effect op zowel welke alternatieven voor aardgas werden geïmplementeerd als de kosten van de uitfasering van aardgas.

Het effect van multi-criteria beslissingen

In onze derde studie bouwden we voort op onze eerdere vertegenwoordiging van groepsbeslissingen. We modelleerden individuele voorkeuren van huishoudens als uitkomsten van een multi-criteria berekening met vier factoren: financiën, milieu, duur van werkzaamheden in de woning en oppervlakte dat het nieuwe verwarmingssysteem zou innemen. De laatste twee factoren vertegenwoordigden overlast die huishoudens zouden ervaren als ze de isolatie of verwarmingssystem van hun woning zouden vervangen. Huishoudens hadden een profiel van voorkeuren dat het relatieve belang specificeerde dat huishoudens aan elk van de vier factoren gaven wanneer huishoudens combinaties van verwarmingssystemen en isolatieniveaus vergeleken. Wij verkenden zowel drie beleidsmaatregelen uit ons eerdere werk (aardgas- en elektriciteitsbelasting en een maximum prijs van warmte uit warmtenetten) als subsidies voor isolatie en subsidies voor warmtepompen.

Onze bevindingen waren als volgt. Geen zelfstandige combinatie van beleidsmaatregelen was voldoende om huishoudens te stimuleren om van het aardgas te gaan. In plaats daarvan waren profielen van voorkeuren de meest invloedrijke conditie om een dergelijke aardgasafsluiting te realiseren. Wanneer alle huishoudens in de buurt prefereerden om van het aardgas af te gaan, waren hun profielen van voorkeuren niet alleen financieel. In deze profielen hadden zowel financiën als milieu een niet-nul gewicht en milieu had een gewicht tenminste zo hoog als financiën. Wanneer het profiel een nul-gewicht voor oppervlakte en een gewicht van 50% voor duur had, dan moest het profiel gecombineerd met bepaalde beleidsmaatregelen worden: stijgende aardgasbelasting en een maximum prijs van warmte uit warmtenetten. Partiële transities waren ook mogelijk. In deze transities gingen sommige huishoudens in de buurt van het aardgas af. In de meeste partiele transities adopteerden huishoudens individuele warmtesystemen of collectieve warmtesystemen voor slechts een enkel gebouw, in plaats van warmtesystemen die ondersteuning vereisen door het merendeel van de buurt. Collectieve CO_2 emissies van operatie waren ook berekend in het model. In termen van deze collectieve emissies was er een klein verschil tussen de medianen van twee type simulaties. Ten eerste, medianen van partiele transities. Ten tweede, medianen van simulaties waar alle huishoudens hun aardgasaansluiting hielden maar sommige huishoudens hun isolatie verbeterden.

Conclusies
Onze agent-gebaseerde studies illustreren dat groepsbeslissingen en multi-criteria beslissingen invloed kunnen hebben op de warmtetransitie in Nederland op de volgende manieren. Groepsbeslissingen kunnen collectieve projecten zoals warmtenetten of andere gebouw-niveau beslissingen mogelijk of onmogelijk maken. Het nemen van groepsbeslissingen kan ook leiden tot uitkomsten anders dan de uitkomsten van individuele beslissingen. Groepsbeslissingen kunnen ook de kosten van de warmtetransitie beïnvloeden omdat ze invloed kunnen hebben op de alternatieven voor aardgas die geïmplementeerd worden. Financiële beleidsmaatregelen kunnen in principe de afsluiting van aardgas stimuleren; echter verwachten wij dat dit type maatregelen niet effectief zou zijn, omdat huishoudens zowel financiële als niet-financiële factoren in hun beslissingen gebruiken. Verder is er een risico dat sommige financiële beleidsmaatregelen tot hogere energieprijzen kunnen leiden die niet betaalbaar zouden zijn voor sommige huishoudens.

Naast de complexiteit van groepsbeslissingen en multi-criteria beslissingen benadrukt ons werk de relevantie van twee uitdagingen. Ten eerste, dat beleidsmaatregelen kunnen verschillende effecten op heterogene huishoudens hebben. Ten tweede, dat combinaties van beleidsmaatregelen de aantrekkelijkheid van verschillende alternatieven voor aardgas kunnen veranderen.

De implementatie van warmtetransitie projecten in Nederland is uitdagend. Robuuste techno-economische beoordelingen van combinaties van warmtesystemen en isolatiemaatregelen in de gebouwde omgeving zijn onmisbaar voor warmtetransitie projecten. Hier bovenop zijn zowel actor analyses met een focus op heterogeniteit als institutionele analyses, beiden vanuit een socio-technisch perspectief, ook onmisbaar.

Agent-gebaseerde modellering en simulatie is een geschikte methode om de complexiteiten van de warmtetransitie te verkennen. Wij hebben aangetoond in onze studies dat het mogelijk is om met een agent-gebaseerd model techno-economische beschrijvingen te integreren met institutionele context, met gedecentraliseerde beslissingen en met actor heterogeniteit, om hun invloed op de warmte transitie te verkennen. Dit proefschrift brengt de toepassing van deze methode om de warmte transitie te verkennen een stap verder.

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Graciela Luteijn-Nava Guerrero
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Abbreviations

ABM	Agent-based model
ACM	Authority for Consumers and Markets
CAS	Complex adaptive systems
CHP	Combined heat and power
CSE	Complex systems engineering approach
DEI+	Subsidy demonstration energy innovation
EB	Energy tax for consumption
EC	European Commission
EU	European Union
HN	Heat network
HOA	Homeowner association
HPP	Household preference profiles
IAM	Integrated assessment models
IDR	Implicit discount rate
IPCC	Intergovernmental Panel on Climate Change
ISDE	Sustainable energy investment subsidy scheme
KPI	Key performance indicator
LTC	Lifetime-cost
NECP	National energy and climate plan
NPV	Net present value
ODD Protocol	Overview, Design Concepts, and Details Protocol
ODE	Surcharge for sustainable energy
OFAT	One-factor-at-a-time
PAW	Programme natural gas-free neighbourhoods
RE	Regulatory environment
RES	Regional Energy Strategy
SEEH	Energy saving at home subsidy for HOAs
SES-BE	Smart Energy Systems in the Built Environment Programme
STET	Socio-technical energy transition
STS	Socio-technical systems
VNG	Vereniging Nederlandse Gemeenten
VvE	Vereniging van eigenaars

Nomenclature

General

Dmnl	Dimensionless
H_2	Hydrogen gas
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt hour
m^3	Cubic metre
MJ	Megajoule
MWh	Megawatt hour

Chapter 3

ACCI	Ability to compare combined investments
AHD	Annual heat demand
AMC	Annual maintenance costs
CC	Cumulative costs
CHD	Cumulative heat demand
CNG	Cumulative natural gas consumption
dep	Annual percentage change in the retail electricity price
dgp	Annual percentage change in the retail natural gas price
EC	Energy costs
HRZ	Time horizon
IC	Investment costs
INV	Investment
MC	Maintenance costs
nH	Thermal efficiency
ORI	Value orientation
popACCI	Fraction of agents in the model with ACCI=1
popHRZ	HRZ shared by all agents
popORI	Proportion of agents with each value orientation
REP	Retail energy price
THR	Social threshold

CHAPTER 4

β	Time horizon
ρ	Discount rate
ρ_{bnd}	Bounded discount rate (higher than the market discount rate)
ρ_{market}	Market discount rate
τ	Lifetime of a heating system
t	Time step
AC	Annual costs
AP	Cost of appliances
CoF	Annual connection fee
D	In the notation for regulatory environments (RE), D stands for the alternative mode of a disconnection policy, namely, a mandatory disconnection from natural gas.
E	In the notation for regulatory environments (RE), E stands for the alternative mode of P-TXE.
FC	Fixed costs
G	In the notation for regulatory environments (RE), G stands for the alternative mode of P-TXG.
H	In the notation for regulatory environments (RE), H stands for the alternative mode of P-RPH.
HS	Cost of heating systems
IN	Cost of insulation
k€	Thousands of euro
LTCbnd	Lifetime-cost calculation using ρ_{bnd}.
LTCideal	Lifetime-cost calculation using ρ_{market}.
MaF	Maintenance fee
MeF	Measuring fee
P-RHP	Modelled policy with a reference and an alternative mode. Its alternative mode consists of a cap in the price of heat from networks.
P-TXE	Modelled fiscal policy with a reference and an alternative mode. Its alternative mode consists of a linear decrease in the electricity taxes.
P-TXG	Modelled fiscal policy with a reference and an alternative mode. Its alternative mode consists of a linear increase in the natural gas taxes.
RC	Reinvestment costs
s'	Alternative technology state
s	Current technology state
SPG	Sales price of natural gas
TS1:GB3	Technology state with a natural gas boiler and the lowest insulation level.
TS2:EB3	Technology state with an electric boiler and the lowest insulation level.
TS3:GB2	Technology state with a natural gas boiler and medium insulation level.
TS4:EB2	Technology state with an electric boiler and medium insulation level.
TS5:HN2	Technology state with a heat network and medium insulation level.
TS6:HP1	Technology state with a heat pump and the highest insulation level.
TS7:HN1	Technology state with a heat network and the highest insulation level.

UC	Upfront costs
VC	Variable costs
X	In the notation for regulatory environments (RE), X represents the active and inactive mode of a policy. For example, RE=XEHD stands for RE=GEHD and RE=0EHD.

CHAPTER 5

β	Time horizon
ρ	Discount rate
τ	Lifetime of a heating system
t	Time step
AC	Annual costs
CD	Cooking demand
CO_2	Carbon dioxide
CO_2 emissions	CO_2 emissions from heating systems' operation
CoF	Annual connection fee
DC	Duration costs
E	In the notation for regulatory environments (RE), E stands for the active mode of a policy that consists of an annual decrease in electricity tax after 2026.
EC	Environmental cost
FC	Financial cost
FiC	Fixed costs
G	In the notation for regulatory environments (RE), G stands for the active mode of a policy that consists of an annual increase in natural gas tax after 2026.
H	In the notation for regulatory environments (RE), H stands for the active mode of a policy that consists of a cap on the price of heat from networks.
HC	Household costs
HeC	Cost of heating systems
HD	Heat demand
HS	Heat pump subsidies
HwNG	Households using natural gas
I	In the notation for regulatory environments (RE), I stands for the active mode of a policy that consists of a heat pump subsidy.
IC	Investment costs
InC	Costs of insulation measures
IS	Insulation subsidies
MeF	Measuring fee
NG	Natural gas consumption
nH	Efficiency of heating systems
OC	Operation costs

P	In the notation for regulatory environments (RE), P stands for the active mode of a policy that consists of a heat pump subsidy.
RC	Reinvestment costs
RHP	Regulated price of heat from networks
s'	Alternative technology state
s	Current technology state
SC	Subsidy costs
SpC	Spatial costs
TS1:GB3	Technology state with a natural gas boiler and the lowest insulation level.
TS2:GB2	Technology state with a natural gas boiler and medium insulation level.
TS3:GB1	Technology state with a natural gas boiler and the highest insulation level.
TS4:BN1	Technology state with a green gas network, individual hybrid heat pump, and the highest insulation level.
TS5:medHN2	Technology state with a medium temperature heat network and medium insulation level.
TS6:HP1	Technology state with a heat pump and the highest insulation level.
TS7:lowHN1	Technology state with a low temperature heat network, an individual heat pump, and the highest insulation level.
TS8:HH1	Technology state with a hydrogen network, individual hybrid heat pump, and the highest insulation level.
TS9:medHN1	Technology state with a medium temperature heat network and the highest insulation level.
UC	Upfront costs
VC	Variable costs
X	In the notation for regulatory environments (RE), X represents the active and inactive mode of a policy. For example, RE=XEHIP stands for RE=GEHIP and RE=0EHIP.

1

INTRODUCTION

In this chapter, we introduce the reader to our exploration of heat transitions in the built environment in the Netherlands. First, we elaborate on the societal context that motivated this research. Next, we make explicit the research problems that this dissertation addresses and present the research objective and research question. After that, we describe the origin of the material used in this dissertation and provide a description of the intended audience of this study and a reader's guide.

1.1. MOTIVATION: HEAT TRANSITIONS IN THE NETHERLANDS

1.1.1. HEATING AND COOLING IN ENERGY TRANSITIONS IN THE EU

To limit global warming, a transition towards energy systems with fewer greenhouse gas emissions is ongoing in the European Union (EU) [European Commission, 2017a]. Through domestic reductions alone, the EU aims at reducing greenhouse gas emissions to 40% below 1990 levels by 2030, 60% by 2040, and 80% by 2050. To achieve these reductions, the EU has set a series of ambitious measures and targets, including those linked to the package "Clean Energy for all Europeans" [European Commission, 2017a]. There are five key legislative initiatives in this package (listed below), in addition to non-legislative ones.

1. Energy performance in buildings should be improved, since buildings are responsible for approximately 36% of CO_2 emissions in the EU. Buildings must include the measures established in The Energy Performance of Buildings Directive (EU 2018/844) [European Commission, 2019a].

2. The share of renewable energy sources in the EU's energy mix should be increased to 32% by 2030. To support the necessary increase, the recast Renewable Energy

Parts of this chapter are adapted from Nava Guerrero et al. [2019], Nava-Guerrero et al. [2021, 2022]. The first author, who is also the author of this dissertation, conceptualised and performed the research. The other authors have performed an advisory role.
Parts of this chapter refer to article Moncada et al. [2017]; the author of this dissertation and Prof.dr.ir. Zofia Lukszo (one of her promotors) are two of the authors of such article.

Directive (2018/2001/EU) entered into force since the end of 2018 [European Commission, 2014].

3. Energy efficiency should increase to at least 32.5% by 2030, compared to the reference scenario without changes. To this aim, the European Commission (EC) amended the Directive on Energy Efficiency (2018/2002/EU) [European Commission, 2019b].

4. Member States are required to make 10-year plans to achieve their energy targets. These plans, known as national energy and climate plans (NECPs), should consider the period from 2021 to 2030, and also include a longer-term view towards 2050 [European Commission, 2017b].

5. The EU electricity market must be adapted to be more flexible, market-oriented, and able to integrate an increase in the share of renewable energy sources. Non-legislative initiatives are also part of the package; they address coal regions in transition, clean energy for EU islands, and the definition and monitoring of energy poverty in Europe [European Commission, 2017a].

Achieving the targets set in the EU requires changes in the heating and cooling sector, which provides energy to warm and cool the built environment. The EC [2016] explains that this sector is the largest single energy consumer in the EU: in 2016 it accounted for 50% of its annual energy consumption, 13% of oil, 59% of gas, and 68% of gas imports. Moreover, the EC highlights three problems [2016]: that about half of all buildings have old boilers with low efficiency rates and refurbishment rates are low; that renewable energy sources are not mainstream in this sector, and that heat from processes, such as industrial ones, is being wasted. Therefore, over the coming years, member states should oversee heat transitions with changes in both supply and demand.

1.1.2. TOWARDS HEAT TRANSITIONS IN THE DUTCH BUILT ENVIRONMENT

In the Netherlands, a specific challenge to the heat transition is the widespread use of natural gas in the built environment. Currently, a large share of its buildings uses natural gas for heating [Beurskens and Menkveld, 2009]. Over the last decades, the Netherlands has extracted this resource from the Groningen field. This field is the largest in Europe and is located in the north of the Netherlands [Whaley, 2009]. However, the national government has decided to end natural gas extraction from the Groningen field by 2030 [Rijksoverheid, 2018]. Further, since July 2018, new buildings that are small consumers (e.g. houses and small commercial buildings) should in principle not have a connection to the natural gas grid [RVO, n.d.]. Similarly, the national government aims at making all existing homes free of natural gas by 2050 [Rijksoverheid, 2019c]. As a result, the Netherlands faces the enormous challenge of organizing heat provision to the built environment without natural gas.

The national government has implemented and continues to develop laws and policies to support the heat transition. To account for some of the possible changes in heat networks, Lavrijssen and Vitez [2019] explain that a new version of the Heat Act and its accompanying regulations were approved in 2019; further, a new law with a focus on collective heat provision is expected to replace the Heat Act [Rijksoverheid, 2019b].

Moreover, governmental bodies collaborated with companies and civil society to produce the “Climate Agreement” [Rijksoverheid, 2019d], a document with intended measures towards achieving the climate goals during the next decade. The national government has also implemented fiscal policies [Rijksoverheid, 2019a]: in 2020, taxes on natural gas increased and taxes on electricity decreased with respect to 2019; these taxes are expected to continue changing over the next years [Rijksoverheid, 2019d].

Nevertheless, the responsibility to produce heat transition plans lies at the local level. Municipal authorities are required to take control of the heat transition [Rijksoverheid, 2016]; they are required to publish, before 2022, their official visions to achieve the national targets at a local level. Following the proposal of the Climate Agreement, municipal authorities have been organised into 30 regions to prepare for the energy transition. Each region will produce a Regional Energy Strategy (RES) [Klimaatberaad, 2019], with the support of the National RES Programme.

1.1.3. INSTITUTIONAL CHALLENGES OF HEAT TRANSITIONS IN THE HOUSING SECTOR

The implementation of visions and strategies in the Dutch housing sector is expected to be complex. In this sector, dwelling owners are in charge of making investments in energy efficiency [Filippidou et al., 2017]. Therefore, the implementation of visions and strategies would require coordinated decisions from multiple actors, and in some cases, joint investments. These decisions and investments are constrained and influenced by rules and regulations, including those regarding different types of ownership and different types of dwellings.

Types of ownership vary in the Dutch housing sector. In 2019, approximately 57% of dwellings were owner-occupied and 42% were rentals [CBS, 2019]. About 29% of dwellings were owned by a registered social housing corporation, and 13% by other landlords, such as companies, individuals, or institutional investors [CBS, 2019]. In the same year, approximately 64% were single- and 36% were multiple family dwellings [CBS, 2019]. Multiple family dwellings, which include apartments, duplex houses, and some dwellings above commercial spaces [CBS, 2019], are also known as strata buildings [Roodenrijs et al., 2020].

In the non-profit share of the Dutch housing sector, making decisions regarding joint investments has proven difficult. Filippidou et al. [2017] describe that in this share of the sector, the umbrella organization of housing associations (Aedes), the national tenants union, and the national government set the target of achieving an average energy label B by the end of 2020 (see De Minister voor Wonen en Rijksdienst [2014] for some regulatory details). In spite of this agreement, renovation rates of residential buildings in the non-profit share of the housing sector are not as high as desired [Filippidou et al., 2017].

Decisions in the owner-occupied share of the Dutch housing sector are also complex, and in particular, group decisions in strata buildings. Owners of dwellings in strata buildings are required to organise in home owner associations (HOAs) (see Book 5 of the Civil Code [2018]; specifically, articles 111 and 112). HOAs are in charge of managing and maintaining common elements of the building, such as its façade or roof, and are subject to governmental regulations [Rijksoverheid, 2019e]. HOAs are also ruled with systems of quorums and majorities, and internal regulations, to make decisions. Therefore, owners of dwellings in strata buildings are not only responsible for investments in energy efficiency, but also for reaching agreements regarding joint investments [Filippidou et al., 2017]. Although group decision-making in this context is a key aspect of energy transitions, literature exploring this phenomenon is limited [Roodenrijs et al., 2020].

Group decision-making is not the only decision-making challenge in the Dutch heat transition. Authors have identified barriers that influence individual energy efficiency investments. Hesselink and Chappin [2019] describe such barriers as factors that stop households from adopting a new technology. Based on existing literature, they describe those barriers in four categories: structural, economic, behavioural, and social behavioural. Overall, barriers indicate households cannot be assumed to have perfect financial rationality; their decisions are multi-criteria and their rationality can be bounded. A second challenge is that collective infrastructure projects require decisions not only by individual households or HOAs; instead, they require multiple households and HOAs to coordinate their decisions.

1.2. RESEARCH OBJECTIVE AND QUESTIONS

The objective of this dissertation is to explore the effects that individual and group investment decisions in heating systems and insulation measures by homeowners could have on heat transitions in the residential sector in the Netherlands. We consider insulation measures because of the explicit goals of both the EU and the Netherlands to reduce heat demand [European Commission, 2019a, Rijksoverheid, 2017]. We consider heating systems due to the EU's concern regarding old boilers [European Commission, 2016], and because of the goal of the Netherlands to organise heating without natural gas [Rijksoverheid, 2019c]. Our overarching research question is:

How could the heat transition in the Netherlands be influenced by homeowners' individual and group decisions regarding investment in heating systems and insulation measures?

In Chapter 3, 4, and 5, we use the following sub-questions to guide our work:

1. *How to explore the influence of homeowners' decisions regarding investment in heating systems and insulation measures on the heat transition in the Netherlands?*
2. *How could individual and group decisions between building owners, and within HOAs in strata buildings, influence the course of the heat transition in a neighbourhood in the Netherlands, under different policy interventions?*
3. *How could multi-criteria decisions by households influence the course of the heat transition in a neighbourhood in the Netherlands, under different policy interventions?*

1.3. RESEARCH APPROACH

To answer the research question and sub-questions, we used a complex systems engineering (CSE) approach with a conceptual framework that we first described in Moncada et al. [2017]. This framework allows us to explore combinations of technological, economic, legal, and social interventions. As explained on page 2 of

Moncada et al. [2017], the CSE approach *"addresses not only the challenges and possibilities of technical artefacts but also multi-actor complexity of socio-technical systems"*. This approach relies on modelling and simulation methods to explore technological and institutional challenges of energy transitions.

The conceptual framework incorporates the perspectives of socio-technical systems (STS) [Cooper and Foster, 1971, Herder et al., 2008, Trist, 1981] and complex adaptive systems (CAS) [Holland, 1988, Waldorp, 1993]. Using these perspectives, we structure energy transition challenges in terms of actors (individuals or organizations [Enserink et al., 2010]), institutions (rules and regulations [North, 1991]), and technology. Moreover, we conceptualise their interactions based on the notions that actors and technology form networks, and that those networks can have complex interactions [Herder et al., 2008, North and Macal, 2007]. Figure 1.1 illustrates this conceptual framework.

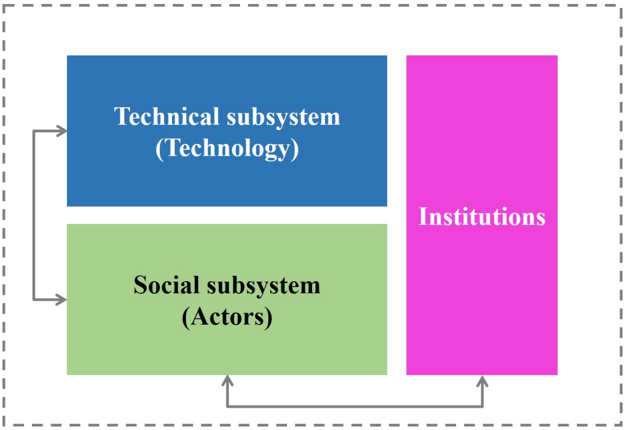

Figure 1.1: Framework for the analysis of socio-technical systems. Based on Moncada et al. [2017].

We used agent-based modelling and simulation as the main method to explore our research question and sub-questions [Borshchev and Filippov, 2004, Grimm and Railsback, 2005, North and Macal, 2007, Railsback and Grimm, 2019]. This method builds on the perspective of CAS to represent how individual agents shape the behaviour of the overarching system with their decisions and interactions. The resulting agent-based models (ABMs) can then be used to explore scenarios of change in the system. Further description of this method is provided in Chapter 2, Section 2.3.3.

The nature of our research was exploratory. Our modelling work was informed by recent policy developments and scientific literature. Our ABMs were informed by desk research, estimates, and assumptions. We retrieved scientific literature mainly by consulting the search engine Scopus [Elsevier, n.d.] and considered education repositories (such as those containing theses and doctoral dissertations) to be out of scope for our searches. In addition to the main modelling and simulation work, we used statistical analysis and visualization techniques to inspect and interpret outcomes. Further, we conducted sensitivity analyses and discussed publications to validate our findings.

Throughout the doctoral project there were various knowledge exchange moments. Progress and publications were periodically presented or reported to the User Committee of NWO Project 14183 "Modelling lab for smart grids, smart policies and smart entrepreneurship" and User Committee and fellow researchers from the overarching Programme "Smart Energy Systems in the Built Environment". Within and outside the framework of these presentations and reports, we had informal discussions with fellow academics and stakeholders involved in heat transitions. Moreover, early versions of our work were presented at the "3rd International Workshop on Agent-Based Modelling of Urban Systems" and the "4th International Conference on Smart Energy Systems and 4th Generation District Heating" in 2018.

Finally, together with staff form the TU Delft, the PhD candidate supervised two master graduation projects: Wessels [2020] and Westera [2018]. One of these projects [Wessels, 2020] was initiated by the PhD candidate. The report that resulted from the graduation project by Wessels [2020] informed some of the choices in our agent-based work, as described in Chapter 5.

1.4. ORIGIN OF THE MATERIAL

This dissertation is accompanied by the four journal papers below, published throughout the PhD project, and three agent-based models with their simulation results.

1. **Nava Guerrero, G. D. C.**, Hansen, H. H., Korevaar, G., & Lukszo, Z. (2022). An agent-based exploration of the effect of multi-criteria decisions on complex socio-technical heat transitions. Applied Energy. 306(Part B). `https://doi.org/10.1016/j.apenergy.2021.118118`

    - *Agent-based model*: **Nava-Guerrero, G. D. C.**, Hansen, H. H., Korevaar, G., & Lukszo, Z. (2022). Agent-based model described in journal article “An agent-based exploration of the effect of multi-criteria decisions on complex socio-technical heat transitions”. Publisher of agent-based model: 4TU Repository. DOI of agent-based model: `https://doi.org/10.4121/18865433`.
    - *Supplementary data*: **Nava-Guerrero, G. D. C.**, Hansen, H. H., Korevaar, G., & Lukszo, Z. (2022). Supplementary data for journal article "An agent-based exploration of the effect of multi-criteria decisions on complex socio-technical heat transitions". Publisher of supplementary data: 4TU Repository. DOI of supplementary data: `https://doi.org/10.4121/18865406`

2. **Nava-Guerrero, G.D.C.**, Hansen, H.H., Korevaar, G., & Lukszo, Z. (2021). The effect of group decisions in heat transitions: An agent-based approach. Energy Policy, 156(112306). `https://doi.org/10.1016/j.enpol.2021.112306`

    - *Agent-based model*: **Nava-Guerrero, G. D. C.**, Hansen, H. H., Korevaar, G., & Lukszo, Z. (2022). Agent-based model described in journal article “The effect of group decisions in heat transitions: An agent-based approach”. Publisher of agent-based model: 4TU Repository. DOI of agent-based model: `https://doi.org/10.4121/18865415`

- *Supplementary data*: **Nava-Guerrero, G. D. C.**, Hansen, H. H., Korevaar, G., & Lukszo, Z. (2022). Supplementary data for journal article "The effect of group decisions in heat transitions: An agent-based approach". Publisher of supplementary data: 4TU Repository. DOI of supplementary data: `https://doi.org/10.4121/18865385`

3. **Nava Guerrero, G. D. C.**, Korevaar, G., Hansen, H. H., & Lukszo, Z. (2019). Agent-based modeling of a thermal energy transition in the built environment. Energies, 12(5), 856. `https://doi.org/10.3390/en12050856`

   - *Agent-based model*: **Nava-Guerrero, G. D. C.**, Korevaar, G., Hansen, H. H., & Lukszo, Z. (2022). Agent-based model described in journal article "Agent-based modeling of a thermal energy transition in the built environment". Publisher of agent-based model: 4TU Repository. DOI of agent-based model: `https://doi.org/10.4121/18865367`.
   - *Supplementary material*: **Nava-Guerrero, G. D. C.**, Korevaar, G., Hansen, H. H., & Lukszo, Z. (2022). Supplementary material from journal article "Agent-based modeling of a thermal energy transition in the built environment". Publisher of supplementary material: 4TU Repository. DOI of supplementary material: `https://doi.org/10.4121/18865355`

4. Moncada, J.A., Park Lee, H.K., **Nava Guerrero, G.D.C.**, Okur, Ö., Chakraborty, S.T., & Lukszo, Z. (2017). Complex Systems Engineering: Designing in sociotechnical systems for the energy transition. EAI Endorsed Transactions on Energy Web 17. `https://doi.org/10.4108/eai.11-7-2017.152762`

The following parts of this dissertation are adapted from the previous four journal articles:

- **Chapter 1**: Parts of Chapter 1 are adapted from Nava Guerrero et al. [2019], Nava-Guerrero et al. [2021, 2022]. Parts of the chapter refer to article Moncada et al. [2017].
- **Chapter 2**: An earlier version of Section 2.3 was published in Nava Guerrero et al. [2019]. Section 2.4 is adapted from Nava Guerrero et al. [2019], Nava-Guerrero et al. [2021, 2022]. Some other parts of Chapter 2 are adapted from Nava Guerrero et al. [2019], Nava-Guerrero et al. [2021, 2022]. Parts of the chapter refer to article Moncada et al. [2017].
- **Chapter 3:** An earlier version of Chapter 3 was published as Nava Guerrero et al. [2019]. Parts of the chapter refer to article Moncada et al. [2017].
- **Chapter 4**: An earlier version of Chapter 4 was published as Nava-Guerrero et al. [2021]. Parts of the chapter refer to article Moncada et al. [2017].
- **Chapter 5**: An earlier version of Chapter 5 was published as Nava-Guerrero et al. [2022]. Parts of the chapter refer to article Moncada et al. [2017].
- **Chapter 6**: Parts of this chapter are adapted from Nava Guerrero et al. [2019], Nava-Guerrero et al. [2021, 2022]. Parts of the chapter refer to article Moncada et al. [2017].

1.5. AUDIENCE

Three key groups are considered as the audience of this dissertation. First, researchers who develop computational models to study socio-technical transitions, and in particular, heat transitions in the Netherlands. Second, practitioners who develop or use those computational models to offer advice to different actors. Finally, anyone interested in enabling heat transitions in the Netherlands, from households and neighbourhoods who are the end users of technologies, to public actors discussing and designing policy interventions.

1.6. OUTLINE OF THE DISSERTATION

The structure of this dissertation is illustrated in Figure 1.2, and the remaining chapters are structured as follows. In Chapter 2, we provide additional context regarding heat transitions in the Dutch built environment, discuss knowledge gaps, present our conceptual framework, and position this dissertation within the literature. In Chapter 3, we propose and demonstrate how to explore heat transitions with agent-based models; this chapter lays the foundation for Chapter 4 and Chapter 5. In Chapter 4, we explore the effect of group decisions on heat transitions and apply the concept of implicit discount rates to represent agents with bounded financial rationality. In Chapter 5, we explore the effect of multi-criteria decisions and present an extension of the agent-based model presented in Chapter 4. Finally, in Chapter 6, we provide an overview of research outcomes and answer the main research question. Moreover, we discuss the limitations of our work, draw recommendations for future research and model use, and present our final remarks.

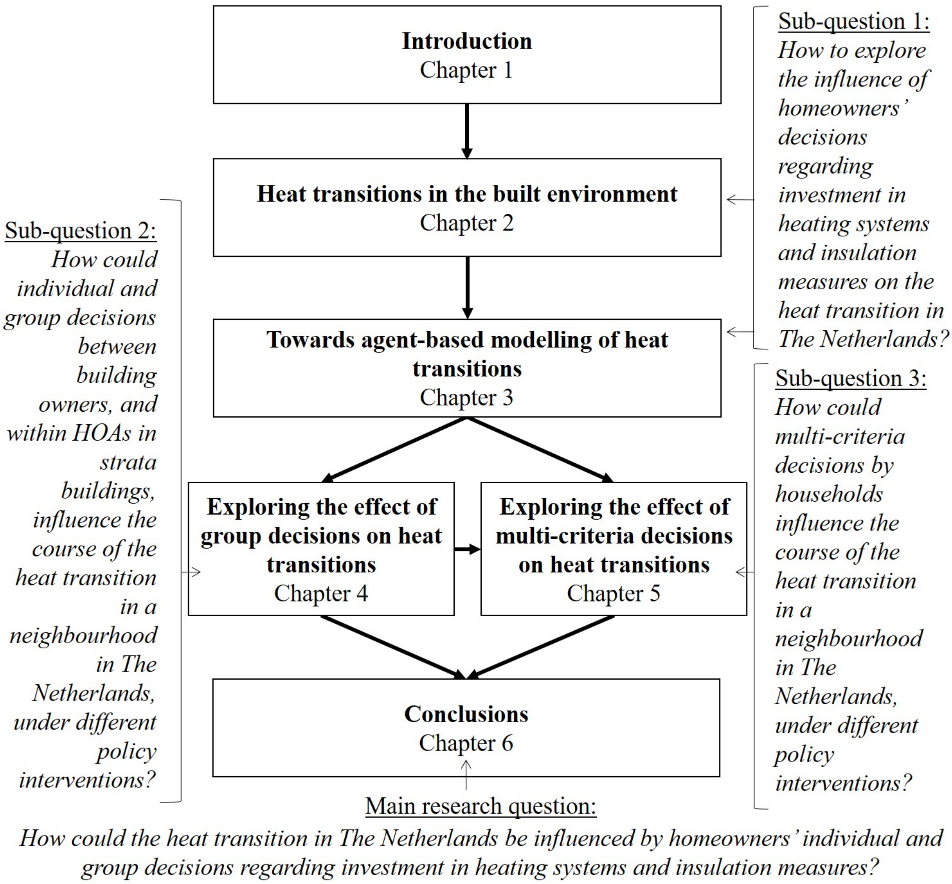

Figure 1.2: Structure of this dissertation.

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2

HEAT TRANSITIONS IN THE BUILT ENVIRONMENT

In this chapter, we set the scene for Chapter 3, 4, and 5, in which we present our modelling work. In Section 2.1, we present a description of formal institutions that are relevant for the heat transition in the Netherlands and motivate the use of a modelling approach to study this challenge. In Section 2.2, we provide an overview of some types of computational models to support decision-making for the heat transition, and in Section 2.3, we elaborate on the conceptual framework that we applied throughout this dissertation, including socio-technical systems (STS), complex adaptive systems (CAS), and agent-based modelling. Then, in Section 2.4, we discuss knowledge gaps in ABMs of energy transitions. Finally, in Section 2.5, we conclude by positioning our work within scientific literature.

2.1. FORMAL INSTITUTIONS IN THE DUTCH HEAT TRANSITION

The institutional landscape of the heat transition in the Netherlands is rapidly changing. To enable the heat transition, amendments to laws have recently been approved, and new regulations, decisions, and agreements continue to be published. In this section, we provide a non-exhaustive overview of formal institutions that play a role in the heat transition.

The following four laws are relevant for our work. Firstly, the Electricity Law [2021], which addresses the internal electricity market. Its first version entered into force in 1998, in line with the Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market in electricity.

An earlier version of Section 2.3 was published in Nava Guerrero et al. [2019]. Section 2.4 is adapted from Nava Guerrero et al. [2019], Nava-Guerrero et al. [2021, 2022]. Some other parts this chapter are adapted from Nava Guerrero et al. [2019], Nava-Guerrero et al. [2021, 2022]. The first author, who is also the author of this dissertation, conceptualised and performed the research. The other authors have performed an advisory role. Parts of this chapter refer to article Moncada et al. [2017]; the author of this dissertation and Prof.dr.ir. Zofia Lukszo (one of her promotors) are two of the authors of such article.

Secondly, the Gas Law [2021], which addresses the internal natural gas market. Its first version entered into force in 1998, in line with the Directive 98/30/EC of the European Parliament and of the Council of 22 June 1998 concerning common rules for the internal market in natural gas. Thirdly, the Heat Law [2019], which addresses the supply of heat to consumers. Its first version entered into force in 2013, and currently, a new law named Collective Heat Law and commonly known as Heat Law 2.0 is being developed and discussed [Rijksoverheid, 2019a]. Finally, the Crisis and Recovery Law [2020], which addresses the accelerated development and realization of spatial and infrastructure projects. Its first version entered into force in 2010. A 2019 amendment to this law has enabled municipalities to conduct experiments in which regulations can deviate from the content of the Gas Law [PAW, 2019].

Energy market regulation is also relevant to the heat transition. In the Netherlands, energy markets are regulated by the Authority for Consumers and Markets (ACM). Among other activities, they enforce rules, promote compliance, and provide information and guidance [ACM, n.d.a]. Tariff regulation for network operators is one of their tasks [ACM, n.d.b], as well as regulation of some tariffs for the supply of heat [ACM, n.d.c].

In addition to laws and regulations explicitly concerning energy markets, regulations regarding the property of buildings are relevant to our research; specifically, the Book 5 of the Civil Code [2018], deeds of division, and other regulations. The Book 5 of the Civil Code [2018] states that multi-family buildings must have a deed of division, formal regulations, and an HOA. Among other information, the deed of division should specify which parts of the property are being used as individual dwellings, and the regulations, how debts and costs are distributed as well as the establishment of an HOA. Some decisions that concern only an individual dwelling can be made individually; other decisions that concern more than one dwelling must be made collectively by the owners of the dwellings that would be affected or who share ownership. To that aim, voting systems with quorums and thresholds are in place. Different decisions require different thresholds; for example, absolute majorities, two thirds, four fifths, or even other thresholds that may have been set by a given HOA.

Other governmental decisions and agreements also influence the institutional landscape of the heat transition. Firstly, a decision regarding natural gas. The national government intends to reduce and eventually end natural gas extraction from the Groningen field [Rijksoverheid, 2018], which is located in the north of the country. Secondly, a decision regarding new buildings. Since July 1 2018, in principle, new residential buildings should not be connected to the natural gas network [Rijksoverheid, 2019b]. Thirdly, the Climate Agreement. This agreement was made by the government, together with companies and other organizations; its aim is to contribute to the reduction of CO_2 emissions in the country [Rijksoverheid, 2019c].

Moreover, according to an overview published by VNG [2021], financial energy transition policies are available for the residential built environment. Such policies, which can vary per type of user, include loans, taxes and tax exemptions, and subsidies. Although financial public policies are not the only type of policies relevant to the heat transition, we focus on this type of policy in order to inform the techno-economic dimension of our ABMs. Below, in line with the focus of this dissertation, we describe a selection of policies that concern owner-occupied residential buildings. Our descriptions are based on official government websites or the websites of each programme. Where applicable, we used a version of the names of the measures in the English language[1] but maintained their initials in the Dutch language.

- *National Heat Fund* - Provision of financing products for private homewoners, HOAs, and schools [Het Nationaal Warmtefonds, n.d.]. Depending on the product, penalty-free early repayment, low interest, and no closing costs might be offered. An Energy Savings Mortgage was under development at the time of writing; its target group would be residents of owner-occupied dwellings with limited borrowing capacity who are part of a municipal neighbourhood project or a housing corporation.

- *Energy taxes* - There are different measures concerning energy taxes [Rijksoverheid]. The national government has increased the natural gas tax and decreased the electricity tax to encourage households to opt for heating systems without natural gas. Tax refunds are in some cases available to companies and institutions. Tax reductions apply per electricity connection. Further, from 2020, companies contribute more than households to the Surcharge for Sustainable Energy (see points below). Energy taxes are lifted for electricity generated with solar panels for self-consumption, as long as the solar panels do not supply power to the network.

- *Surcharge for Sustainable Energy (ODE)* - There are two types of energy taxes [Rijksoverheid, 2020]: the energy tax for consumption (EB) and the ODE. The ODE is used to enable investments in sustainable energy.

- *Netting scheme for solar panels* - The electricity generated with solar panels and fed into the electricity grid is deducted from the electricity bill of small consumers [Rijksoverheid, 2019d]. This scheme is in place until the end of 2022. After that year and until 2031, the scheme will be gradually phased out.

- *Programme natural gas-free neighbourhoods (PAW)* - Intergovernmental initiative to enable actors, including municipalities, to learn how to phase-out natural gas in selected neighbourhoods, and how to scale up the process [PAW, n.d.].

- *Sustainable energy investment subsidy scheme (ISDE)* - Depending on the type of user (homeowner or business), users can apply for subsidies for solar boilers, heat pumps, insulation measures, connection to a heat network, or small-scale wind turbines and solar panels [RVO, n.d.b].

- *Energy saving at home subsidy for HOAs (SEEH)* - Subsidies intended for energy advice, process supervision, multi-year maintenance plans, and energy-saving measures in multi-family buildings. It excludes commercial properties within the HOAs [RVO, n.d.c].

[1] We consulted the websites Business.gov.nl [a,b,c] and Government of the Netherlands [2022] for an English version of the name of some of the measures.

- *DEI+: Subsidy demonstration energy innovation* - Support for projects in which innovative products and services are developed to enable (financially and socially) cost-efficient transitions to a built environment without natural gas, maintaining or improving the built environment, or scaling-up the transition [RVO, n.d.a]. The target groups are entrepreneurs and end users.

2.2. COMPUTATIONAL MODELS TO SUPPORT DECISION-MAKING

Formal institutions are a substantial part of the socio-technical system of heat provision in the Netherlands. They influence actors, technology, and their interactions. Including institutions in models and simulations can improve the insights obtained from studies on the heat transition. Various types of computational models are suitable for exploring heat transitions while including not only technical factors, but also economic, social, or institutional ones. In this section, we provide a brief overview of quantitative energy models and introduce socio-technical modelling approaches.

2.2.1. QUANTITATIVE ENERGY MODELS

Quantitative energy models are one of the tools presented in scientific literature to explore energy transitions. Nilsson et al. [2020] describe two types of models as follows. Firstly, integrated assessment models (IAM), which are often used internationally. IAMs are used to inform actors such as the Intergovernmental Panel on Climate Change (IPCC) and the European Commission. Models of this type integrate various disciplines and their aim is to generate useful information for decision-makers, in spite of uncertainties [UNFCCC, n.d.]. Secondly, energy-economic and macroeconomic models, which are often used for national policy making. These models integrate economic and technical components at more detailed level.

In the Netherlands, different actors have developed computational models to calculate and compare costs and benefits of technology options and policies for the heat transition [Brouwer, 2019, Henrich et al., 2021]. These models are known as calculation models (or "rekenmodellen" in the Dutch language) [Brouwer, 2019]. Examples include CEGOIA by CE Delft [CE Delft, n.d.], Warmte Transitie Atlas by Over Morgen [Over Morgen, n.d.], Aardgasvrije wijken by DWA [DWA, n.d.], Vesta MAIS by PBL [PBL, n.d.], ETM by Quintel [Quintell Intelligence, n.d.], and Caldomus by Innoforte [Innoforte, n.d.]. According to Brouwer [2019], most of these calculation models can be described as optimization models; for instance, model users can investigate which forms of heating are most cost-effective. Henrich et al. [2021] confirmed that consultancies are using this type of energy models to support municipalities in the development of Heat Transition Visions.

Although multi-actor perspectives can be incorporated in quantitative models, socio-technical transitions are often out of their scope. Instead, some quantitative models tend to focus on techno-economic factors [Li et al., 2015, Nilsson et al., 2020]. For example, Henrich et al. [2021] studied different models by means of desk research and in-depth interviews with various actors. They found that the impact of social and socio-economic data in heat transition projects in the Netherlands is limited. Although model developers provide social or socio-economic data to contextualise their results, model developers find it unpractical to incorporate those factors into their energy models.

2.2.2. SOCIO-TECHNICAL MODELLING APPROACHES

Various approaches have been proposed in the scientific literature to explore energy transitions with computational models from an explicit socio-technical perspective. Below, we provide an overview of three approaches.

Firstly, Nilsson et al. [2020] argue that linking quantitative models (such as IAMs and energy-economic and macroeconomic models) and socio-technical studies can enrich the knowledge base for public decision making. To this aim, a bridging framework to link those models to socio-technical system approaches is proposed. The framework integrates nine components: a systems model, socio-technical regime, local action, landscape, niche-innovations, policy and governance, scenario drivers and uncertainties, scenario model, and future system view.

Secondly, Li et al. [2015] define the concept of "socio-technical energy transition" (STET) models to describe the growing body of quantitative energy models that also capture socio-technical factors. According to Li et al. [2015], STET models should meet three requirements: techno-economic detail, explicit actor heterogeneity, and transition pathway dynamics; they argue that, in addition to STET models, various other models have incorporated some but not all of these requirements. Examples of STET models include ABMs [Li et al., 2015].

Finally, in line with Bollinger et al. [2018], Henrich et al. [2021] argue that multi-model ecologies are a promising research direction to explore the heat transition. Multi-model ecologies are systems of models that interact with each other [Bollinger et al., 2015]. Proponents of multi-model ecologies [Bollinger et al., 2018] argue that it is not possible to holistically explore the complexities of energy systems and socio-technical change with single models; instead, the need for multiple scales, disciplines, and perspectives calls for multi-model ecologies.

2.3. DEFINITION OF OUR CONCEPTUAL FRAMEWORK

Agent-based modelling is one of the modeling approaches that, together with the perspectives of STS and CAS, can be used to design in energy transitions. In this section, we build on our work in Moncada et al. [2017] (described in Section 1.3) and apply it to the context of thermal energy transitions in the built environment.

2.3.1. SOCIO-TECHNICAL SYSTEMS (STS)

Through the lens of STS, thermal energy systems in the built environment can be described as networks of *technology* interacting with networks of *actors* in complex ways, through *institutions* [Cooper and Foster, 1971, Herder et al., 2008, Trist, 1981]. *Technology* is the physical component of a system. *Actors* are individuals, organizations or other social entities who are able to either make decisions that affect the system or influence other actor decisions [Enserink et al., 2010]. When actors behave rationally, they aim at optimizing their own objectives; however, their rationality may be bounded [March, 1978, Simon, 1997]. Actors' objectives may vary from one actor to another, and they may converge, overlap or conflict. As a result, actors may modify their decisions and can engage in cooperation or competition [Bengtsson and Kock, 1999]. Finally, *institutions* [North, 1991] are rules and regulations that govern interactions between actors and between actors and technology.

2.3.2. COMPLEX ADAPTIVE SYSTEMS (CAS)

Thermal energy systems in the built environment can also be described through the lens of CAS. According to Holland [Holland, 1988, Waldorp, 1993], CAS are systems whose structure and behaviour emerges from interactions between its low-level autonomous components, known as agents. In these systems, a large number of changing agents act, interact with each other, and react to their dynamic environment. These agents have bounded rationality, are able to learn, may to some extent anticipate the future, and act in parallel in a network. As opposed to systems with central control, in CAS, system behaviour arises from the aggregated competition and cooperation of individual agents, and therefore, conventional mathematical tools are insufficient to explain their behaviour.

2.3.3. BASIC NOTIONS OF AGENT-BASED MODELLING

Agent-based modelling, also known as individual-based modelling [Grimm and Railsback, 2005], is a method for computational simulation that builds on CAS [North and Macal, 2007, Railsback and Grimm, 2019]. ABMs are used to explore possible states of a system to understand plausible futures, trends, tendencies, and behaviours that can occur under specific circumstances [Nikolic and Kasmire, 2013]. Through computational simulation with ABMs, the complex and nonlinear changes that characterise CAS can be studied [North and Macal, 2007]. Properties of CAS, such as emergence, adaptation, anticipation of the future, and the lack of central control, can be represented with this method.

Through agent-based modelling, the representation of a system is based on knowledge of the behaviour, or assumed behaviour, of individual agents whose interactions generate complex system structures and dynamics [Borshchev and Filippov, 2004]. This is possible for systems where agents have a certain degree of autonomy, their environment is dynamic, and social interaction takes place between agents [van Dam, 2009]. In the work by Olivella-Rosell et al. [2015], for instance, a probabilistic ABM of electric vehicle charging demand takes advantage of the possibility to simulate heterogeneous agents whose individual actions impact the distribution network.

The main components of an ABM are *agents*, the *environment*, and *time* [Nikolic and Kasmire, 2013]. First, in the context of STS, *agents* are software representations of actors, i.e., real-world entities able to make decisions [van Dam, 2009]. Agents are problem solvers with clear boundaries and interfaces; they exist within an environment, have objectives, behave rationally, control their own behaviour, and are able to act in anticipation [Jennings, 2000]. At any given time, an agent is described by a set of parameters known as their state [Wooldridge and Jennings, 1995]. New states may result from agents' decisions and changes in behaviour, which are based on agents' rules [Holland, 1995]. While agents can be rational and decision rules can be in place for agents to achieve their objectives, their rationality may be bounded [North and Macal, 2007]. Second, the *environment* consists of information and structure, may contain multiple agents and their information, and may be static or dynamic [Dam et al., 2013]. Through their actions and interactions, agents may influence their environment, which in turn may influence the behaviour of agents [Dam et al., 2013]. Finally, *time* is ubiquitous in ABMs because these models are used to conduct computational simulations, which represent changes in a system over discrete time [Dam et al., 2013]. Changes take place during each time step. These changes and their outcomes can be influenced by the previous state of the agents and the system, and in turn, can influence their future states.

Since ABMs are representations of systems and not the systems themselves, they rely on assumptions and simplifications of the actual system [Nikolic, 2009]. Decisions regarding which assumptions to include and which simplifications to make can be made in collaboration with stakeholders from the actual system that is being modeled [Dam et al., 2013]. It is also possible to use agent-based modelling as a tool for adaptive and participatory research, as is the case in companion modelling [Etienne, 2014]. In all cases, agent-based modelling requires transparency regarding assumptions and simplifications so that the implications of its results can be discussed in the light of those assumptions and simplifications [Dam et al., 2013].

Agent-based modelling is a proven method for studying STS as CAS. Vespignani [2012] reviewed some of the recent progress in modelling dynamical processes in complex socio-technical systems. Using diffusion and contagion phenomena as a prototypical example, they explained that the introduction of agent-based modelling has allowed the integration of large amounts of data and the generation of results with unprecedented level of detail. Dam et al. [2013] presented an approach to agent-based modelling of socio-technical systems. This approach has already been applied to a large number of cases, some of which are available in Dam et al. [2013]. More specifically, reviews of computational models for energy transitions show that agent-based modelling is a relevant method to address these types of problems. Li et al. [2015] presented a review of socio-technical energy transition models included ABMs, and Hesselink and Chappin [2019] presented a review of ABMs of the adoption of energy efficient technologies by households.

2.4. KNOWLEDGE GAPS IN ABMS OF ENERGY TRANSITIONS

ABMs have been widely used to explore socio-technical energy transitions [Hansen et al., 2019]. However, knowledge gaps that are relevant to heat transitions remain. Firstly, Hansen et al. [2019] reports that few works have focused on the heat transition instead of electricity-related questions. Secondly, Hesselink and Chappin [2019] highlight that ABMs often represent the adoption of individual instead of competing technologies. Moreover, although policy interventions are not limited to financial measures, financial measures rather than non-financial policies are often modelled in ABMs. Thirdly, to the best of our knowledge at the time of writing, our work in Nava-Guerrero et al. [2021] (Chapter 4) and our work in Nava-Guerrero et al. [2022] (Chapter 5), were the only ABMs of energy transitions with an explicit focus on collective decisions within and between HOAs.

A search in the engine Scopus [Elsevier, n.d.] retrieved only our work in Nava-Guerrero et al. [2021].[2] Other works that were not retrieved by such search (Busch et al. [2017] and Fouladvand et al. [2020]) do incorporate the notion of a necessary minimum density of demand or number of households for heat projects to be feasible. However, organisations that instigate projects, instead of active individual household agents, are included in the work by Busch et al. [2017], and in the work by Fouladvand et al. [2020], HOAs are not mentioned. Another exaple is the work by Pagani et al. [2020]. They propose a framework to assess scenarios to extend a heat network; they account for household behaviour to predict heat demand, and for a building's likelihood to connect to a heat network. Although they consider multi-family buildings and private or public ownership, HOAs are not discussed.

After concluding the research reported in this dissertation, we became aware of at least one ABM of diffusion of technologies [Schiera et al., 2019] that considers multi-family buildings. In Schiera et al. [2019], the authors explore the diffusion of rooftop photo-voltaic cells in an area that includes single-family buildings and condominiums. Although they do not explicitly address the concept of HOAs, they represent a hypothetical voting system in which the majority of apartments in a multi-family building can choose to use the entire surface of the building's roof; their voting system is limited to a building rather than an entire neighbourhood.

Further, scientific literature on heat transitions in the Netherlands is recent and limited. To exemplify, we conducted a search in the engine Scopus [Elsevier, n.d.]. We searched for entries with the following keywords in the publication's title, abstract, or keywords: *(heat OR heating OR thermal) AND (netherlands or dutch) AND (energy) AND (agent-based OR transition)*. We obtained 88 results dating from 1980 to 2021. After refining the search to entries that contained the keyword "agent-based", we obtained 11 results dating from 2007 to 2021. Figure 2.1 illustrates the resulting 88 and 11 entries, plus our work in Nava Guerrero et al. [2019]; this work was not retrieved in our search because although it contains an illustrative example of the heat transition in the Netherlands, the words "netherlands" or "dutch" are not included in its title, abstract, or keywords.

From the 12 available agent-based studies, besides our own two studies [Nava Guerrero et al., 2019, Nava-Guerrero et al., 2021], few works focus on the adoption by households of heating systems that are alternatives to natural gas boilers. A number of studies [Bliek et al., 2010, Haque et al., 2017a,b, Nizami et al., 2019, Warmer et al., 2007] center on control and congestion management or coordination mechanisms and demand response in electricity grids. One work [Bloemendal et al., 2018] presents practical steps to improve a planning method for aquifer thermal energy storage (ATES) systems, and one work [Chappin et al., 2009] explores adoption in the Dutch paper and board industry. Finally, the work in de Wildt et al. [2021] presents an approach to assess, ex-ante, value conflicts in the heat transition. Although the last work models households that decide to replace or maintain their natural gas boilers and includes two financial policies, it is not a model of adoption; instead, households make decisions to satisfy their

[2]We searched for the following keywords in the publication's title, abstract, or keywords: (energy OR heat OR heating OR electric OR electricity OR thermal) AND (agent-based OR individual-based OR multi-agent) AND ("homeowner's association" OR "homeowner association" OR "association of homeowners" OR "home owner association" OR "association of home owners" OR HOA OR VVE).

values.

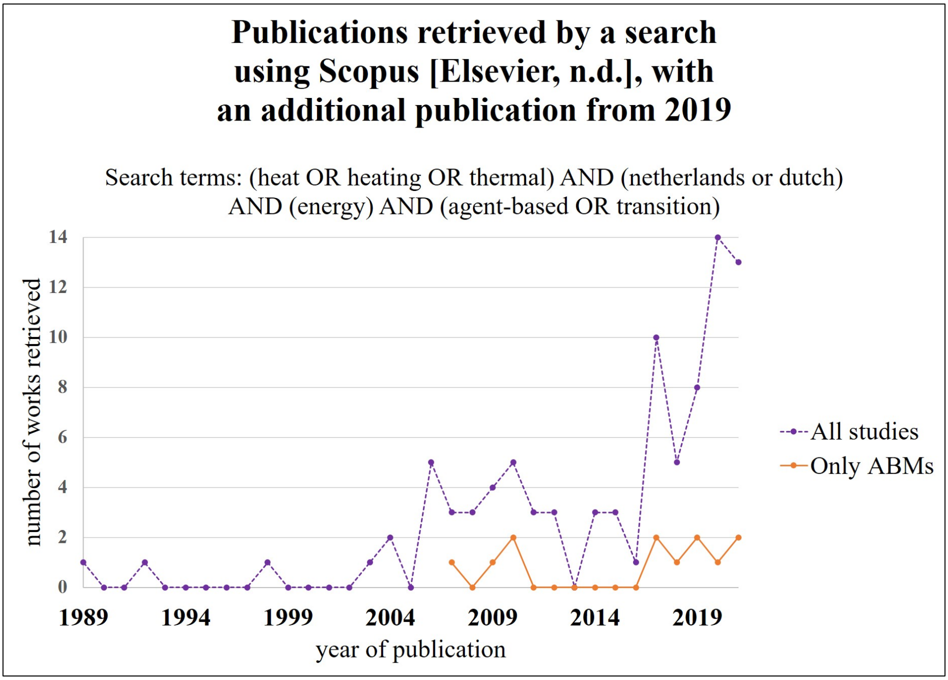

Figure 2.1: Results from a search for publications regarding the heat transition in the Netherlands using Scopus [Elsevier, n.d.], with an additional publication from 2019.

Works that do center on the phase-out of natural gas boilers are as follows. The work in Faber et al. [2010] explores the diffusion of micro-cogeneration in the Netherlands as an alternative to incumbent boilers. Results indicate that such diffusion could be inhibited if the demand for natural gas decreased due to insulation. However, the study focused on only one alternative heating system and excluded a heating system being adopted and shared by multiple households. In the work by Fouladvand et al. [2020], which explores the emergence and continuation of thermal energy communities, various alternatives to natural gas are available to households. A minimum member requirement for a community to form and the satisfaction of households were found to be relevant factors in the formation of these communities. Dynamics and constraints within homeowner associations, however, are not explicitly addressed; moreover, the study does not explicitly explore policy interventions.

Overall, Figure 2.1 shows that scientific literature regarding heat transitions in the Netherlands is scarce but increasing. In practice, the heat transition is ongoing and new questions and new answers are emerging rapidly. In the following chapters we extend the discussion on agent-based studies on heat transitions, both from the Netherlands and from other countries. Furthermore, in Chapter 4 and 5 we also discuss other types of literature, namely, expert reports and news.

2.5. CONCLUSIONS

The heat transition in the Netherlands is complex and involves interactions between actors and technology. Quantitative models that are used in different countries often focus on the techno-economic aspects of technological change. In contrast, agent-based modelling and simulation is one of the methods to explore complexity in energy transitions by also accounting for social interactions and institutions.

In the remaining chapters of this dissertation, we seek to contribute to the body of scientific literature trying to address the following knowledge gaps:

- According to Henrich et al. [2021], Li et al. [2015], Nilsson et al. [2020], the suitability of some quantitative models to explore energy transitions from a socio-technical perspective is limited.
- According to Hansen et al. [2019], ABMs of energy transitions are often used to explore the electricity system rather than heat-related questions.
- According to Hesselink and Chappin [2019], ABMs of the adoption of energy technologies or measures are often used to explore single instead of competing technologies.

To the best of our knowledge at the time of writing:

- ABMs of the adoption of energy technologies or measures have not explicitly focused on dynamics within and between HOAs [Nava-Guerrero et al., 2021, 2022].
- ABMs of the heat transition in the Netherlands have not explored the performance of financial policies on the adoption of competing heating systems to phase out natural gas (Section 2.4).

Moreover, our work adds to the existing literature in the following ways:

- We follow the CSE approach discussed in Section 1.3 and explore interactions between actors, technologies, and institutions presented in this chapter, as described in Chapter 3, 4, and 5. Furthermore, we add to the energy transition themes explored with CSE in Moncada et al. [2017].
- In line with the concept of STET models [Li et al., 2015], we explore the recent topic of the heat transition in the Netherlands while balancing techno-economic detail, explicit actor heterogeneity, and transition pathway dynamics.
- Although working with multi-model ecologies was out of the scope of this project, our modelling and simulation studies can serve as starting points to combine the type of quantitative models discussed in 2.2.1 with ABMs of socio-technical heat transitions.

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3

TOWARDS AGENT-BASED MODELLING OF HEAT TRANSITIONS

ABSTRACT

To reduce greenhouse gas emissions to 80% below 1990 levels by 2050, an energy transition is taking place in the European Union. Achieving these targets requires changes in the heating and cooling sector. Designing and implementing this energy transition is not trivial, as technology, actors, and institutions interact in complex ways. We provide an illustrative example of the development and use of an agent-based model (ABM) for thermal energy transitions in the built environment, from the perspective of socio-technical systems (STS) and complex adaptive systems (CAS). In our illustrative example, we studied the transition to heating without natural gas in a simplified residential neighbourhood. We used the ABM to explore socio-technical conditions[1] that could support the neighbourhood's transition over 20 years while meeting the neighbourhood's heat demand. Our illustrative example showed that through the use of STS, CAS, and an ABM, we can account for technology, actors, institutions, and their interactions while designing for thermal energy transitions in the built environment.

Keywords: built environment; residential; thermal; technology; insulation; complex adaptive systems; socio-technical systems; ABM.

A version of this chapter has been published as a journal article in Energies [Nava Guerrero et al., 2019]. The first author, who is also the author of this dissertation, conceptualised and performed the research. The other authors have performed an advisory role.
Parts of this chapter refer to article Moncada et al. [2017]; the author of this dissertation and Prof.dr.ir. Zofia Lukszo (one of her promotors) are two of the authors of such article.
[1]The word "socio-technical" replaces the word "socioeconomic" from Nava Guerrero et al. [2019].

SUPPLEMENTARY MATERIALS

- **Nava-Guerrero, G. D. C.**, Korevaar, G., Hansen, H. H., & Lukszo, Z. (2022). Agent-based model described in journal article "Agent-based modeling of a thermal energy transition in the built environment". Publisher of agent-based model: 4TU Repository. DOI of agent-based model: `https://doi.org/10.4121/18865367`.

- **Nava-Guerrero, G. D. C.**, Korevaar, G., Hansen, H. H., & Lukszo, Z. (2022). Supplementary material from journal article "Agent-based modeling of a thermal energy transition in the built environment". Publisher of supplementary material: 4TU Repository. DOI of supplementary material: `https://doi.org/10.4121/18865355`

3.1. INTRODUCTION

An energy transition is ongoing in the European Union (EU) [European Commission, 2016]. Since 2011, the EU has aimed at reducing greenhouse gas emissions to 80% below 1990 levels by 2050, including to 60% by 2040 and to 40% by 2030. One way to achieve these goals is to increase the share of renewable energy resources in the energy system. However, this change would not be trivial. Due to the intermittent nature of many renewable energy resources, the energy system would have to be able to ensure stability and security of supply under variable generation [Holtinnen et al., 2013]. Energy systems that are able to meet this and other challenges are conceptualised as "smart energy systems" [Lund et al., 2012, Mathiesen et al., 2015].

Accounting for the heating and cooling sector (H&C) is key to the design and implementation of smart energy systems [Lund et al., 2014]. This sector, which provides energy to warm and cool the built environment, is the largest single energy consumer of the EU. In 2016, it accounted for 50% of the EU's annual energy consumption, 13% of oil, 59% of gas, and 68% of gas imports [European Commission, 2016]. As is the case in other sectors and infrastructures, designing and implementing changes in the H&C sector is challenging. The involvement of multiple individuals and organizations in decisions regarding technological changes is required [Herder et al., 2008], and institutions and technology need to be harmonised [Mathiesen et al., 2015]. Therefore, designing for an energy transition in the H&C sector requires an approach that accounts for technology, individuals and organizations, and rules and regulations.

In this chapter, we address the first research sub-question of this dissertation, which is an addition with respect to the version of this chapter published as Nava Guerrero et al. [2019]: *How to explore the influence of homeowners' decisions regarding investment in heating systems and insulation measures on the heat transition in the Netherlands?* We provide an illustrative example of the development and use of agent-based model (ABMs) of thermal energy transitions in the built environment from the perspective of socio-technical systems (STS) and complex adaptive systems (CAS). ABMs are computational models that can be used to represent and explore the complexity of systems where individuals and organizations, and technology, interact in complex ways through rules and regulations. These models can also be used to design interventions in these systems. Our example addresses the transition of a residential neighbourhood towards heating without natural gas.

The remainder of this chapter is structured as follows. In Section 3.2, we present the materials and methods that we used for the illustrative example, which we describe in Section 3.3. In Section 3.4, we report and discuss results. Finally, in Section 3.5, we reflect on the use of ABM, STS, and CAS in our example and introduce future work.

3.2. MATERIALS AND METHODS

In Section 3.3 and Section 3.4, we present an illustrative example of the development of an ABM of a thermal energy transition in the built environment. Our example addresses the transition to heating systems without natural gas in residential neighbourhoods.

Our illustrative example is our first step towards our application of STS and CAS in the development and use of an ABM in the context of a case study. Therefore, the problem that we present in Section 3.3 is intentionally simplified. The model that we conceptualised, developed, and used is an illustrative model. This model, which can be modified and extended, is a sketch that will guide the development of forthcoming case studies. The model contains both assumptions regarding input data and simplifications regarding technology, agents, and institutions.

In the following subsections, we explain the main methods used in the illustrative example. In Section 3.2.1, we elaborate on model development and reporting. In Section 3.2.2, we explain how we used the model for computational simulations. In Section 3.2.3, we present our approach to analyzing simulation results.

3.2.1. MODEL DEVELOPMENT

We developed an ABM based on the approach proposed by Dam et al. [2013]. This approach proposes 10 steps to guide the development of ABMs of socio-technical systems. The steps are (1) problem formulation and actor identification, (2) system identification and decomposition, (3) concept formalization, (4) model formalization, (5) software implementation, (6) model verification, (7) experimentation, (8) data analysis, (9) model validation, and (10) model use. We followed steps 1 to 8. Steps 9 and 10 will be addressed in forthcoming case studies.

In Section 3.3, the description of our ABM is based on the Overview, Design concepts, and Details (ODD) Protocol by Grimm et al. [2010]. We based our description on the ODD protocol for two of its known advantages: It can be used for a wide range of ABM applications in different fields, and it clarifies the features that were and were not included in the model, which can serve as input for further discussions and research [Grimm et al., 2010].

Several modelling toolkits are available to build ABMs, including NetLogo [Wilensky, 1999] and GAMA [Grignard et al., 2013]. We chose NetLogo (Version 6.0.4, Center for Connected Learning and Computer-Based modelling, Northwestern University, Evanston, IL, USA) because this software is “free, well-written, easy-to-install, easy-to-use, easy-to-extend, and easy-to-publish-online” [Sklar, 2007] (p. 7).

3.2.2. COMPUTATIONAL SIMULATIONS

After building and verifying the model, we used it for experimentation. Our experiments simulated changes that could occur in a neighbourhood as a result of the behaviour of agents, the environment, and their interactions. To simulate these changes, we changed the model's input parameters and observed changes over a fixed simulation time. Each unique set of input parameters of the model is an experimental scenario. In a simulation run, an experimental scenario is used to start up the model, and changes occur through a series of time steps based on the model code.

We simulated each experimental scenario once, as our model was deterministic. Simulation runs of experimental scenarios were conducted through the behaviour Space of NetLogo [Wilensky, 1999], a built-in simulation tool. Experiments took less than one minute to complete in a processor Intel(R) Core(TM) i7-6600U with 8GB RAM.

3.2.3. ANALYSIS OF RESULTS

In order to analyse results, we collected data from each time step of each simulation run. These data were exported by NetLogo [Wilensky, 1999] in a CSV file. To visualise and analyse results, we used the statistical computing software R project (version 3.5.1, R Core Team, R Foundation for Statistical Computing, Vienna, Austria) [R Core Team, 2018] and R studio (version 1.1.463, RStudio Team, RStudio, Inc., Boston, MA, USA) [RStudio Team, 2018], with the packages dplyr (version 0.7.8) [Wickham et al., 2018b], sqldf (version 0.4−11) [Grothendieck, 2017], ggplot2 (version 3.1.0) [Wickham et al., 2018a], and car (version 3.0−2) [Fox et al., 2018]. We relied on a nonparametric statistical test and visual inspection of plots and tables to describe and analyse results. When a model has undergone validation, further statistical analyses of its results can be conducted.

3.3. ILLUSTRATIVE EXAMPLE: FROM NATURAL GAS-BASED TO NATURAL GAS-FREE HEATING IN RESIDENTIAL NEIGHBOURHOODS

In the Netherlands, a large share of the built environment relies on natural gas for heating [Beurskens and Menkveld, 2009], but in the future, this is likely to change. In March 2018, the national government announced its decision to end natural gas extraction from the Groningen field by 2030 [Rijksoverheid, 2018]. The Groningen field is the largest in Europe and is located in the North of the Netherlands [Whaley, 2009]. Moreover, since July 2018, new buildings that are small consumers, such as houses and small commercial buildings, have had to be built without a connection to the gas grid [RVO, n.d.]. As a result of these changes, the built environment in the Netherlands has the challenging task to organise heat supply that is naturally gas-free. At the local level, municipalities are responsible for taking control of the thermal energy transition [Rijksoverheid, 2016].

We focused our illustrative example on the transition of the Dutch built environment to heating systems that do not use natural gas. For the purpose of simplicity, we only considered residential buildings. As the first step in the approach to agent-based model development described in Section 3.2.1, we defined our research question as: *Which socio-technical conditions support Dutch neighbourhoods' transition to natural gas-free* *heat supply by 2040 while meeting the neighbourhoods' heat demand?*

While there can be multiple and complex objectives of thermal energy transitions (e.g., maintaining user comfort, public participation, acceptability of projects), this work focused on two key performance indicators (KPIs) related to reduced fossil fuel use: The neighbourhood's *annual natural gas consumption* (MWh) and the *cumulative costs of the transition* (thousands of Euros), including investments, maintenance, and energy costs.

The remaining parts of this section are structured as follows. In Section 3.3.1, we describe the thermal energy transition through the lenses of STS and CAS. In Section 3.3.2, we define the modelling questions and present the model overview, based on the ODD protocol. In Section 3.3.3, we describe the experimental design for the computational simulation. Results are presented and discussed in Section 3.4.

3.3.1. CONCEPTUALIZATION OF AN ILLUSTRATIVE NEIGHBOURHOOD

The transition towards natural gas-free heating in residential neighbourhoods is complex. While local governments in the Netherlands are in charge of taking control of the thermal energy transition, the transition cannot be achieved only through top–down technological decisions. From the perspectives of STS and CAS, neighbourhoods can be seen as networks of individual actors who own technology, interact with each other, and are able to make their own decisions.

Our simple conceptualization of the neighbourhood considers each household to be an actor. Each household is assumed to live in a single dwelling, and the dwelling's insulation and heating system are considered to be the technologies of interest to the model. For the sake of simplicity, we assumed that all households can make capital investment decisions for their dwelling. Each household was assumed to initially own a natural gas boiler and to be able to decide to keep their boiler or replace it with an alternative. The heating systems that were assumed to be available were micro-CHPs (micro combined heat and power), electric radiators, air heat pumps, and geothermal heat pumps. While micro-CHPs consume gas, we assumed that they are available for agents to purchase. The household can also decide to keep their dwelling's current insulation level unchanged or to improve it. A higher insulation level results in lower heat demand. Some households are influenced by the decisions of other households after observing how many households in the neighbourhood have improved their insulation or replaced their heating system. Since each household is able to make its own decisions and these decisions can vary from one household to the next one, the neighbourhood's transition depends on households' individual decisions. This is the CAS notion of system outcomes being the result of individual decisions rather than of centralised control.

Households can make decisions in different ways. Some take action to reduce natural gas consumption and prioritise natural gas reduction over costs minimization, while other do not. Some households are influenced by observations regarding the number and type of heating systems and the dwelling insulation levels in their neighbourhood, while others are not. Some households have better information regarding costs of technology options than others. All households have budget constraints that affect their investment decisions.

Following the review in [Hesselink and Chappin, 2019] [2], we integrated notions from structural, economic, behavioural, and social–behavioural barriers to explore the

[2]The published article referred to [Jennings, 2000] instead of [Hesselink and Chappin, 2019].

adoption of residential heating systems. We assumed that households do not have knowledge of future retail energy prices, do not always have sufficient capital to make an investment, have to pay upfront capital costs, are bounded by their own desired payback period and by their ability to compare combinations of heating systems and insulation, and can be influenced by other households' inactivity or investment decisions.

While natural gas reduction in the neighbourhood depends on individual decisions by households, the cost of the transition is also influenced by external factors that cannot be controlled by households. These include the investment cost of insulation measures, investment and maintenance costs of heating systems, and electricity and natural gas prices, which influence the operation costs of heating systems. While households have access to present market costs, future costs are uncertain, and households have no access to data of past prices. Therefore, while households can estimate the financial performance of their preferred insulation and heating system options, their actual financial performance is uncertain until after the fact.

Institutions also play a role in the transition to natural gas-free residential heating. Our conceptualization includes changes in energy prices, the sunsetting of natural gas boilers, and the effect of better information in the investment decisions that households make. We assumed that the electricity price changes annually and at a constant rate, and that the natural gas price also changes annually and at its own constant rate. Furthermore, we assumed that it is no longer possible for households to purchase new natural gas boilers. Finally, we assumed that an information campaign that informs households about cost-effective investments in technology is sometimes in place.

3.3.2. MODEL OVERVIEW

We based our ABM on the simple conceptualization from Section 3.3.1. The model represents a neighbourhood in which households use their heating systems to meet their heat demand and can choose to invest in replacing their heating system or improving their dwelling's insulation level. We used the model to simulate experimental scenarios that represent variations between households' decision rules and external factors. The purpose was to identify the conditions under which the transition was achieved and gain insights into the costs of such a transition and the changes in household technologies that took place. We operationalised this objective, based on the research question, into the following modelling questions:

1. Under which socio-technical conditions did the neighbourhood transition fully to natural gas-free heating?

2. What were the costs of the transition?

3. Which changes in household insulation and heating systems took place during these transitions?

MODEL ENTITIES, STATE VARIABLES, AND SCALE

Entities in our model are either *agents* or *objects* who exist in the *environment* with a *temporal scale*. Agents represent households, are able to make decisions, and are described by state variables. Objects represent heating systems, are described by properties (such as capital costs and thermal efficiency), and are simply used by agents. The environment represents information that is external to agents and objects. Below, we elaborate on agents, their state variables, the environment, and the temporal scale. Objects' properties are specified in Appendix 3.7.

Each agent has nine state variables that describe the agent at any point in time: Insulation level, heating system, annual natural gas consumption, cumulative costs, time horizon (HRZ), investment (INV), value orientation (ORI), social threshold (THR), and ability to compare combined investments (ACCI). Insulation level and heating system describe the technology that an agent owns. Cumulative costs and annual natural gas consumption are outputs from the use of heating systems by agents, from their investment decisions, and from external factors. HRZ, INV, ORI, THR, and ACCI are inputs for agents' investment decisions. Agents' states are listed in Table 3.1 and explained further in the following paragraphs.

Variable	Units	Description	Possible Values
Insulation level	Dimensionless	Insulation level of a dwelling	Low, Medium or High
Heating system	Dimensionless	Type of heating system	Natural gas boiler, electric radiator, micro-CHP, air heat pump, geothermal heat pump
Annual natural gas consumption	[MWh]	Gas consumption in one year	Positive real numbers
Cumulative costs	Thousands of Euros	Investment, maintenance and operation costs	Positive real numbers
HRZ	Years	Time horizon	Positive integers
INV	Years	Indicates the number of years left before a time equal to the agent's HRZ has passed since the agent's last investment	Positive integers
ORI	Dimensionless	Value orientation	Environmental, Social, Financial
THR	Dimensionless	Threshold after which socially oriented agents will make a decision	0 ≤ Fraction ≤ 1
ACCI	Dimensionless	Ability to compare combined investments	0 ≤ Fraction ≤ 1

Table 3.1: States of households.

Agents have an *insulation level* and own a *heating system*. Three insulation levels are possible, with the lowest level representing poorly insulated dwellings, and the highest, quasi-passive dwellings. Five heating systems are possible, two of which consume electricity, i.e., electric radiator, air heat pump, and geothermal heat pump. When an agent invests in a new technology, one or both of these state variables are updated.

Cumulative costs are the thousands of Euros that an agent has spent up to a point in a simulation run. When agents invest in technology, the capital costs of that technology increase the agent's cumulative costs. Similarly, maintenance and use of heating systems also increase the agent's cumulative costs. Thermal efficiency and capital and maintenance costs vary between heating systems, and capital costs vary between insulation levels, as specified in Appendix 3.7. In addition, cumulative costs are influenced by energy prices. While agents cannot control the costs of technology, the thermal efficiency of heating systems, or the energy prices, agents can influence their own cumulative costs through their investment decisions in technology.

Annual natural gas consumption results from the use of a heating system by an agent. It is influenced by the type of heating system that the agent owns and the agent's insulation level. Each heating system uses either natural gas or electricity and has its own thermal efficiency, and each insulation level results in a different heat demand. While agents cannot control whether a type of heating system uses natural gas or electricity, or the heat demand that results from each insulation level, agents can influence their own annual natural gas consumption from the following year through their investment decisions in technology in the present year.

Each agent's *time horizon* (HRZ) is the payback period that an agent considers when assessing whether an investment would be cost-effective. For example, when an agent's HRZ = 5, they estimate the cumulative natural gas consumption and the cumulative costs of each investment option over a 5-year period, including investment, maintenance, and energy costs (Equations 3.1 to 3.5, below). In Equations 3.1 to 3.5, CNG is cumulative natural gas consumption, CHD is cumulative heat demand, nH is thermal efficiency, CC are cumulative costs, EC are energy costs, MC are maintenance costs, IC are investment costs, AHD is annual heat demand, REP is retail energy price, AMC are annual maintenance costs. Then, the agent selects the cheapest option that they believe minimises cumulative natural gas consumption or the option that they believe minimises cumulative costs, depending on the agent's ORI. After making an investment, an agent will only consider new investments after HRZ has passed, this is, when the state variable *investment* (INV) is equal to or lower than zero.

$$CNG = \frac{CHD}{nH} \tag{3.1}$$

$$CC = EC + MC + IC \tag{3.2}$$

$$CHD = AHD * HRZ \tag{3.3}$$

$$EC = \frac{CHD}{nH} * REP \tag{3.4}$$

$$MC = AMC * HRZ \tag{3.5}$$

- Equation 3.1 applies to technologies that consume natural gas and not electricity.
- In Equation 3.2, information regarding maintenance costs and investment costs is part of the environment and is available to agents.
- In Equation 3.3, annual demand is retrieved from the environment. See Appendix 3.7, Table 3.10.
- In Equation 3.4, retail electricity or natural gas price of the present year are used, depending on the technology.
- In Equation 3.5, annual maintenance costs are retrieved from the environment. See Appendix 3.7, Table 3.9.

The *value orientation* (ORI) of the agent is set to either “environmental”, “financial”, or “social”. Environmental agents aim to minimise their natural gas consumption. When faced with multiple alternatives that would reduce natural gas consumption to zero, environmental agents select the alternative that would minimise their cumulative costs. Financial agents focus exclusively on minimizing cumulative costs. Social agents also aim at minimizing cumulative costs, but they are only willing to replace their heating system or improve their insulation after a given fraction of all households owns either a heating system or has an insulation level different than their own. This fraction is specified by the *social threshold* (THR) state of the agent. If the fraction of total agents with either a different heating system or insulation level than their own is not higher than a social agent’s THR, the social agent would not invest in new technology. When social agents observe agents in the neighbourhood, they observe their states from the end of the previous year.

The agent’s *ability to compare combined investments* (ACCI) is a proxy for the impact of an information campaign about cost-effective investments in heating systems and insulation measures. We assumed that, after being reached by an information campaign, agents can compare all possible combinations of insulation levels and heating systems when making an investment decision. ACCI is represented as a binary variable that indicates whether the agent has been reached by the information campaign (ACCI = 1) or not (ACCI = 0). For example, when an agent with a natural gas boiler and low insulation has an ACCI = 0, they only consider investment options 1 to 7 from the list below. If the same agent has an ACCI = 1, they also consider options 8 to 15. We assumed that agents never choose an insulation level lower than their existing one.

1. Business as usual (natural gas boiler and low insulation)
2. Micro-CHP and low insulation
3. Electric radiator and low insulation
4. Air heat pump and low insulation

5. Geothermal heat pump and low insulation
6. Natural gas boiler and medium insulation
7. Natural gas boiler and high insulation
8. Micro-CHP and medium insulation
9. Micro-CHP and high insulation
10. Electric radiator and medium insulation
11. Electric radiator and high insulation
12. Air heat pump and medium insulation
13. Air heat pump and high insulation
14. Geothermal heat pump and medium insulation
15. Geothermal heat pump and high insulation

In the model, agent rationality is bounded. First, individual agents' estimates are constrained by their HRZ and ACCI. Agents with longer HRZ are willing to choose technologies with higher investment costs and lower maintenance and energy costs, while agents with shorter HRZ prefer options with lower investment costs. Therefore, it is possible for choices of agents with longer HRZ to result in lower annualised costs. Similarly, when agents have an ACCI = 0, they are not able to compare all investment options that are available to them, as described above. Second, agents have imperfect information regarding their environment. While they have perfect knowledge of investment and annual maintenance costs of each heating system, agents assume that electricity and natural gas prices do not change. Agent estimates are thus only correct in scenarios where prices remain constant. As a result, an agent can have lower or higher heating costs than expected. Finally, agents are subject to path dependency: Their present decisions condition their future options. When the cumulative costs of an investment decision differ from their estimated costs, agents may not have the capital to change their technology according to the new natural gas and electricity prices, as reflected by the variable INV. In the current version of the model, HRZ, ORI, THR, and ACCI do not change during a simulation.

The *environment* consists of external factors and information about the state of the neighbourhood. First, external factors are prices of electricity and natural gas and the prices and technical specifications of available technologies. We assumed that prices of electricity and natural gas can change every year, that installed technology does not age, and that, with one exception, prices and technical specifications of technology remain constant. This means that the efficiency of installed technology remains constant, as well as the specifications of technologies available in the market. An exception is made for micro-CHPs. While we assumed that installed micro-CHPs do not age, we simulated a decrease on their market price based on Energinet and Energistyrelsen [2012] in Fleiter et al. [2016]. Second, information about the state of the neighbourhood consists of the neighbourhood's annual natural gas consumption and cumulative costs, the number of each type of heating systems installed, and the number of dwellings with each insulation level in the neighbourhood. While agents cannot influence external factors, agent decisions influence the state of the neighbourhood: The neighbourhood's natural gas consumption is the sum of the natural gas consumption of all households, and the neighbourhood's cumulative costs is the sum of cumulative costs of all households.

In the model, the *time scale* is defined as one year per time step, and no *spatial scale* is defined. Agents are assumed to live in the same neighbourhood. At all times during a simulation run, each agent knows the number of agents that, by the end of the previous year, had each type of heating system and had each level of insulation.

PROCESS OVERVIEW AND SCHEDULING

In each year of the model, external factors change; agents' variable INV is updated to reflect the passage of time since their last investment; all agents give maintenance to their heating systems and use them to produce heat; and agents who are able to invest make investment decisions. Maintaining and operating their heating systems generates costs for agents and may require natural gas. These costs and natural gas consumption, when applicable, are added to agents' cumulative costs and natural gas consumption, respectively. Every agent who is able to invest selects their preferred insulation level and heating system, based on their individual decision rules. An investment generates costs for the agent, which are added to their cumulative costs. The neighbourhood's cumulative expenses and annual natural gas consumption are calculated.

3.3.3. EXPERIMENTAL DESIGN

We used the model to represent a neighbourhood in which, initially, all households had natural gas boilers and low insulation levels. We initialised the model with 24 agents that were not able to invest during the first 5 years. The number of agents and years before their first opportunity to invest were chosen arbitrarily and aimed at maintaining the simplicity of our illustrative example. The inability of agents to invest at the beginning of the simulation was designed to represent past investments and the potential need of agents to save before their next investment.

We used the model to simulate experimental scenarios over 20 years. The number of simulated years was chosen to be consistent with EU targets to reduce greenhouse gas emissions over the next few decades and the decision of the Netherlands to end natural gas extraction in Groningen in 2030. Additional details regarding initialization and input data for heating systems, insulation levels, and market prices are available in Appendix A.

Experimental scenarios represented variations in the environment and between agents. An experimental scenario consisted of five experimental variables, described in Table 3.2. The first two variables defined the environment: The annual percentage change in retail natural gas price (dgp) and the annual percentage change in the retail electricity price (dep). For example, in an experimental scenario with constant dgp (dgp = 0) and a dep of +4% (dep = 0.04), natural gas price remained constant, and electricity price increased by 4% every year. These variables can be considered to be proxies for both relevant market forces and policies, such as taxes or subsidies. The last three variables of an experimental scenario defined a population of agents: The fraction of agents in the model with an ACCI = 1 (popACCI), the HRZ shared by all agents (popHRZ), and the proportion of agents with each value orientation (popORI). PopORI consists of three fractions: First, the fraction of agents who are environmentally oriented; second, the fraction of agents who are socially oriented; third, the fraction of agents who are financially oriented. For example, in a population with popACCI = 1.00, popHRZ = 5, and popORI = [0.50, 0.25, 0.25], all households were able to compare combined investments, all households had a time horizon of 5 years, 50% of households were environmentally oriented, 25% were socially oriented, and 25% were financially oriented.

We used the model to simulate 756 experimental scenarios, which is the number of all possible combinations of variables in Table 3.3. Simplifications were made in the choice of variable values in order to maintain the simplicity of the illustrative example. In all experimental scenarios, all agents had the same HRZ, so that popHRZ = HRZ for all agents. Similarly, all agents had ACCI = 0 or ACCI = 1, so that popACCI = ACCI for all agents. Furthermore, a limited number of values for popORI, popACCI, popHRZ, dgp, and dep were tested. In the future, when using this model for a case study, the choice of values for experimental variables in scenarios should be modified based on the type of problem and modelling questions.

Simulation results and agent-based model are available as supplementary materials; see page 34.

Variable	Units	Description	Possible Values
dgp	%/year	Annual percentage change in the retail natural gas price	Real numbers
dep	%/year	Annual percentage change in the retail electricity price	Real numbers
popACCI	Dimensionless	Fraction of households in the population that is able to compare combined investments.	0 ≤ Fraction ≤ 1
popHRZ	Dimensionless	Time horizon shared by all households in the population, in years.	Positive integers
popORI	Dimensionless	Fraction of households in the population with each value orientation: Environmental (Env), social (Soc) and financial (Fin).	0≤Env,Soc,Fin≤1; [Env,Soc,Fin]; Env+Soc+Fin=1

Table 3.2: Experimental variables.

Type of Variation	Groups of Variations
dgp	−0.04, 0, 0.04
dep	−0.04, 0, 0.04
popORI	1=[0.33, 0.33, 0.33]; 2=[0.50, 0.25, 0.25]; 3=[0.25, 0.50, 0.25]; 4=[0.25, 0.25, 0.50]; 5=[1, 0, 0]; 6=[0, 1, 0]; 7=[0, 0, 1]
popACCI	0 and 1
popHRZ	1, 5, 10, 15, 20, 30

Table 3.3: Values of variables in experimental scenarios.

3.4. RESULTS AND DISCUSSION FROM THE ILLUSTRATIVE EXAMPLE

To analyse simulation results and answer the research question and modelling questions, we analysed the KPIs resulting from our 756 simulation runs: The annual natural gas consumption at the last time step of a simulation run and the cumulative costs of the neighbourhood in the model. Figure 3.1 is a scatterplot of these KPIs. In Figure 3.1, we observed that both annual natural gas consumption and cumulative costs varied between experimental scenarios. The transition to a natural gas-free neighbourhood was considered to be fully achieved when none of the agents consumed natural gas by year 20. In our simulation runs, this transition resulted in different cumulative costs, as indicated in Figure 3.1 by multiple dots over the vertical axis where annual natural gas consumption equals zero. Because of our simple experimental design and deterministic nature of our model, multiple experimental scenarios led to the same annual natural gas consumption and cumulative expenses. As a result, a single dot in Figure 3.1 and in the following plots could represent multiple overlapping dots.

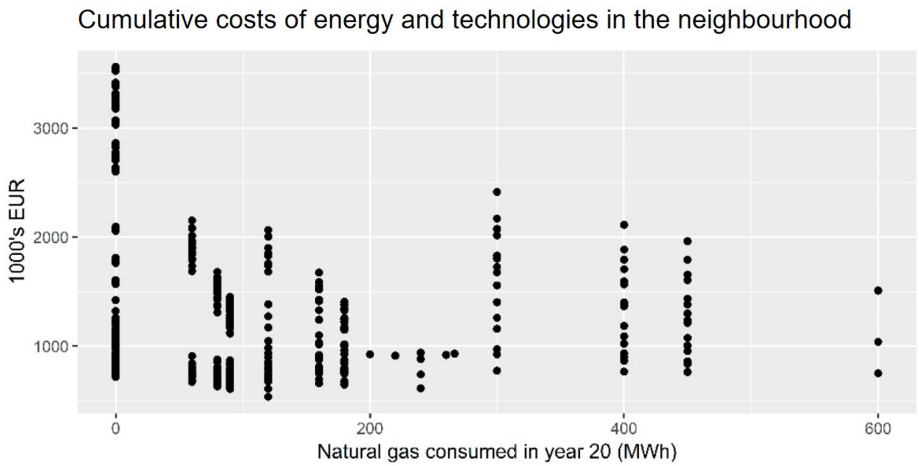


Figure 3.1: Scatterplot of cumulative costs of energy and technologies in the neighbourhood as a function of natural gas consumed in year 20, for all-simulation-runs. A single dot may represent multiple dots that overlap. Title is adapted with respect to Nava Guerrero et al. [2019].

We divided the set of results from all simulation runs in two subsets: "gas-free-subset" and "gas-dependent-subset". The gas-free-subset consisted of results from experimental scenarios where the transition was fully achieved. The gas-dependent-subset consisted of results from all other simulation runs. We named the complete set of results "all-simulations-runs".

A different approach would have been to study all experimental scenarios in which a given fraction of agents still consumed natural gas by the end of the simulation run. This would have allowed the analysis of conditions that led to a partial transition. This approach would be sensible when the model has stochasticity. Another approach would have been to study the entire data set. Because of the deterministic nature of our model, limited number of agents, and simple experimental design, we chose to study only experimental scenarios in which the transition was fully achieved.

As seen in Table 3.4, a complete transition occurred in only 128 (gas-free-subset) out of 756 simulation runs (all-simulation-runs), which accounts for less than 17.0% of all-simulation-runs. In the following subsections, we refer back to the subsets from Table 3.4 while answering the modelling questions.

Subset	Number of Scenarios	Definition
All-simulation-runs	756	Results from all simulation runs.
Gas-dependent-subset	628	Subset of all-simulation-runs in which the neighbourhood consumed natural gas in year 20, and thus did not achieve the transition to a gas-free neighbourhood.
Gas-free-subset	128	Subset of all-simulation-runs in which the neighbourhood did not consume natural gas in year 20, and thus fully achieved the thermal energy transition to a gas-free neighbourhood.

Table 3.4: Definition of dataset and subsets of results from simulations.

3.4.1. MODELLING QUESTION 1: SOCIO-TECHNICAL CONDITIONS

Figure 3.2 shows the neighbourhood's annual natural gas consumption by year 20 for all-simulation-runs. The boxplots from popORI = 1, 2, 3, 4, and 7 (see Table 3.3) show outliers with high ending natural gas consumption. These points belong to simulation runs from two types of experimental scenarios: First, those where popHRZ = 1, and second, those where popHRZ = 5 and natural gas price decreased. The horizontal line in popORI = 5 indicates that natural gas consumption in year 20 was always zero for simulation runs in this group, and therefore always in the gas-free-subset. Similarly, for popORI = 6, natural gas consumption was the same in every simulation run, and always in the gas-dependent-subset. In the remaining groups (popORI = 1, 2, 3, 4, and 7), the transition was fully achieved only when the popHRZ was 5 or 10 years, natural gas prices increased, and electricity price decreased. These findings are summarised in Table 3.5, where we present two sets of sufficient scenario conditions for simulation runs to be in the gas-free-subset.

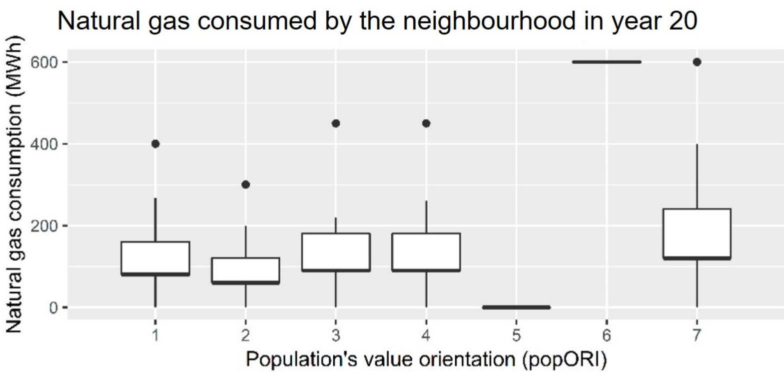


Figure 3.2: Boxplots of natural gas consumed by the neighbourhood in year 20 in all-simulation-runs, classified in population groups according to value orientation. PopORI: 1 = [0.33, 0.33, 0.33], 2 = [0.50, 0.25, 0.25], 3 = [0.25, 0.50, 0.25], 4 = [0.25, 0.25, 0.50], 5 = [1, 0, 0], 6 = [0, 1, 0], 7 = [0, 0, 1]. Title is adapted with respect to Nava Guerrero et al. [2019].

Type of Variation	Set 1	Set 2
popORI	5	1, 2, 3, 4, 7
popHRZ	–	5, 10
dgp	–	increasing
dep	–	decreasing

Table 3.5: Values of variables in experimental scenarios.

In set 1, the transition was always achieved because all agents decided to replace their boilers for gas-free alternatives, as they were programmed to be environmentally oriented. In all scenarios in set 2, some agents aimed to minimise their costs rather than their natural gas consumption, as they were financially oriented. In these simulation runs, by the time that agents chose natural gas-free technologies, natural gas price had increased, and electricity price had decreased. As a result, agents estimated that an option involving a natural gas-free technology would be cheaper. However, simulation runs that also had popHRZ > 10 were not part of the gas-free-subset, even when there were increasing natural gas prices and decreasing electricity prices. In those cases, agents were not able to make a second investment before the end of the simulation run: After making an investment, agents waited for a period equal to their HRZ before considering a new investment.

3.4.2. MODELLING QUESTION 2: COST OF THE TRANSITION

To determine how the transition would affect the costs of heating in the neighbourhood, we calculated the neighbourhood's cumulative costs of the gas-dependent-subset and gas-free-subset. Table 3.6 shows higher average and median cumulative costs for the gas-free-subset than for the gas-dependent-subset, and Figure 3.3, a wide range of values within the gas-free-subset. A Wilcoxon rank sum test showed that the distributions of the cumulative costs of the gas-free subset and gas-dependent subset were indeed different. We selected the Wilcoxon rank sum, a nonparametric test, because the assumption of normality, needed for a student-T test, was not met. Results from the Wilcoxon rank sum test and Shapiro-Wilk normality test are provided in Table 3.7.

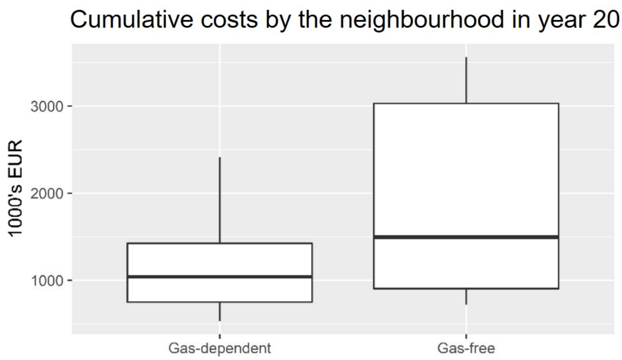


Figure 3.3: Cumulative costs by the neighbourhood in year 20, for all-simulation-runs, classified in gas-dependent and gas-free. Title is adapted with respect to Nava Guerrero et al. [2019].

Group	Number of Scenarios	Mean	Standard Deviation	Median	IQR[a]
All-simulation-runs	756	1238	640	1040	760
Gas-dependent-subset	628	1105	420	1040	676
Gas-free-subset	128	1889	1027	1495	2126

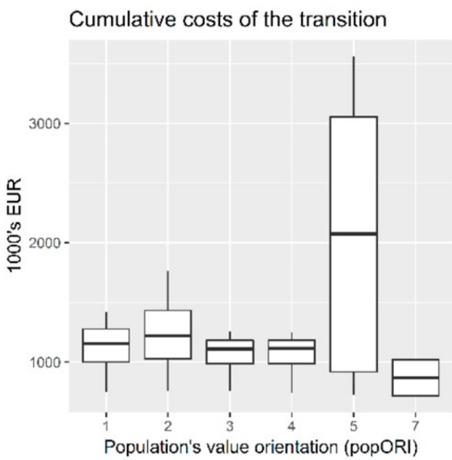
[a] IQR = Interquartile range

Table 3.6: Cumulative costs by the neighbourhood in year 20 (thousands of Euros).

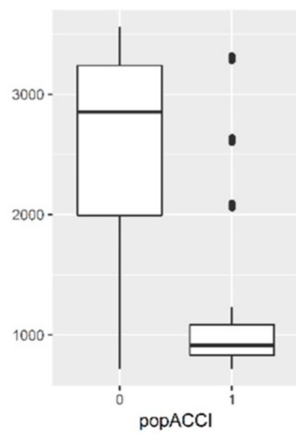
Test	Results	Conclusion
Wilcoxon rank sum test	W=22403, p-value=2.745e-15	Groups are not equal.
Shapiro-Wilk normality test	W=0.96395, p-value=1.077e-12	Normality cannot be assumed.

Table 3.7: Results from statistical tests for all-simulation-runs, grouped as gas-free or gas-dependent.

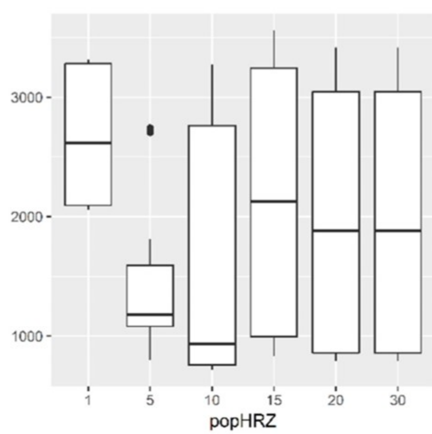
Because of the limited number of agents, our simple experimental design and the deterministic nature of the model, we limited further analyses to visual inspection of the plots. Figure 3.4 shows cumulative costs of the gas-free-subset, grouped by (a) popORI, (b) popACCI, and (c) popHRZ. Figure 3.4b-3.4c shows the outliers. In Figure 3.4b, outliers belong to simulation runs where popORI = 5 and popHRZ = 1. The three groups of outliers were produced by the three variations in the change of electricity price (increasing, constant, or decreasing). In Figure 3.4c, outliers belong to simulation runs where popORI = 5 and popACCI = 0.00.



(a) Grouped by popORI.



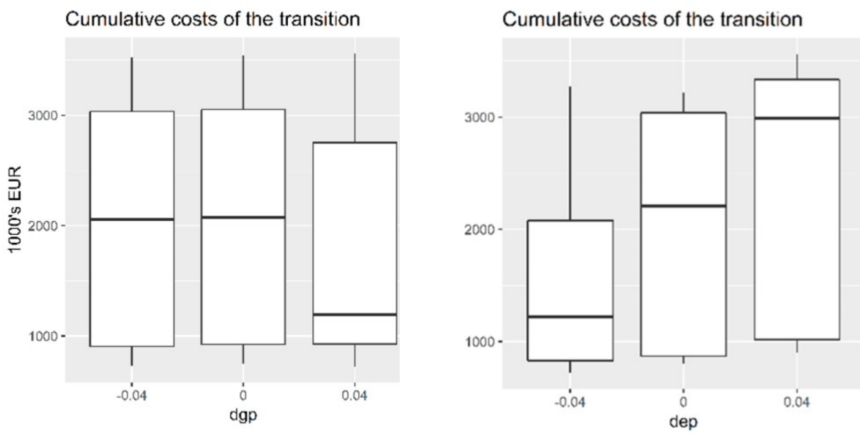
(b) Grouped by popACCI.



(c) Grouped by popHRZ.

Figure 3.4: Cumulative costs of the transition: Gas-free-subset, grouped by (a) popORI; (b) popACCI, and (c) popHRZ.

In Figure 3.4a, the boxplot for popORI = 5 shows a wider range of values than all other groups of popORI. A similar pattern can be observed in Figure 3.4c, where groups with popHRZ = 10, 15, 20, and 30 have a wider range of values. A possible and partial explanation for this wider range for simulation runs where popORI = 5 is that all simulation runs in this group are part of the gas-free subset (108 simulation runs), as opposed to four simulation runs with each of the other groups with different popORI (popORI = 1, 2, 3, 4, and 7). Finally, external factors may have also contributed to these differences, as in all simulation runs in the gas-free-subset where popORI ≠ 5 had increasing natural gas prices (positive dgp) and decreasing electricity prices (negative dep). Boxplots of the gas-free-subset grouped by these experimental variables are presented in Figure 3.5.



(a) Grouped by dgp. (b) Grouped by dep.

Figure 3.5: Cumulative costs of the transition: Gas-free-subset, grouped by (a) dgp and (b) dep.

Interaction effects between experimental variables could have resulted in different ranges of values between groups. Figure 3.6 is a grid of plots in which simulation runs from the gas-free-subset are classified according to popACCI, popORI, and popHRZ. Each plot in the grid displays cumulative costs for scenarios with a unique combination of popACCI and popORI. Within the same plot, simulation runs are grouped by popHRZ with a boxplot for each popHRZ. Plots for popORI ≠ 5 show points only for popHRZ = 5 and 10, as only simulation runs from these scenarios were part of the gas-free-subset, as summarised in Table 3.5..

Visual inspection of Figure 3.6. suggested that when popACCI = 0.00, a longer popHRZ resulted in higher cumulative costs. By contrast, when popACCI = 1.00, a longer popHRZ resulted in lower cumulative costs. These trends can be observed more clearly in the plots for popORI = 5 (fifth row from top to bottom). In Figure 3.4, the boxplot for popORI = 5 displays a wide range of values without revealing interaction effects of popHRZ and popACCI. By contrast, visual inspection of Figure 3.6 suggested that the interaction between popHRZ and popACCI influenced cumulative costs.

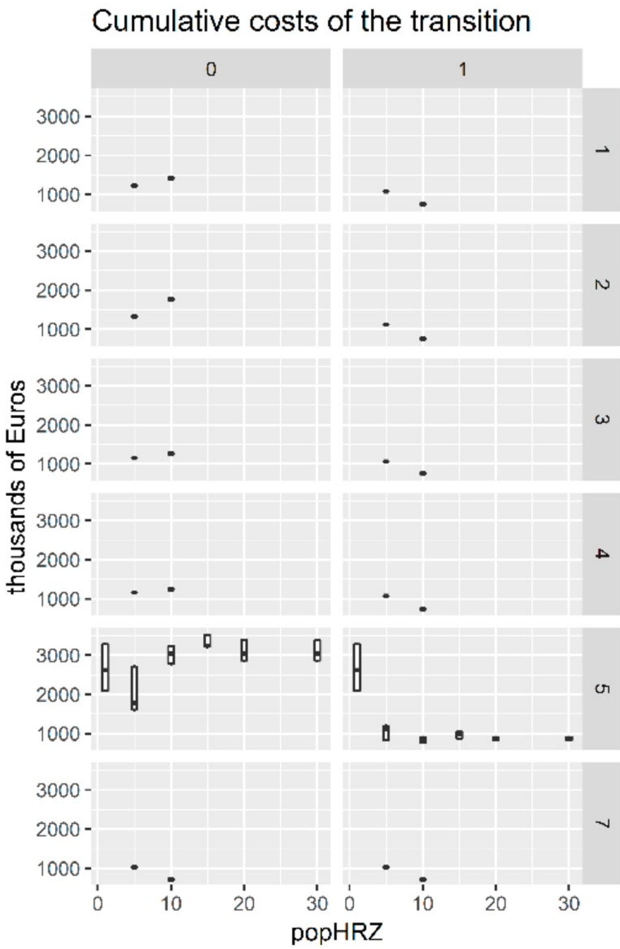


Figure 3.6: Cumulative costs of the transition (gas-free-subset). Each plot displays results from simulation runs with a unique combination of popACCI (grey labels on top of each column) and popORI (grey labels to the right of each row). In each plot, a boxplot is displayed for simulation runs with the same popHRZ, e.g., the plot in the top right corner displays simulation runs in which popACCI = 1.00 and popORI = 1, the first boxplot corresponds to popHRZ = 5, and the second one, to popHRZ = 10.

The combined effects of popACCI and popHRZ resulted from the modelling choices. When all agents were able to compare costs of combined investment options, agent's decisions may have more cost-effective results than when popACCI = 0.00. When popACCI = 1.00, agents could replace both their heating system and improve their insulation level at the same time. As a result, during the course of a simulation run, the combination of insulation and heating system that they chose could potentially keep the agents' costs lower than when agents were only able to choose either a change in insulation or a change in heating system. Since agents were not able to make a new investment before their HRZ elapsed, agents unable to make combined investment decisions would have no choice but to use a heating system and keep an insulation level that could result in higher costs.

3.4.3. MODELLING QUESTION 3: CHANGES IN TECHNOLOGY AND INSULATION

By the end of each simulation run, agents in all experimental scenarios of the gas-free-subset had either air heat pumps or radiators. Geothermal heat pumps were never chosen because they were perceived by agents as less cost-effective. Simulations where agents had either boilers or micro-CHPs in year 20 were always excluded from the gas-free-subset, as both heating systems used natural gas.

While all agents in all simulation runs in the gas-free subset had natural gas-free heating systems in the last time step, agents may have made multiple investment decisions before investing in the air heat pump or radiator that they had by year 20. Therefore, we considered the “pathways” of technological changes that occurred in the transition of each simulation run in the gas-free-subset. The “heating systems’ pathway” recorded the series of all changes in the number of heating systems of each type that took place in the neighbourhood over time in a simulation run. Similarly, the “insulation pathway” recorded the series of all changes in the number of dwellings with each insulation level that took place in the neighbourhood during the simulation.

Figure 3.7 and Figure 3.8 are grids of line plots of heating system and insulation pathways, respectively, of the gas-free-subset. In each grid, scenarios in the gas-free-subset are classified according to popHRZ and a combination of dgp, popACCI, and dep. The graph on the top right corner of Figure 3.7, for instance, shows the number of dwellings with each heating system over time in simulation runs where popHRZ = 30, dgp = −0.04, popACCI = 0.00, and dep = −0.04. In Figure 3.7, plots with a black frame indicate simulation runs where agents replaced their heating system more than once. In all but four line plots in each figure, the plots display results from only one simulation run, where popORI = 5. The four line plots with a blue frame each contain results from six simulation runs with the same dep, dpg, popHRZ, and popACCI but different popORI. Results in these plots correspond to simulation runs that met set 2 of sufficient scenario conditions from Table 3.5. Because each of these line plots displays results for more than one simulation run, their lines overlap or cross. Therefore, Figure 3.9 and 3.10 provide a zoom-in on these plots from both Figure 3.7 and Figure 3.8.

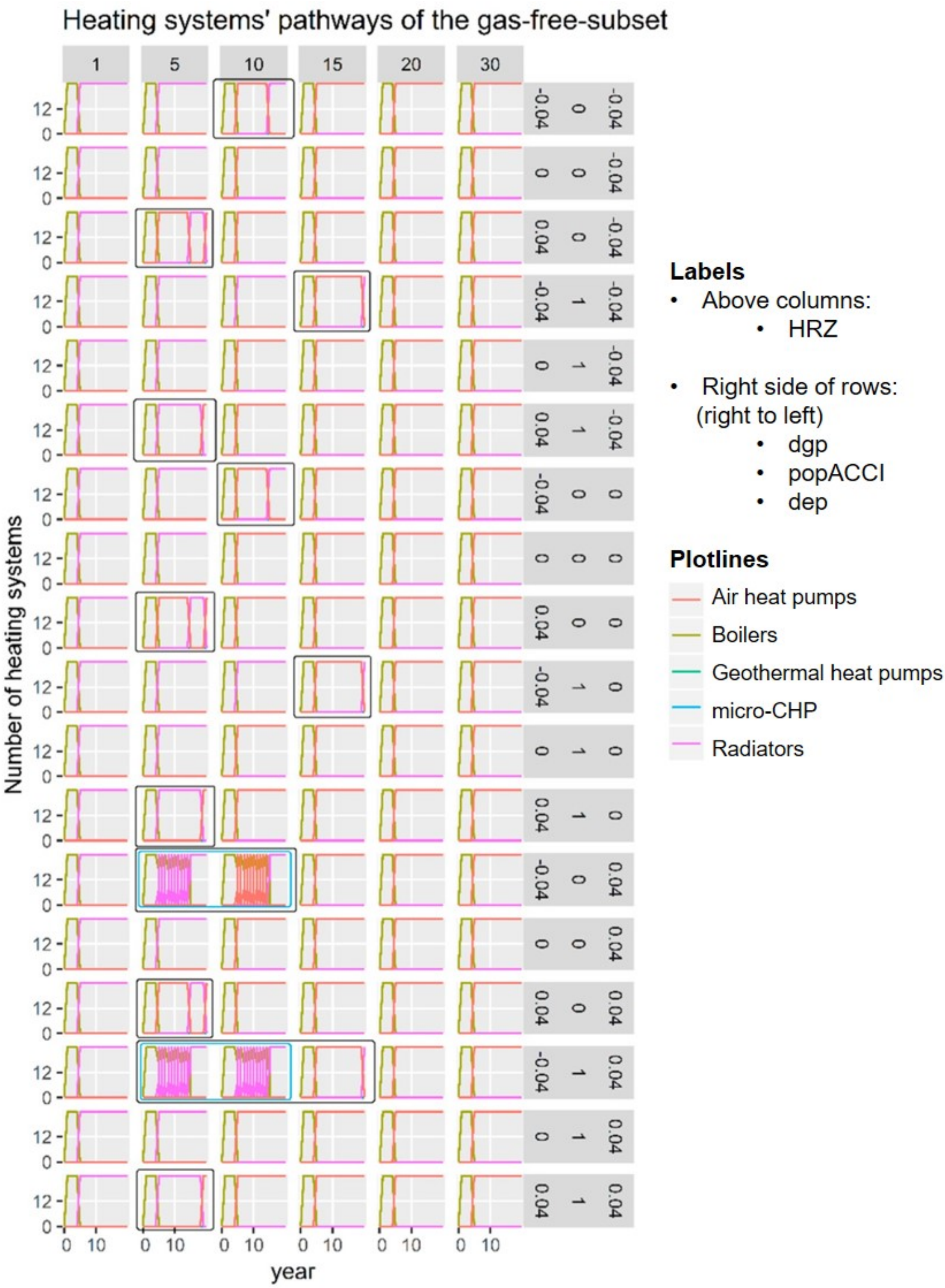


Figure 3.7: Heating system pathways of the gas-free-subset, classified by popHRZ (grey labels on top of each column) and a unique combination of dgp, popACCI, and dep (labels on the right side of each row). Each line plot shows the number of dwellings with each heating system over time. Blue frames indicate pathways from simulation runs where popORI = 1, 2, 3, 4, 5, or 7. Each plot without a blue frame contains only the pathway for popORI = 5. Black frames indicate pathways in which agents invested in heating systems more than one time during the simulation run. Legend is adapted with respect to Nava Guerrero et al. [2019].

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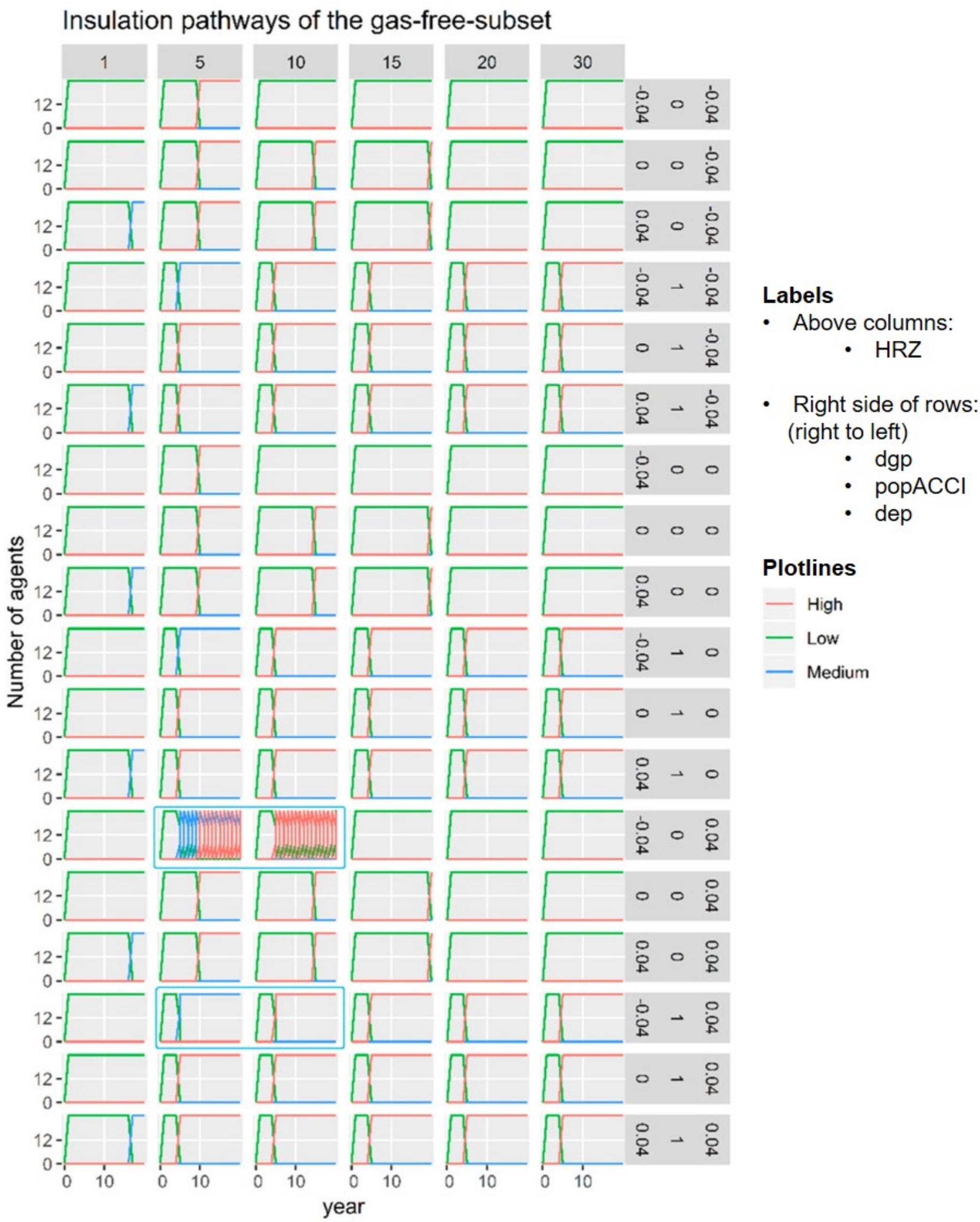

Figure 3.8: Insulation pathways of the gas-free-subset, classified by popHRZ (grey labels on top of each column) and a unique combination of dgp, popACCI, and dep (labels on the right side of each row). Each line plot shows the number of dwellings with each insulation level over time. Blue frames indicate pathways from simulation runs where popORI = 1, 2, 3, 4, 5, or 7. Each plot without a blue frame contains only the pathway for popORI = 5. Legend is adapted with respect to Nava Guerrero et al. [2019].

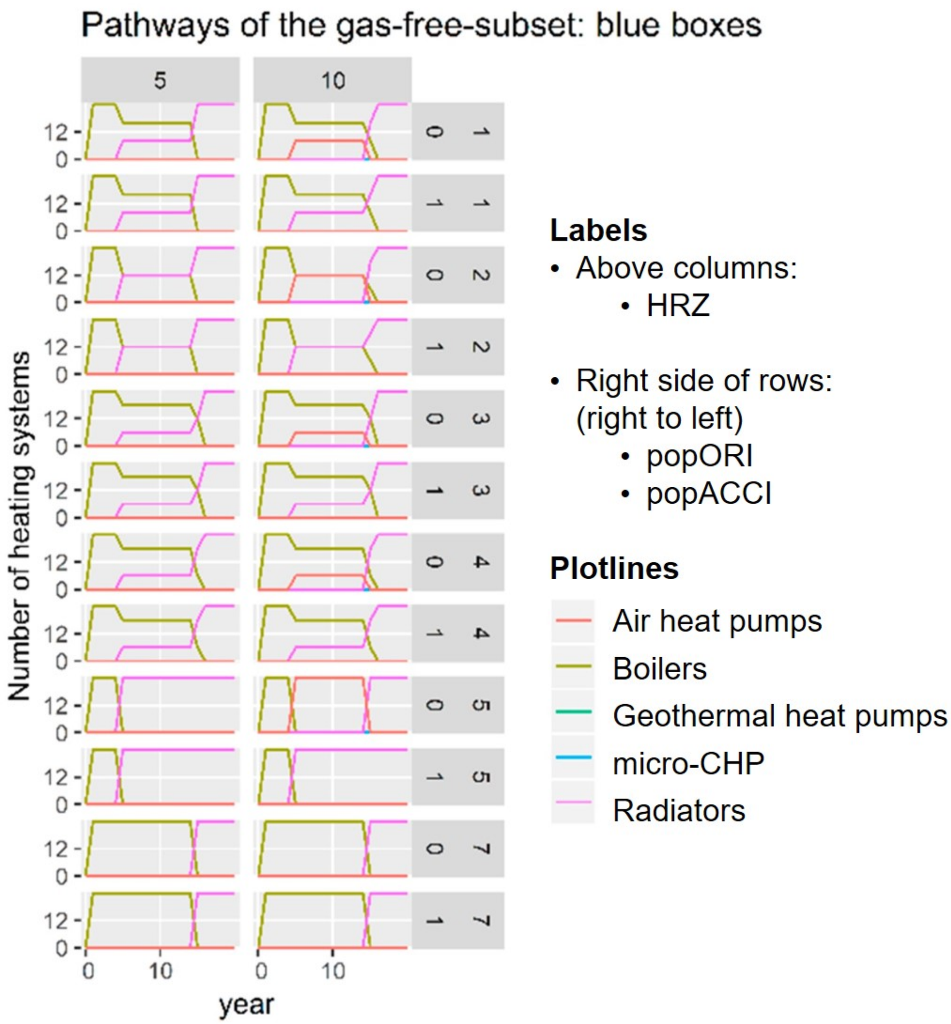

Figure 3.9: Pathways of the gas-free-subset when popHRZ = 5 or 10, dgp = 0.04, and dep = −0.04, classified by popHRZ (grey labels on top of each column) and a unique combination of popORI and popACCI (labels on the right side of each row). Each line plot shows the number of dwellings with each heating system over time. These plots are a zoom-in on the content of the blue frames in Figure 3.7. Legend is adapted with respect to Nava Guerrero et al. [2019].

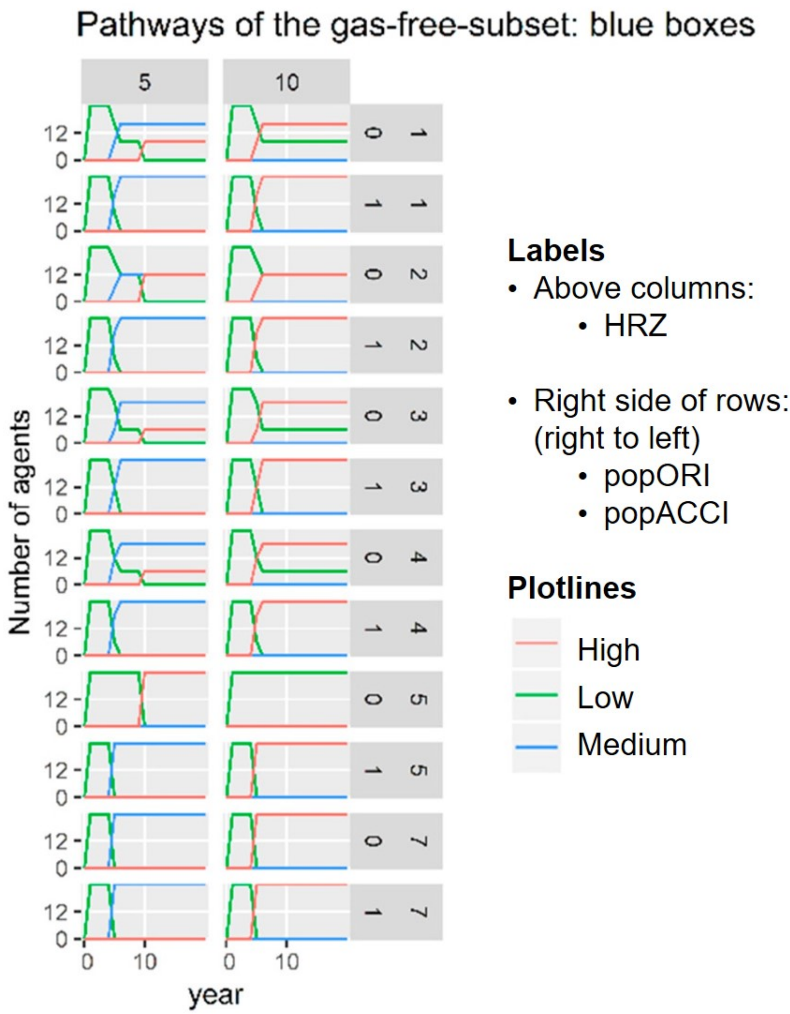

Figure 3.10: Pathways of the gas-free-subset when popHRZ = 5 or 10, dgp = 0.04, and dep = −0.04, classified by popHRZ (grey labels on top of each column) and a unique combination of popORI and popACCI (labels on the right side of each row). Each line plot shows the number of dwellings with each insulation level over time. These plots are a zoom-in on the content of the blue frames in Figure 3.8. Legend is adapted with respect to Nava Guerrero et al. [2019].

Visual inspection of Figure 3.7 and Figure 3.8 led to conclusions regarding choices in technology. Figure 3.7 suggests that under longer popHRZ, agents preferred air heat pumps, while in shorter ones, they preferred radiators. When popHRZ < 20, after an initial investment in year 5, agents were able to invest again before the end of the simulation run. In exceptional cases, agents chose to invest again in a heating system before the end of the simulation run. When agents considered an investment, they had no knowledge of future energy prices. As a result, their estimated costs were incorrect in simulation runs where energy prices changed. Agents could then decide to replace their technology for one that was more financially attractive after energy prices had changed. In turn, Figure 3.8 suggests that agents with ACCI = 1 tended to improve their insulation from low to high level early in the simulation run and that medium insulation was chosen in some cases by agents with shorter HRZ.

Simulation runs in which not all agents had the same popORI led to more complicated results than simulation runs where agents had the same popORI. Figure 3.9 and 3.10 show heating system and insulation pathways for experimental scenarios with popORI = 1, 2, 3, 4, 5, and 7. Line plots for popORI = 1, 2, 3, and 4 display more changes in technology and insulation than line plots for popORI = 5. Agents with different popORI made different decisions.

3.4.4. INTEGRATION AND DISCUSSION

As an illustrative example of the development and use of ABMs of thermal energy transitions in the built environment, we studied a residential neighbourhood's transition to natural gas-free heating from the perspectives of STS and CAS. The research question was: *Which socio-technical conditions support Dutch neighbourhoods' transition to natural gas-free heat supply by 2040 while meeting the neighbourhoods' heat demand?* We operationalised this research question into the following three modelling questions.

First, *in which scenarios did the neighbourhood transition fully to natural gas-free heating?* In Section 3.4.1, we identified the simulation runs in which the neighbourhood transitioned fully to natural gas-free heating. This transition occurred in simulation runs where all agents were environmentally oriented, and in simulation runs where four conditions were met: At least 25% of the agents were financially oriented, their time horizon was equal to 5 or 10 years, the natural gas price increased, and the electricity price decreased over time.

Second, *what is the cost of the transition in these scenarios?* In Section 3.4.2, we found that the median of the cumulative costs of the transition was higher than the median of the cumulative costs in simulation runs where the neighbourhood continued to use natural gas. We found indication of the costs of the transition being higher when agents were environmentally oriented. However, we also found indication of a wider range of values in the group of simulation runs of the gas-free-subset where all agents were environmentally oriented. A possible explanation of these differences is that in most experimental scenarios of the gas-free-subset, all agents were environmentally oriented, which meant that simulation runs where some agents were socially or financially oriented were underrepresented. A complementary explanation is the combined effect of agent ability to compare combined investments and their time horizon. When they were able to select more cost-effective alternatives, they enjoyed their benefits throughout the simulation run. When agents could only make less cost-effective choices, they were financially burdened.

Third, *which changes in insulation and heating systems took place during these transitions?* In Section 3.4.3, we found indication that agents with longer time horizons preferred heat pumps, while those with shorter time horizons preferred radiators. Agents with ACCI = 1 tended to change their insulation level from low to high early in the simulation run. Experimental scenarios in which not all agents had the same popORI led to more complicated results at the level of the neighbourhood, as agents made different decisions regarding heating systems and insulation.

We limited our analysis to simulation runs where no natural gas was consumed in the neighbourhood by year 20. This choice excluded experimental scenarios where, potentially, the majority of agents were using natural gas-free technologies. Alternative approaches would have been to select a threshold for natural gas consumption and study simulation runs below this threshold, or to study all results. In a future case study, this choice could be based on the research question and subquestions. Furthermore, our results included multiple ties. When using a model with agent heterogeneity and stochasticity, we would expect fewer ties in the results and more continuous distributions of results. Further statistical analysis would then be relevant while analyzing results.

Choices regarding the experimental design also influenced the conclusions that could be drawn from the study. First, to simplify our example, we explored limited and discrete variations of each experimental variable. Instead, continuous variations could reveal thresholds on which the behaviour of the model would change. Second, the experimental variables remained constant over each simulation run. This implied that agents did not learn from their decisions, from other agents, or from the environment. If time horizon, value orientation, or ability to compare combined investments changed over a simulation run, different behaviour could be observed. Similarly, different changes in electricity and natural gas prices every year would reflect the uncertain nature of these factors. Third, agents in the same experimental scenario were rather homogeneous. Their only difference, in some scenarios, was their value orientation. Agents also had the same heating system and insulation level at the beginning of all simulation runs. Instead, the model could be used to simulate heterogeneity between and within simulation runs. The simulation time also affected the results. Agents with time horizons longer than 15 years were not able to invest more than one time. A longer simulation time could lead to a larger gas-free-subset.

Additional assumptions and simplifications concerned agents and technology. Agents were not able to forecast market prices: They compared their investment options using prices from the present year. Ability to make forecasts about market prices could be included. After an investment, agents did not invest during a period equal to their time horizon. This means that agents in the model could go as long as 20 years without an investment. This could be modified to allow agents to invest after shorter periods. Social agents were influenced by other households through a basic representation of a social effect. Instead, a network structure and decision-making theories could be integrated in the model, and special scales could be explicitly defined. This would allow the spatial location of agents to play a role in the information that the agent is able to access. At any time during a simulation run, agents had knowledge regarding technologies and insulation levels in the neighbourhood from the end of the previous year. Incomplete information about the neighbourhood could be included. Technologies did not age and agents had no incentive to replace an old heating system for a new heating system of the same type. Including a decrease on the performance of heating systems would be a way of representing an incentive for such a change. Similarly, only four types of technologies were available to agents, and any type of technology could be used in any dwelling. Additional constraints could be added to represent conditions such as heat pumps requiring higher insulation levels. Moreover, the only technology with a changing price in the model was micro-CHPs. However, different prices could be accounted for. Demand in the model was constant and not influenced by consumer behaviour. The effect of household behaviour on heat demand could be represented. Lastly, the model was deterministic. Stochastic elements could be included to represent uncertainty. In a case study, these assumptions and simplifications could be explored further, and sensitivity analyses could be conducted.

Finally, the main question of our illustrative example was: *Which socio-technical conditions support the Dutch neighbourhoods' transition from natural gas-based to natural gas-free heat supply until 2040 while meeting the neighbourhoods' heat demand?* Natural gas-free heating was achieved when all households were environmentally oriented and when the time horizon was 5 or 10 and electricity price decreased, and natural gas decreased. The ability to compare combinations of insulation and heating systems made room for more cost-effective decisions. When households had this ability, longer time horizons resulted in lower costs, and when agents did not have this ability, longer time horizons resulted in higher costs. These results could serve as input for the design of a case study.

3.5. CONCLUSIONS

In this chapter, we addressed the first sub-question of this dissertation, which is: *How to explore the influence of homeowners' decisions regarding investment in heating systems and insulation measures on the heat transition in the Netherlands?* We presented an illustrative example of agent-based modelling of thermal energy transitions in the built environment. We developed and used this model from the perspective of STS and CAS. In the illustrative example, we observed natural gas consumption and cumulative costs in a residential neighbourhood. The neighbourhood's natural gas consumption and cumulative costs changed as a function of individual decisions of households. Households could improve their dwellings' insulation or replace their heating system. Actors were households, technology consisted of dwellings' insulation level and heating systems, and institutions were implicit in changes in energy prices, the sunsetting of natural gas boilers, and households' ability to compare combinations of heating systems and insulation levels, which was a proxy for the impact of an information campaign about cost-effective investments.

While the illustrative example and its model were intentionally simple and its results were straightforward, they contained key elements of agent-based modelling. First, agents had bounded rationality: They were not always able to select cost-effective alternatives and they did not have knowledge of future energy price or technology prices. Second, a social network effect was incorporated in a simple way: Social agents reacted after observing their neighbors' actions when some conditions were met. Third, the system had no central control: Transition at the level of the neighbourhood depended on individual choices of households. Finally, agents reacted to their environment and influenced it: Changes in prices influenced agent decisions and, in turn, their decisions influenced the neighbourhood's transition.

By developing and using ABMs from the perspective of STS and CAS, we can gain insights regarding the interactions between actors, institutions, and technology. Forthcoming work will address case studies of thermal energy transitions in the built environment. Our illustrative model can be used as a starting point to collaborate with stakeholders and modify simplifications, assumptions, experimental design, and analysis of results.

3.6. ACKNOWLEDGEMENTS

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3.7. APPENDIX A. ADDITIONAL DESCRIPTION OF THE ABM, BASED ON THE ODD PROTOCOL

3.7.1. DESIGN CONCEPTS

- *Basic principle:* The neighbourhood's cumulative costs and annual natural gas consumption results from individual decisions of households to use and replace their technology. Those decisions are based on some of agents' state variables and external factors.

- *Emergence:* The neighbourhood's cumulative costs, annual natural gas consumption, number of heating systems of each type, and insulation levels.

- *Adaptation:* While households use current retail energy prices to select the heating system and insulation level that best meets their objectives, their state variables HRZ, ORI, THR, and ACCI remain constant during a simulation run.

- *Objectives:* Households are either natural gas minimisers (environmentally oriented) or cumulative cost minimisers (financially and socially oriented). Socially-oriented agents act only if a fraction of their peers has acted.

- *Learning/prediction:* Households do not use learning mechanisms nor forecasting. They assume that the current retail energy prices will remain constant.

- *Sensing:* Households are assumed to know the present price of heating systems, insulation levels, electricity and natural gas, and the number of heating systems of each type, and insulation levels in the neighbourhood by the end of the previous year.

- *Interaction:* Socially-oriented households consider replacing their heating systems or improving their insulation only when a fraction of their peers has also made changes.
- *Stochasticity:* While the model is initialised stochastically, all properties of households but one are assigned deterministically (value orientation: ORI). Therefore, households are identical except for their value orientation. As a result, stochastic initialization does not have an effect on model outcomes.
- *Collectives:* The model does not account for aggregations between households. An example of aggregation would be multiple households investing together in one heating system to meet their heat demand.
- *Observation:* The neighbourhood's cumulative costs, annual natural gas consumption, number of heating systems of each type, and insulation levels are the variables used for observing system level behaviour.

3.7.2. Initialization

A total of 24 households with low insulation level and 24 natural gas boilers are initialised. While dwellings are conceptualised as objects, for simplicity, in the NetLogo [Wilensky, 1999] implementation, insulation level is a state of each household.

Throughout the simulation, agents have the same HRZ, ORI, THR, and ACCI. In all scenarios, THR has a value of 0.30. Depending on the experimental scenario, different fractions of those households are environmentally, financially, or socially oriented (ORI).

3.7.3. Input data

The model uses input data for retail energy prices (Table 3.8), heating systems (Table 3.9) and insulation levels (Table 3.10).

Parameter	Value	Source
Retail natural gas prices for the first year [Euro/kWh]	0.08	Based on [Eurostat, n.d.b]
Retail electricity prices for the first year [Euro/kWh]	0.16	Based on [Eurostat, n.d.a]

Table 3.8: Input data for retail energy prices from year 2016.

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Parameter	Value for Each Type of Technology	Source
Thermal efficiency [dmnl]	1, 0.60, 1, 2.6, 3.3	Assumptions and [Fleiter et al., 2016]
Electrical efficiency [dmnl]	0, 0.28, 0, 0, 0	Assumptions and [Fleiter et al., 2016]
Capital costs [€/kW]	0, 2100, 300, 1130, 1675	Assumptions and [Fleiter et al., 2016]
Annual maintenance costs per kW of capacity [€/year per kW]	11.18, 42, 10, 22.6, 33.5	Assumptions and [Fleiter et al., 2016][a]

[a] Fleiter et al. [2016] refer to annual costs of operation and maintenance as a single category of costs that is a percentage of the investment costs. We use numbers from their overview as inputs in our assumptions; for simplicity, we assume that those numbers correspond only to annual maintenance costs (AMC from Equation 3.5 on page 41). In addition to AMC, we define operation costs as energy costs (EC in Equation 3.2 on page 40) and estimate EC separately.

Table 3.9: Input data for technologies, per technology: Natural gas boiler, micro-CHP, electric radiators, air heat pumps, and geothermal heat pumps.

Parameter	Value for Each Level	Source
Capacity required from a technology to meet demand [kW]	15, 8, 5	Assumptions
Capital costs when dwellings have low level [€]	NA *, 5500, 10000	Assumptions
Capital costs when dwellings have medium level [€]	NA *, NA *, 6000	Assumptions
Heat demand [kWh]	25000, 10000, 5000	Assumptions

Table 3.10: Input data for insulation levels, per dwelling: Low, medium and high.

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4

Exploring the effect of group decisions on heat transitions

Abstract

The Netherlands aims at reducing natural gas consumption for heating in the housing sector. Although homeowners are responsible for replacing their heating systems and improving dwelling insulation, they are not always able to make individual decisions. Some projects require group decisions within and between buildings. We use an agent-based modelling and simulation approach to explore how these individual and group decisions would influence natural gas consumption and heating costs in an illustrative neighbourhood, under a set of assumptions. We model the combination of insulation and heating system that households would prefer as the outcome of a lifetime-cost calculation with implicit discount rates, and we use quorum constraints to represent group decisions. We model three fiscal policies and a policy to disconnect all dwellings from the natural gas network. Results show that the disconnection policy was the only necessary and sufficient condition to incentivise households to replace their heating systems and that group decisions influenced the alternatives that were chosen. Since results were influenced by group decisions within buildings and by the market discount rate, we recommend further research regarding policies around these topics. Future work can apply our approach to case studies, incorporate new empirical knowledge, and explore group decisions in other contexts.

Keywords: strata buildings; homeowner associations (HOA); implicit discount rate (IDR); group decision-making; technology adoption; quorum constraints.

A version of this chapter has been published as a journal article in Energy Policy [Nava-Guerrero et al., 2021]. The first author, who is also the author of this dissertation, conceptualised and performed the research. The other authors have performed an advisory role.
Parts of this chapter refer to article Moncada et al. [2017]; the author of this dissertation and Prof.dr.ir. Zofia Lukszo (one of her promotors) are two of the authors of such article.

SUPPLEMENTARY MATERIALS

- **Nava-Guerrero, G. D. C.**, Hansen, H. H., Korevaar, G., & Lukszo, Z. (2022). Agent-based model described in journal article "The effect of group decisions in heat transitions: An agent-based approach". Publisher of agent-based model: 4TU Repository. DOI of agent-based model: `https://doi.org/10.4121/18865415`
- **Nava-Guerrero, G. D. C.**, Hansen, H. H., Korevaar, G., & Lukszo, Z. (2022). Supplementary data for journal article "The effect of group decisions in heat transitions: An agent-based approach". Publisher of supplementary data: 4TU Repository. DOI of supplementary data: `https://doi.org/10.4121/18865385`

4.1. INTRODUCTION

A heat transition is taking place in the Netherlands. Natural gas is widely used in the country to heat the built environment [Beurskens and Menkveld, 2009]. However, the national government has the ambition of reducing the consumption of this fuel over time [Rijksoverheid, 2019c]. Since July 2018, buildings with a relatively low energy consumption for space heating, i.e. houses and small commercial buildings, should be built without being connected to the natural gas grid [RVO, n.d.]. Moreover, the national government aims at making all existing homes free of natural gas by 2050 [Rijksoverheid, 2019c]. These goals are in line with those of the European Union to improve the energy performance of buildings and increase the share of renewable energy sources that are used to heat the built environment [European Commission, 2016].

To enable this transition, national authorities are revising laws and policies. For instance, a new version of the Heat Act [2019], which concerns heat networks, was approved in 2019 [Lavrijssen and Vitez, 2019]; a Heat Act 2.0 is also expected [Rijksoverheid, 2019b]. Another example is the adjustment of fiscal policies. In 2020, taxes on natural gas and electricity increased and decreased, respectively, compared to their values in 2019 [Rijksoverheid, 2019a]. Price caps for heat delivered by heat networks are also being revised. Until now, regulatory authorities have set heat price caps that depend on the price of natural gas; however, authorities are now revising such caps and considering their potential decoupling from the natural gas price [Voortgangsoverleg Klimaatakkoord, 2019]. In addition, public and private actors produced the Climate Agreement, a document with climate-related measures for the coming years [Rijksoverheid, 2019d].

Nevertheless, the responsibility to formulate heat transition plans lies at the local level. Since 2019, an amendment to The Dutch Crisis and Recovery Act [2020] allows municipalities to carry out experiments to phase out natural gas in areas such as testing grounds [PAW, 2019]. A testing ground, or "proeftuin" in the Dutch language, is a location where a group of households organise and receive a contribution from the central government to test solutions for the transition towards a natural gas-free future [PAW, n.d.]. Moreover, municipalities are required to prepare visions for their local heat transition before 2022 [Rijksoverheid, 2016]. In accordance with the Climate Agreement, local authorities are organizing at a regional level to achieve this goal. Municipalities were grouped in 30 regions, and each region is to prepare a Regional Energy Strategy (RES) for the transition [Rijksoverheid, 2019d].

The implementation of a RES will not be trivial: it will require multiple actors to coordinate their decisions. In the housing sector, individual owners and groups of owners would have to make joint decisions. Building owners are responsible for investments to improve energy efficiency and replace heating systems [Filippidou et al., 2017]. However, they are not always able to start a project on their own. Projects such as heat networks (or their expansion) require sufficient heat demand in order to be feasible or remain affordable [Lund et al., 2014, Mahapatra and Gustavsson, 2009]; therefore, such projects would require building owners to coordinate their decisions.

A second complication is that some buildings, known as strata buildings, consist of multiple dwellings and can have more than one owner. Owners must organise in homeowner associations (HOA, in Dutch language called Vereniging van Eigenaren), which are regulated by the Book 5 of the Civil Code [2018] and by the HOA's individual deed of division. Formally, members make group decisions using voting systems with quorums; therefore, owners of dwellings in strata buildings are responsible for individual investments as well as for reaching agreements regarding joint investments in energy efficiency [Roodenrijs et al., 2020]. As a result, depending on the scope of a RES, its implementation would require group decisions within and between HOAs, and potentially, between neighbourhoods.

It follows that group decision-making is a key aspect of energy transitions because it can constrain household individual decisions. However, literature exploring this phenomenon is limited and studies often focus on individual decision-makers [Roodenrijs et al., 2020]. For instance, Klöckner and Nayum [2017] explore psychological and structural facilitators and barriers to energy upgrades by private households in Norway, but they exclude households living in strata buildings. Michelsen and Madlener [2013] investigate motivational factors behind homeowner's decisions between residential heating systems in Germany, but exclude households living in multi-family dwellings, classified as more than two dwellings. In an empirical analysis of the decision-making process of homeowners for energy renovation measures in the Netherlands, Broers et al. [2019] exclude condominiums. The focus on individual decision-makers rather than strata buildings extends to agent-based modelling and simulation studies, which we discuss in Section 4.2.

Our aim is to explore how group decision-making in strata buildings could affect the heat transition in the owner-occupied share of the housing sector in the Netherlands. Since new buildings must comply with energy performance standards and are therefore built without a natural gas connection, we focus on the stock of buildings that currently uses natural gas for heating. We study the problem at the level of a neighbourhood and its HOAs. Our main research question is:

How could individual and group decisions between building owners, and within HOAs in strata buildings, influence the course of the heat transition in a neighbourhood in the Netherlands, under different policy interventions?

We explore the question from a computational modelling and simulation approach. In particular, we use an agent-based approach that we proposed in Moncada et al. [2017], Nava Guerrero et al. [2019], which is based on the perspectives of socio-technical systems (STS) and complex adaptive systems (CAS). We conceptualise and build a computational model to explore possible developments in an illustrative neighbourhood over time, under a set of assumptions regarding households' decision-making. We conceptualised the illustrative neighbourhood by including dwelling features that are present in the Dutch residential built environment. We observe whether households disconnect from natural gas, what their heating costs are, and whether their individual decisions are influenced by group decisions.

The remaining parts of this chapter are structured as follows. In Section 4.2, we discuss knowledge gaps in agent-based studies of energy transitions. We further explain our research approach in Section 4.3 and present our agent-based model (ABM) in Section 4.4. Then, in Section 4.5, we present results and discussion. Finally, in Section 4.6, we conclude by answering the main research question and discussing policy implications.

4.2. KNOWLEDGE GAPS IN ABMS OF ENERGY TRANSITIONS

As explained in our previous work [Moncada et al., 2017, Nava Guerrero et al., 2019], we use the perspectives of STS [Cooper and Foster, 1971, Herder et al., 2008, Trist, 1981] and CAS [Holland, 1988, Waldorp, 1993] throughout our work. These perspectives allow us to describe the multi-actor and multi-level nature of the heat transitions. Through the lens of STS, actors are individuals and organizations [Enserink et al., 2010] who make decisions and affect each other or the system. They may cooperate or compete [Bengtsson and Kock, 1999], and might have bounded rationality [March, 1978, Simon, 1997]. Actors and technology are described as networks with complex interactions, which take place under rules and regulations, defined as institutions [North and Macal, 2007]. Through the lens of CAS, actors can be conceptualised as agents, i.e. low-level components of a system whose actions, interactions, and reactions lead to the system's behaviour.

Both STS and CAS are used in agent-based modelling, a method for computational modelling and simulation in which systems are represented through knowledge of (assumed) behaviour of individual agents [Borshchev and Filippov, 2004, Grimm and Railsback, 2005, North and Macal, 2007, Railsback and Grimm, 2019]. An ABM has agents, environment, and time [Dam et al., 2013]. Agents represent actors, exist within the environment [van Dam, 2009], and are described at any time by their state, i.e. a set of parameters or state variables [Grimm et al., 2010, Wooldridge and Jennings, 1995]. Agents and environment are influenced by their current and previous states and those of each other.

Although agent-based modelling has been widely used to model and simulate energy transitions due to its suitability for representing STS and CAS [Li et al., 2015], in this work, we seek to address the following three knowledge gaps within ABMs of adoption of technologies.

First, as noted by Hansen et al. [2019], studies have seldom had an explicit or exclusive focus on the heating sector. Authors have focused on inquiries regarding the electricity sector and fewer studies have investigated the adoption of either heating systems or insulation measures. Some exceptions include the exploration of competing micro-CHP and incumbent condensing boilers by Faber et al. [2010], insulation activity by Friege [2016], wood-pellet heating by Maya Sopha et al. [2011, 2013], heat pumps by Snape et al. [2015], and a neighbourhood's transition towards heating without natural gas in our earlier work Nava Guerrero et al. [2019].

Second, as noted by Hesselink and Chappin [2019], studies have seldom explored the adoption of multiple and competing technologies. Instead, works have usually explored the adoption of individual technologies, e.g. photovoltaic cells. Some exceptions include the previously mentioned work by Faber et al. [2010] and the works by Mittal et al. [2019a] and Mittal et al. [2019b]. The latter two concern multiple solar-based energy models in the context of residential renewable energy systems and zero energy communities, respectively. Another exception is our earlier work Nava Guerrero et al. [2019], which includes competing combinations of heating systems (micro-CHPs, electric radiators, air heat pumps, and geothermal heat-pumps) and insulation measures.

Third, to the best of our knowledge, group decision-making within and between HOAs has not yet been explicitly incorporated in ABMs of energy transitions. Instead, authors have represented other ways in which households influence each other's decisions. As noted in the review by Hesselink and Chappin [2019], authors have often used social network theory to model the spread of information, perception, or innovations. Examples include the previously mentioned Friege [2016], Maya Sopha et al. [2011] and Maya Sopha et al. [2013], and Mittal et al. [2019a] and Mittal et al. [2019b], to mention a few. Similarly, authors have accounted for social factors without the explicit use of network theory. For instance, Snape et al. [2015] model a distribution of positive and negative opinions as a proxy for a local social network influence. Similarly, in Nava Guerrero et al. [2019], agents that are socially oriented are triggered to adopt a technology when a fraction of their peers has also changed its technology.

Moreover, instead of modelling group decisions to collectively adopt a technology, authors have limited the technology options that are available to households in strata buildings. For instance, from the previous works, Mittal et al. [2019a] explore household adoption of different renewable energy models. They distinguish households, which are agents, as home-owners, tenants, and apartment-owners. They assume that both tenants and apartment-owners are unable to buy or lease rooftop PV panels, and that only 57% of house-owners are able to do so due to physical constraints of the building.

Busch et al. [2017] model the emergence of heat networks as a multi-actor and multi-stage process that can be instigated, for example, by a community organisation. In their model, density of demand, among others, influences the feasibility of heat network projects. Their implementation depends on factors such as the capabilities of their instigator (which is an agent) and whether sufficient heat demand remains available.

We address these knowledge gaps in the following ways. First, we have an explicit focus on heat provision in the owner-occupied share of the housing sector. Second, we include multiple and competing combinations of heating systems and insulation measures. Third, we propose a way to account for the effects of group decisions in strata buildings on the transition towards heating without natural gas.

4.3. RESEARCH APPROACH

Our approach consists of three steps, as proposed in Moncada et al. [2017], Nava Guerrero et al. [2019]. First, we structure the problem in terms of actors, technology, institutions, and interactions. Second, we conceptualise and formalise an agent-based model (ABM). Finally, we use the ABM to simulate changes to heating systems and insulation levels in the illustrative neighbourhood over 30 years. The simulation and analysis of results was guided by the following sub-questions:

1. In an ABM of an illustrative neighbourhood in the Netherlands,
   - how to represent individual household preferences?
   - how to represent group decisions between and within HOAs?
2. Under which socio-technical conditions would the illustrative neighbourhood phase out natural gas?
3. Under different socio-technical conditions:
   - how would the combinations of heating systems and insulation measures that households prefer vary?
   - how would the combinations of heating systems and insulation measures that result from individual household and group decisions vary?
   - how would the costs of the transition vary?

The ABM represents an illustrative neighbourhood that includes dwelling features that are present in the residential built environment in the Netherlands, as described in Section 4.4.2. The model is parameterised using desk research, estimates, and assumptions. When applying our ABM to specific neighbourhoods, parameters and assumptions can be validated on a case by case basis.

We implement the ABM using the NetLogo software (version 6.0.4) [Wilensky, 1999].

We analyse simulation results using the statistical computing software R Project (version 3.6.2) [R Core Team, 2018] through R Studio (version 1.1.463) [RStudio Team, 2018], where we loaded the packages ggplot2 (version 3.2.1) [Wickham, 2016] and $sqldf_0$.4–11 [Grothendieck, 2017]. Our analysis consists of visual inspection of numerical trends. As validation, we conduct a sensitivity analysis and consult expert publications and news.

4.4. AGENT-BASED MODELLING OF HEAT TRANSITIONS

4.4.1. HEAT TRANSITIONS IN THE DUTCH HOUSING SECTOR AS A STRUCTURED PROBLEM

In this section, we present our conceptualization of heat transitions in the owner-occupied share of the Dutch housing sector, at the level of one neighbourhood, from the perspectives of STS and CAS. We illustrate this view in Figure 4.1, and describe it below.

First, we conceptualise technology as dwellings, buildings, and external infrastructure. Some dwellings are independent buildings, such as terraced houses, and others are part of strata buildings, such as apartments. Each dwelling has an insulation level, a heating system, and heat-related appliances, such as stoves. Dwellings are connected to external infrastructure: the natural gas network to fuel their heating systems and appliances, and the electricity network. Dwellings can also be connected to a heat network. In Figure 4.1, technology is part of the technical subsystem, in green.

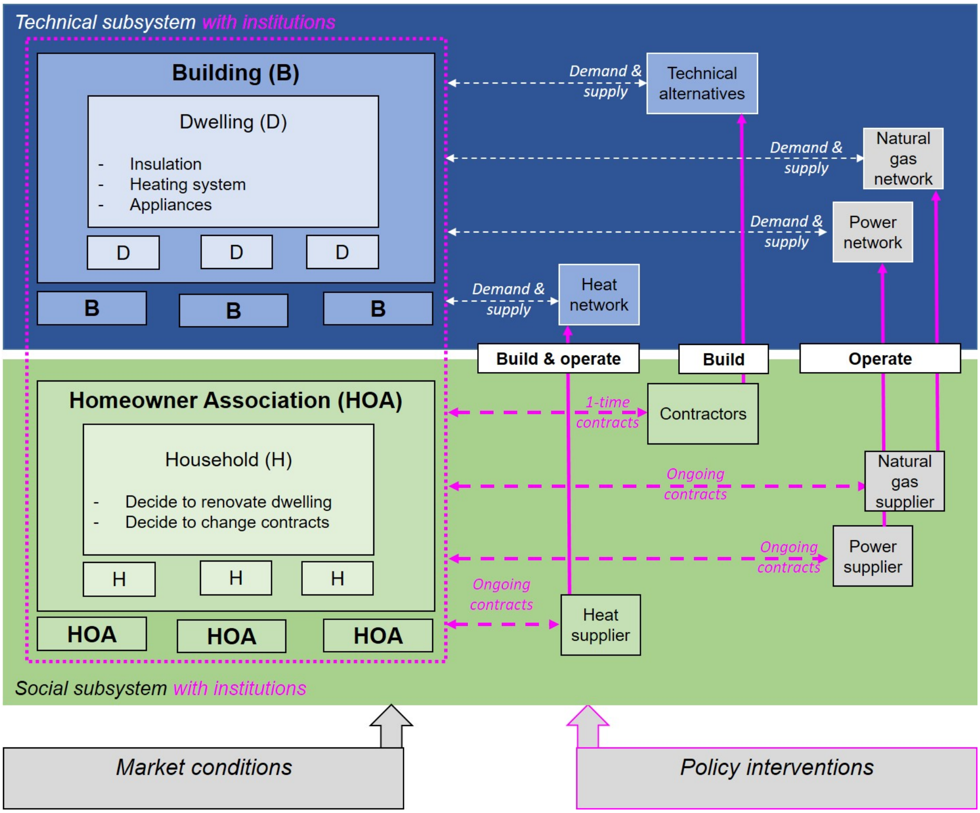

Figure 4.1: Illustration of our view of the problem at the level of one neighbourhood, from the perspective of STS and CAS.

Second, we conceptualise actors as households, energy suppliers, and contractors. Households in strata buildings are grouped in HOAs. Energy suppliers include suppliers of natural gas, electricity, and heat from networks. Contractors sell and install heating systems and insulation measures in dwellings. In Figure 4.1, actors are part of the social subsystem, in blue.

Third, we conceptualise institutions as contracts between households and suppliers and between households and contractors, regulations within and between HOAs, and public policy interventions. Institutions permeate both the technical and social subsystems. In Figure 4.1, they are illustrated in magenta.

Policy interventions are included at the bottom-right of Figure 4.1 and are external to the neighbourhood, i.e. they influence the social and technical sub-systems but these sub-systems do not influence the policies. Market conditions, i.e. prices of energy, heating systems, and insulation measures, are external factors for the same reason.

4

4.4.2. MODEL DESCRIPTION

The description of the ABM is based on the ODD protocol by Grimm et al. [2010], which has been found useful to clarify content and features, and to provide input for further analysis. Accordingly, we present a model overview, design concepts, and details.

MODEL OVERVIEW

Purpose. The purpose of this ABM is to explore how group decisions by households could influence household adoption of competing combinations of insulation measures and heating systems without natural gas under policy interventions. We explore a residential and owner-occupied illustrative neighbourhood with independent and strata buildings, where households have perfect or bounded financial rationality.

We use the key performance indicators (KPIs) from Table 4.1 to measure the influence of group decisions on natural gas connections and use, heating costs, and "group lock out". A household has group lock out when it was not able to adopt its preferred option due to a group decision.

KPI	Units	Description
Households using natural gas	Number of households	Number of households that are using natural gas.
Natural gas consumption	MWh	Cumulative sum of natural gas consumption of all households.
Heating costs	k€	Cumulative sum of investment and running costs. Investment costs are upfront costs to change states. Running costs include annual fees and fuel costs.
Households with group lock out	Number of households	Number of households with group lock out at a given point in time.

Table 4.1: KPIs.

Entities, variables, and scales. The ABM has agents, objects, environment, and time. Agents are households; the environment is information from quorums, market conditions and policy interventions, and one time step models a year. We study simulation results for 30 years, starting in 2019.

Households – The state variables that describe households are summarised in Table 4.2. Households live in dwellings that are either independent (terraced house) or part of strata buildings (apartment), as described by the type of dwelling. Apartments are grouped in HOAs, identified by the building ID. For implementation reasons, terraced houses are part of an HOA with a single member (themselves). The technology state (TS) of a household describes its dwelling's combination of heating system, insulation level, and appliances. At all times, households can choose between seven TSs, summarised in Table 4.4. We selected these TSs to explore the situations from Table 4.3.

State variable	Type	Description
Type of dwelling	Static	Apartment or terraced house.
Building ID	Static	Identifier that links a household to its HOA.
TS	Variable	Current TS, from the 7 possible TS from Table 4.4.
Previous TS	Variable	Previous TS different to its current TS.
IDR	Static	Market discount rate (ρ_{market}) for households with perfect financial rationality, and a higher discount rate (ρ_{bnd}), for households with bounded financial rationality.

Table 4.2: State variables of households.

Situation	Motivation
TSs that involve one household vs TSs that require coordination between and within HOAs.	As discussed in the previous sections (4.1-4.4.1).
TSs that require smaller renovations vs those that require major ones.	Filippidou et al. [2017] argue that deep renovations rather than individual improvements in energy efficiency are needed for the non-profit housing sector in the Netherlands to meet its targets.
TSs with lower upfront costs vs TSs with higher ones.	Upfront costs have a greater marginal impact on NPV calculations compared to cash flows at later times, with discount rates greater than zero; however, large upfront investments could also reduce future operation costs.
TSs consisting only of demand reductions vs those consisting of the phasing out of natural gas.	Available policies target different objectives. For example, there are subsidies for insulation [Rijksoverheid, 2016] and also subsidies for heat pumps [Rijksoverheid, 2017].

Table 4.3: Situations that we explore with our chosen TSs.

TS	Type	Heating system	Insulation level[a]	Appliances
1:GB3	Individual	Natural gas boiler	3	Natural gas
2:EB3	Individual	Electric boiler	3	Electric
3:GB2	Individual	Natural gas boiler	2	Natural gas
4:EB2	Individual	Electric boiler	2	Electric
5:HN2	Collective: neighbourhood	Heat network	2	Electric
6:HP1	Individual (for terraced houses); Collective: HOA (for apartments)	Heat pump	1	Electric
7:HN1	Collective: neighbourhood	Heat network	1	Electric

[a] Where an insulation level of 3 is the lowest and 1 the highest.

Table 4.4: TSs available to households.

A household's previous TS is the last TS that a household had before its current TS.

Finally, IDR stands for implicit discount rate. A household's IDR is the discount rate that the household uses when comparing and selecting its preferred TS using a net present value (NPV) calculation which depends on investment and operational costs of heating systems and insulation improvements. Note that even if a household's IDRs did not change across simulation runs, the household's ranking of TSs could change since NPV outcomes depend on investment costs and operational costs, which are influenced by market conditions and financial policies. For details, see the paragraph *Individual preferences sub-model*, on page 80.

IDRs represent financial and non-financial factors that influence household decisions. Schleich et al. [2016] explain that IDRs are estimates based on observed technology adoption choices; they are the discount rate that would render a specific choice reasonable in an NPV calculation. In other words, they represent the opportunity costs of capital and additional barriers that prevent optimal financial decision making. As noted by Schleich et al. [2016], authors have found IDRs to be typically higher than the costs of capital in studies of the adoption of energy technologies by households [Dubin and McFadden, 1984, Hausman, 1979, Train, 1985]. Further discussion of our use of IDRs and its limitations can be found in Section 4.4.3.

In the remainder of this chapter, we use a household's "preference" to refer to the most-preferred TS based on the household's NPV-calculation in the household's current state.

Quorums – We define two quorums: HOA Quorum and HN (heat network) Quorum. The former represents the percentage of households in an HOA that must approve a collective project in order for the project to be binding for all households in the HOA. The latter represents the percentage of households in the neighbourhood that must be willing and able to join a heat network for such heat network to be constructed.

Market conditions – Market conditions consist of electricity, natural gas and heat retail prices of energy suppliers, and contractors' fees for carrying out changes in heating systems and insulation.

Policy interventions – We include two types of public policy interventions: fiscal and disconnection. We base these policies on the Climate Agreement [Rijksoverheid, 2019d], the Crisis and Recovery Act [PAW, 2019], and the Heat Law [2019]. The fiscal policies are assumptions of an annual linear increase in taxes on natural gas (P-TXG), an annual linear decrease in taxes on electricity (P-TXE), and regulated price of heat from networks in the form of heat prices that are coupled to natural gas prices (P-RHP). The disconnection policy would require households to replace heating systems and appliances that use natural gas. We include the disconnection policy as a thought experiment based on the amendment to The Dutch Crisis and Recovery Act [2020] and the hypothetical disconnection of a testing ground [PAW, 2019].

Each policy intervention has a reference and an alternative mode. In the reference mode of the disconnection policy, households are not required to disconnect from the natural gas network, and in the alternative mode, they are. The fiscal policy interventions are operationalised as follows. In both modes of P-TXG and P-TXE, real data is used for 2019 and 2020. This data is presented in Appendix A. From 2021 to 2026, taxes on natural gas increase as suggested by the Climate Agreement: 1 Eurocent per cubic meter per year, equivalent to 0.001024€/kWh per year. After 2026, in the reference mode of P-TXG, taxes on natural gas remain constant, and in the alternative mode, they continue to increase at the same rate. Between 2021 and 2026, taxes on electricity decrease by a total of 5 Eurocents per kWh, as suggested by the Climate Agreement. In our ABM, this decrease is linear: 0.833 Eurocents per year. After 2026, in the reference mode of P-TXE, they remain constant, and in the alternative mode, they continue to decrease at the same rate until zero. In the reference mode of P-RHP, the heat price increases in proportion to the sales price of natural gas (SPG), which we define as the sum of its retail price and taxes (see Equation 4.1 and Equation 4.2). In the alternative mode of P-RHP, the regulated heat price remains constant.

$$SPG(t) = retailpriceofnaturalgas(t) + taxonnaturalgas(t) \tag{4.1}$$

Equation 4.1: Sales price of natural gas.

$$Heatprice(t) = (1 + \frac{SPG(t) - SPG(t-1)}{SPG(t-1)}) * Heatprice(t-1) \tag{4.2}$$

Equation 4.2: Heat price in the reference mode of P-RHP.

Based on the two modes of each of the four policy interventions, 16 combinations of modes are possible. We refer to these combinations as regulatory environments (REs). In the name of each RE, the alternative mode of each policy intervention is indicated with a suggestive letter: G for P-TXG, E for P-TXE, H for P-RPH, and D for the disconnection policy. The reference mode is always indicated with 0. We fix the order of the policy interventions as just mentioned. For instance, we denote by GEHD the RE where all policy interventions are in alternative mode, and we denote by GE00 the RE where P-TXG and P-TXE follow the alternative mode, but P-RHP and disconnection policy follow their reference mode.

Process overview and scheduling. *Process overview* – The main processes in the model, which take place every time step, are:

1. Households compute their individual preferences over TSs under the current market conditions and RE. See the paragraph *Individual preferences sub-model*, on page 80, for details.
2. The group decision-making process takes place in two steps.
   (a) The first step takes as input the individual preferences of the households in the HOA and outputs whether there is HOA Quorum for a heat pump (TS6:HP1) or a heat network (TS5:HN2 and TS7:HN1). For heat networks, we count households with preferences for either TS5:HN2 and TS7:HN1.
   (b) In the second step, towards the HN Quorum we count all households in HOAs in which the HOA Quorum was met for heat networks (winner-takes-all in each HOA).
3. Households determine their TS in the next time step based on their individual preferences and the outputs of the group decision-making process. This individual process has three steps.
   (a) If the HN Quorum was met or a heat network from a previous time step exists, HOAs with HOA Quorum for heat networks decide between TS5:HN2 and TS7:HN1 as follows. If most households prefer TS5:HN2, all households with insulation level of 2 or lower adopt TS5:HN2 and households with an insulation level of 1 adopt TS7:HN1. Otherwise, all households adopt TS7:HN1.
   (b) Households in HOAs with HOA Quorum for TS6:HP1 (heat pump) adopt TS6:HP1.
   (c) Households in HOAs in which the HOA Quorum was not met for a collective TS adopt their most-preferred individual TS.[1]

Scheduling – In the first time step, the households using natural gas are computed to record the initial conditions of the neighbourhood. Every following time-step, energy prices are updated and the ABM records the neighbourhood's natural gas consumption. After that, the main processes take place: households compute (in random order) their individual preferences, the group decision-making processes are carried out, and once these have all completed, their results are observed by households and households' next TS is determined. Households replace heating systems that reached the end of their lifetime and broke down. Finally, households using natural gas, heating costs, and households with group lock out are computed.

[1] See Section 4.5.5 for a clarification regarding decisions by terraced houses.

DESIGN CONCEPTS

Our ABM incorporates the following design concepts: heterogeneity, objectives, prediction, group decisions, sensing, interaction, stochasticity, collectives, and observation.

Heterogeneity is the first design concept. Households are heterogeneous because they have different types of dwellings and different IDRs. Their objective is to minimise heating costs via NPV calculations (see 4.4.2). We model households that have perfect prediction of future market conditions and policy interventions and that are grouped in HOAs, which are collectives.

Group decisions are a second design concept. As part of the group decision-making process, households can sense the outcome of group-decisions within their HOA and between HOAs in the neighbourhood. These are the only interactions between households in the ABM.

Observation and stochasticity are also part of the ABM. Observation takes place via the KPIs from Table 4.1. Stochasticity is part of the model initialization: IDRs are assigned uniformly at random to households. Therefore, the distribution of IDRs in an HOA may not be representative of the entire population.

DETAILS

Initialization. We conceptualise and model an illustrative neighbourhood in which heat networks are a financially competitive option with respect to other alternatives to natural gas, but are not yet present in the neighbourhood. Our illustrative neighbourhood has 520 dwellings: 160 terraced houses, 5 buildings of 60 apartments each, and 10 buildings of 6 apartments each. We selected this set to represent both independent dwellings and dwellings in strata buildings of different sizes. We represent a HN Quorum of 75% and a homogeneous HOA Quorum of 70% for all HOAs.

Initially, households have TS1:GB3, i.e. low insulation and natural gas-fuelled boiler and appliances. For simplicity, we assume that all boilers need to be replaced after the first time step because they reached the end of their lifetime. These features roughly represent dwellings from the period between 1965 to 1974, with energy labels C to D, and annual natural gas use from Table 4.5. Description and estimates are loosely based on CBS [2019] and an online tool by Milieu Centraal and Rijksoverheid [n.d.].

Type of dwelling	Natural gas consumption
Apartment	980 m^3
Terraced house	1330 m^3

Table 4.5: Initial annual natural gas consumption of dwellings in the ABM.

We assume a ρ_{market} of 2.33%. This value is the average interest rate for 30 annuity mortgage products in the Netherlands, on March 10, 2020, for existing buildings at 100% of market value over 30 years [Hypotheker, 2020]. We assume that households would be able to complement their mortgage with an additional loan for energy-related renovations, and that such additional loans would have the same discount rate used for mortgages.

We assume a ρ_{bnd} of 36%, which was the value of ρ_{bnd} in an empirical case study of a UK district heating scheme by Burlinson et al. [2018]. They used traditional and behavioural theories to explore decision-making of energy consumers, which they found to undervalue future energy costs. The high IDR was partially explained by consumer inattention and heuristics.

We use the ABM to simulate the changes in the TS of households in the neighbourhood over time, and study simulation results for 30 years, starting from 2019. We use the simulations to compute the KPIs over time, under different combinations of factors (see Table 4.6). Each combination is one of 48 experimental scenarios. When the ABM is initialised, each household randomly gets a discount rate. When discount rates are homogeneous, the model is deterministic; otherwise, there is stochasticity. To account for this stochasticity, we simulate the former scenarios only once, and the latter, 10 times.

Factor	Description	Variations	Values
RE	Combination of policy interventions	16	G000, G0H0, GE00, GEH0, G00D, G0HD, GE0D, GEHD, 0000, 00H0, 0E00, 0EH0, 000D, 00HD, 0E0D, 0EHD
Population of IDRs	Fraction of households with ρ_{bnd} and fraction of households with ρ_{market}.	3	0–1, 0.25–0.75, 1–0

Table 4.6: Factors for the simulation.

Input data. Input data consists of market conditions, i.e. energy prices and prices of TSs (see Appendix A4.9).

Individual preferences sub-model. Households compare available TSs to determine their preferred one. As illustrated in Figure 4.2, a household's TS constrains the TSs from which the household can choose. There are three constraints: (1) an improvement in insulation cannot be undone, e.g. insulation cannot go from level 2 to level 3, so it is not possible to transition, for instance, from TS4:EB2 to TS2:EB3; (2) after a dwelling was disconnected from natural gas, it cannot be reconnected; (3) under the disconnection policy, TSs that use natural gas are unavailable.

Households use the lifetime-cost (LTC) sub-model from Equation 4.3 to compute their preferences over TSs[2]. Our LTC sub-model can be seen as a refinement of the LTC sub-model by Burlinson et al. [2018], which is based on Hausman [1979].

$$LTC(s,s',\rho,t) = UC(s,s') + \sum_{k=0}^{\beta} \frac{AC(s',t+k)}{(1+\rho)^k} + \sum_{j=1}^{\left\lfloor \frac{\beta}{\tau}-1 \right\rfloor} \frac{RC(s')}{(1+\rho)^{j\tau}} \tag{4.3}$$

Equation 4.3: LTC sub-model.

[2]Floor brackets in Equation 4.3 are an addition with respect to the version in Nava-Guerrero et al. [2021].

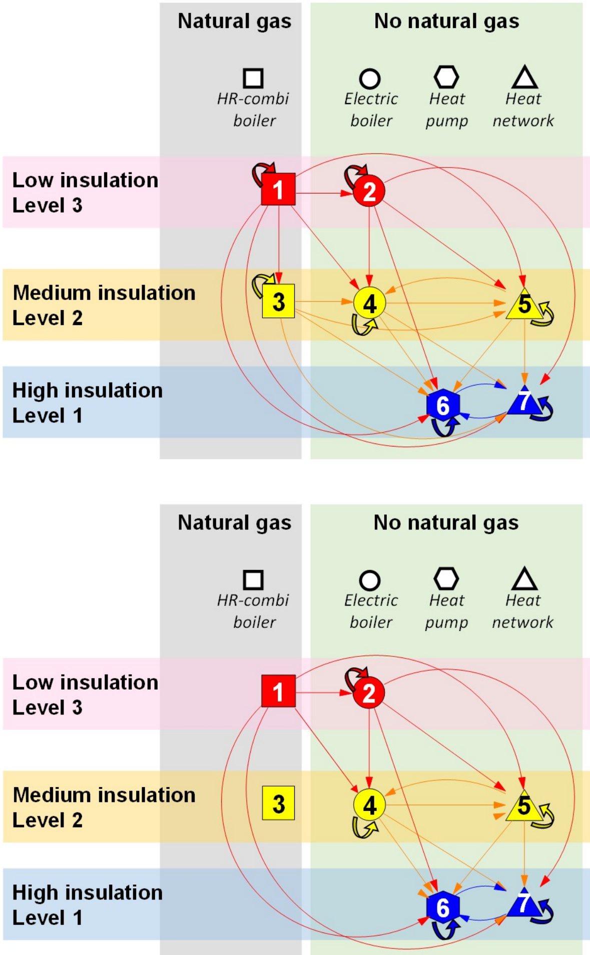

Figure 4.2: Possible changes in household TSs. (a) Possible changes without the disconnection policy, in the upper part of the figure. (b) Possible changes under the disconnection policy, in the lower part of the figure.

We define LTC(s,s',ρ,t) to represent the net present value (NPV) of changing from TS s to TS s' with heating system lifetime given by τ, and maintaining s' over time horizon β, while using discount rate ρ. The LTC of a TS is calculated via the upfront costs (UC), the annual costs (AC), and the reinvestment costs (RC) of a household.

AC can change over time as a result of fiscal policy interventions, and we let AC(s,t) denote the annual cost of a household with TS s at time step t. We assume that households have perfect knowledge of future market conditions and regulatory environments and therefore they can access AC(s,t) for future time steps t in their LTC-calculation. We provide a detailed breakdown of AC in Appendix A.

Each household uses the LTC calculation to compare the lifetime-cost of all TSs available to them, including the current one. Heating systems can have different lifetimes and would therefore require different time horizons for the LTC. Following van den

Boomen et al. [2016], to enable their comparison, we include reinvestment costs (RC) in addition to UC and AC. For instance, if a heating system h1 has a lifetime of 30 years and another heating system h2 has a lifetime of 15 years, we compute the LTC over 30 years without RC for h1 and with one reinvestment for h2 in year 15. We let RC(s) denote the cost of reinvesting in the heating system of TS s. We exclude RC for insulation and appliances: we assume that no RC are required for insulation and that RC for appliances are equal for all TS and would therefore have no differential effect. Furthermore, in order to compare LTC-values for all TSs, we take a uniform horizon β equal to the lifetime of the available heating system with the longest lifetime. For simplicity, we assume that maintaining the same TS requires an initial reinvestment. Finally, UC(s,s') denotes the upfront cost of switching from TS s to TS s', and we assume this cost remains constant during the simulation.

Households use the LTC sub-model to compute ideal estimates (LTCideal) and bounded estimates (LTCbnd). They use a market discount rate (ρ_{market}) in the former (Equation 4.4), and a higher discount rate (ρ_{bnd}) in the latter (Equation 4.5).

$$LTCideal(s,s',t) = LTC(s,s',\rho_{market},t) \tag{4.4}$$

Equation 4.4: LTCideal.

$$LTCbnd(s,s',t) = LTC(s,s',\rho_{bnd},t) \tag{4.5}$$

Equation 4.5: LTCbnd.

Each household uses either LTCideal or LTCbnd to determine its individual preferences. They prefer TSs with lower LTCs. We ignore that if a household were to improve its insulation without changing its heating system (TS1:GB3 to TS3:GB2 or TS2:EB3 to TS4:EB2), the heating system might no longer be at the beginning of its lifetime and might have to be replaced earlier than anticipated. When the change is implemented, the age of the new TS is set to zero.

Operationally, a household has group lock out in a TS s after having made an adoption decision in time step t if there is a TS s' such that LTC(s,s',ρ,t) < LTC(s,s,ρ,t). In other words, it could not adopt its preferred TS due to a group decision.

4.4.3. DISCUSSION OF MODELLING CHOICES

Our modelling choices affect the way in which the model can be used and its results. In this subsection, we discuss our main modelling choices and alternative ways of modelling.

HOUSEHOLD PREDICTION OF FUTURE POLICIES AND PRICES

We assume that households have perfect knowledge of future market and policy developments in their LTC calculation. As a result, households have the same preferred TS over most of the simulation, and hence the only changes in TS happen in the initial years. It would be more realistic to drop this assumption and let households make predictions for annual costs based on current taxes, and let energy taxes (and potentially prices) fluctuate as opposed to using a simple linear growth in taxes. This could lead to more dynamic outcomes where households change their TS more often.

INPUT DATA FOR MARKET CONDITIONS AND THE TECHNOLOGICAL SUBSYSTEM

Input data for market conditions, such as UC, RC, and technical specifications for each TS, influences the preferred TSs of households. As noted in Appendix B, variations in input data could lead to households preferring a different TS. This is also the case for the prices of natural gas and electricity, which we assume to be constant but can in reality be uncertain and fluctuating.

Moreover, we would expect some UC to be different than we estimated. We parameterised the model using estimates and assumptions rather than, for example, requesting commercial quotes. Moreover, we explicitly modelled a neighbourhood in which heat networks could be financially competitive with respect to other alternatives to natural gas. This choice allowed us to explore the effect of group decisions via the HN Quorum and HOA Quorum. However, we expect the cost of building or expanding a heat network, and the UC for households, to be case specific.

A third remark concerns our use of input data for demand reduction associated with a change of TS. Implicitly, we consider theoretical rather than actual demand reduction when households improve dwelling insulation. In practice, researchers have observed a phenomenon known as the energy performance gap. When energy renovations are carried out, households tend to have a higher energy demand than theoretically expected [Filippidou et al., 2019, Majcen et al., 2013]. Accounting for the energy performance gap in our ABM could lead to different results.

Finally, we conceptualised and modelled a heat network that can provide medium (TS5:HN2) and low temperature (TS7:HN1) heating to different dwellings. In future research, it would ideally be replaced by a heat network design that accounts for physical constraints specific to the neighbourhood.

MODELLING OF POLICY INTERVENTIONS

We model simplified policy interventions. In reality, the regulated heat price is published every year by the Netherlands Authority for Consumers and Markets (ACM), a national regulator. The calculations published by the ACM [2019] go beyond our assumption of the heat price changing in the same percentage as the natural gas price. Moreover, our disconnection policy requires households to replace their heating systems the year after the policy is implemented. However, this transition could take place over multiple years. A more realistic way of representing these policies would be to have a more detailed calculation for the regulated heat price and a disconnection policy that allows households to replace their heating systems over a longer time frame.

INDIVIDUAL PREFERENCES

Schleich et al. [2016] recommend the use of different IDRs per household and technologies. In this work, we model a population of households with different IDRs (ρ_{market} or ρ_{bnd}). We assumed that households had a ρ_{bnd} of 36%, a number determined in a case study by Burlinson et al. [2018] regarding heat networks. We expect that this percentage, and even its order of magnitude, can vary on a case by case basis.

Instead of assuming a percentage, one could determine the IDR empirically, and instead of using a single value, one could explore how individual preferences would change within a wide range of IDRs. Further, in our ABM, each household uses the same IDR to compare competing TSs; instead, as recommended by Schleich et al. [2016], household could use different IDRs per TS. Finally, because discount rates do not necessarily make the barriers of technology adoption explicit, their use can hamper the design of effective policies to target non-financial preferences [Schleich et al., 2016].

Accordingly, our use of IDRs constrains the purposes for which our ABM can be used. We represent household decisions under the assumption that IDRs are static, and equal for different TSs. Therefore, this ABM can be used in an "if … then/how … " manner. For instance, a suitable modelling question would be: if 50% of households in a neighbourhood had ρ_{market} and 50% had ρ_{bnd}, how would financial policies, or the disconnection policy, influence natural gas consumption over time, under our set of assumptions? Using our ABM to explore policies to increase adoption would require the explicit inclusion of underlying factors that explain ρ_{bnd}, and policies that could effectively influence those underlying factors.

In addition, we model households that are always financially able to change their TSs. After a change, they do not wait to recover their investment. In reality, households that recently made an investment might not make a new investment, even if it would reduce their future LTC.

In the LTC, we ignore that when a change in TS improves insulation but does not replace a heating system, the remaining lifetime of the heating system would not be as long as if it were a new heating system. This could overestimate the financial attractiveness of changing from TS1:GB1 to TS3:GB2 or from TS2:EB3 to TS4:EB2. Finally, instead of assuming that maintaining the same TS requires an initial reinvestment, the age of the heating system could be considered.

GROUP DECISIONS

Our use of quorum constraints is a simplified representation of group decisions, including the realization of a heat network. Other factors, such as leadership and information processing, have been found to play a role in group decision-making [Roodenrijs et al., 2020]. There are also various ways to realise heat networks [Busch et al., 2017, den Dekker et al., 2020]. Moreover, our ABM has the implicit assumption of household preferences not being influenced during group decision-making processes, and the explicit assumption that all HOAs always use the same quorum. However, preferences may be influenced and type and value of quorums can vary between HOAs and types of decisions. Future work can include an empirically grounded conceptual model for group decisions in our ABM.

4.5. RESULTS AND DISCUSSION

In the following subsections, we answer the second and third sub-questions from Section 4.3. Simulation results and agent-based model are available as supplementary materials (see page 68).

4.5.1. SOCIO-TECHNICAL CONDITIONS FOR THE TRANSITION

The disconnection policy was the only necessary and sufficient condition for households to disconnect from natural gas. This outcome was independent of the population of IDRs. Hence, no combination of fiscal policies enabled the heat transition, and without the disconnection policy, group decisions did not have a differential influence on households' decision to stop using natural gas.

4.5.2. INITIAL INDIVIDUAL HOUSEHOLD PREFERENCES

In Table 4.7 and Table 4.8, we summarise households' individual preferences at the beginning of the simulation. We rank TSs based on their LTC, from lowest to highest. The letter "X" indicates both the reference and alternative mode of a policy. Appendix B contains detailed quantitative results.

4

RE	Preferred TS	Subsequent preferred TSs
XXX0	TS3	TS1, TS7, TS5, TS6, TS4, TS2
XXXD	TS7	TS5, TS6, TS4, TS2

Table 4.7: Individual household preferences in the initial TS, under each RE and using ρ_{market}.

RE	Preferred TS	Subsequent preferred TSs
XXX0	TS1	TS3, TS2, TS4, TS5, TS7, TS6
XXXD	TS2	TS4, TS5, TS7, TS6

Table 4.8: Individual household preferences in the initial TS, under each RE and using ρ_{bnd}.

Firstly, the preferences of households using ρ_{market} were as follows. Without the disconnection policy, households preferred to maintain their natural gas boiler and improve their insulation level from 3 to 2 (TS3:GB2). Under the disconnection policy, households preferred a low temperature heat network with insulation level 1 (TS7:HN1). However, the ranges across REs of the LTC of their first and second most preferred TSs (TS7:HN1 and TS5:HN2) overlapped. These ranges are shown in Table 4.9, where cells with a single number indicate a range smaller than 100€.

Source	TS	Apartments		Terraced houses	
		Ideal estimates (k€)	Bounded estimates (k€)	Ideal estimates (k€)	Bounded estimates (k€)
Natural gas	TS1:GB3	26.1 - 28	5.7	33.7 - 36.3	7.4 - 7.5
	TS3:GB2	24.7 - 26.3	6.4	31.8 - 34	8.4
Electricity	TS2:EB3	53.9 - 60.5	15.1 - 15.3	67.5 - 76.5	19.5 - 19.7
	TS4:EB2	52.6 - 58.3	17.1 - 17.2	65.7 - 73.5	22.2 - 22.4
	TS6:HP1	45.7 - 46.5	24.1	56.3 - 57.3	31.6
Heat from network	TS5:HN2	36.9 - 39.5	17.7 - 17.8	46.7 - 50.1	23.4 - 23.5
	TS7:HN1	36.7 - 38.1	23.1	46.4 - 48.2	30.6 - 30.7

Table 4.9: Ranges of the LTCs in the initial TS.

Uncoupling the heat price from the price of natural gas reduced the financial attractiveness for households to reduce their heat demand by selecting a low temperature heat network (TS7:HN1) rather than a medium temperature one (TS5:HN2). When the heat price remained coupled with the natural gas price, the difference between the LTC of these TSs ranged between 0.6 and 1.4k€ for apartments and 0.9–1.9k€ for terraced houses. When the heat price was decoupled, the difference was 0.2k€ for apartments and 0.3k€ for terraced houses. These differences are equivalent to less than 4% (reference mode) and 1% (alternative mode) of the LTC of TS7:HN1. Although TS7:HN1 was always the cheapest option, in order for households to save 0.6–1.9k€ over 30 years with respect to TS5:HN2, they would have to make an additional investment of UC of 6.5k€ to 8.8k€.

Secondly, the preferences of households using ρ_{bnd} were as follows. Without the disconnection policy, households preferred to remain in their current TS1:GB3. Under the disconnection policy, households preferred TS2:EB3. High IDRs drove these households to prefer a TS with high AC and low UC.

Finally, to enable the transition without the disconnection policy, the LTC of TS3:GB2 would have to be at least as high as the LTC of TS7:HN1. This could be theoretically achieved, for example, by changing the fiscal policies or subsidizing UC.

In the case of households using ρ_{market}, assuming that there is also a cap on the price of heat from networks after 2020, the tax on natural gas after 2026 would have to be in the order of 0.1€/kWh for the LTC of TS3:GB2 to match the LTC of TS7:HN1. Alternatively and theoretically, a subsidy for UC would have to be in the order of 10–15k€.

We also explore the case of households using ρ_{bnd}. For the LTC of TS1:GB3 to match the LTC of TS7:HN1, assuming that there is also a cap on the price of heat from networks after 2020, the tax on natural gas after 2026 would have to be in the order of 3€/kWh. Alternatively and theoretically, a subsidy for UC would have to be in the order of 17-23k€. We consider these calculations to be a thought experiment because the required taxes and subsidies could be unaffordable.

4.5.3. HOUSEHOLD DECISIONS AND GROUP LOCK OUT

When households had homogeneous discount rates, either TS2:EB3 or TS7:HN1 were preferred by all households. As a result, households were able to adopt their preferred TS because it was individual or because they agreed to adopt the same collective TS. Therefore, there was no group lock out. Figure 4.3 illustrates those choices depending on whether the disconnection policy was active and whether all households had ρ_{market} or ρ_{bnd}. Figure 4.3 shows only the first four years of simulation because there were no further changes afterwards. Note that when all households had ρ_{bnd}, they first replaced their natural gas boiler for an electric one (TS2:EB3) and only later improved their insulation (TS4:EB2).

Results differed when households had heterogeneous discount rates (75% had ρ_{market} and 25% had ρ_{bnd}). When there was no disconnection policy, as shown in Figure 4.4, households with ρ_{market} were able to adopt their preferred TS4:EB2, which was individual, and there was no group lock out. However, when the disconnection policy was in place, HOA Quorums and the HN Quorum were not always met. When the HN Quorum was not met (Figure 4.5 A), households with ρ_{market} were not able to adopt their preferred TS7:HN1. Instead, they chose their preferred individual option (TS4:EB2) and experienced group lock out. This was also the case when the HN Quorum was met in the neighbourhood but the HOA Quorum was not met in a given HOA (Figure 4.5 B). The thicker lines in Figure 4.5 B represent results from different experimental scenarios in which there was stochasticity (see 4.4.2). Households with ρ_{bnd} who were able to make individual decisions initially replaced their natural gas boiler for an electric one (TS2:EB3) and improved their insulation the year after (Figure 4.5 A and B).

Therefore, in spite of 75% of households preferring TS7:HN1, group decisions resulted in instances in which the HN Quorum was not met. In these cases, the adoption decisions in the neighbourhood were not a simple mix of individual preferences; instead, the model behaviour displayed emergence.

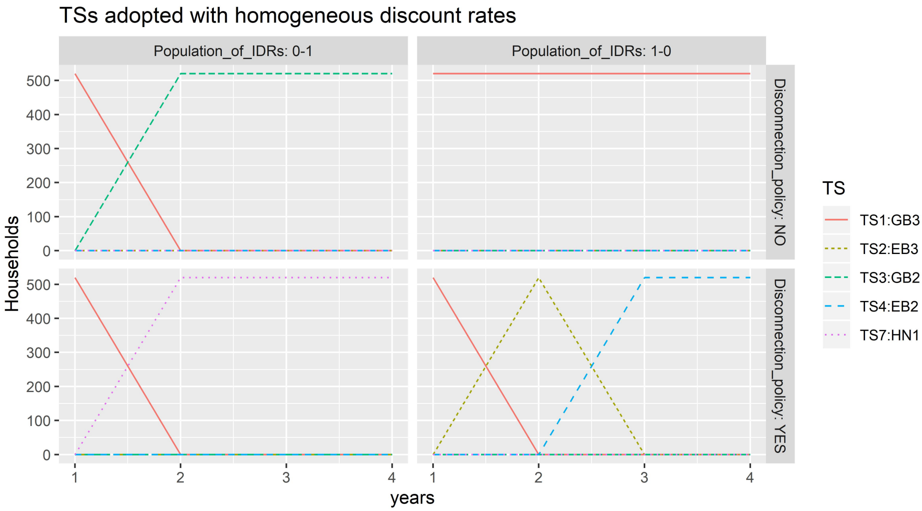

Figure 4.3: TSs adopted in the neighbourhood when households had homogeneous discount rates. The left column represents populations in which all households had ρ_{market} (0–1), and the right, ρ_{bnd} (1–0).

Figure 4.4: TSs when households had heterogeneous discount rates, without the disconnection policy.

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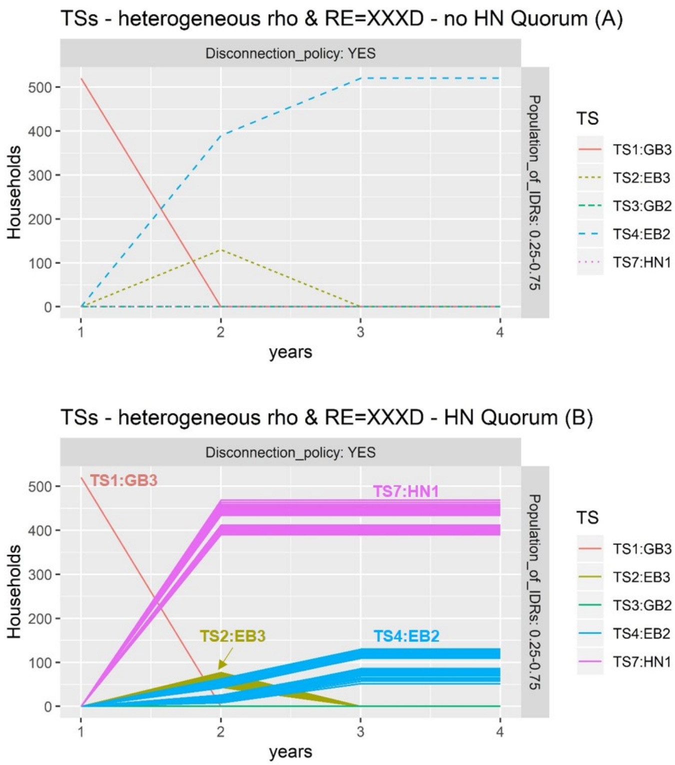

Figure 4.5: TSs when households had heterogeneous discount rates, under the disconnection policy.

The boxplots in Figure 4.6 illustrate one of these situations at the end of 2 years of simulation and under the disconnection policy. In each pair of boxplots, the boxplot to the left represents the households with each TS that had group lock out, and the boxplot to the right, those that did not. The large green boxplot to the right indicates that in most simulation runs, households that chose TS7:HN1 were able to choose their preferred TS, and the small green boxplot to the left indicates that some households that chose TS7:HN1 had group lock out, i.e. they had to choose such TS because it was the preferred by 70% or more of their HOA peers. Likewise, the large red boxplot to the left and flat red boxplot to the right, at zero, indicate that TS4:EB2 was chosen only by households unable to choose their preferred TS (TS7:HN1).

Figure 4.6: TSs adopted in the neighbourhood after 2 years under RE = GEHD and Population of IDRs = 0.25–0.75. In each pair of boxplots, the boxplot to the left represents the households with each TS that had group lock out, and the boxplot to the left, those that did not.

4.5.4. HEATING COSTS OF THE TRANSITION

The heating costs of the transition depended on the TSs that households adopted and the REs. Different REs established different combinations of natural gas taxes, electricity taxes, and price of heat from networks. Therefore, the same choices of TSs could lead to different heating costs depending on the REs. In Figure 4.7, we plot the neighbourhood's cumulative heating costs after 30 years of simulation when households had homogeneous IDRs. Each boxplot represents the heating costs that resulted from household decisions under a group of REs and discount rate. For instance, the first boxplot of Figure 4.7 A represents the heating costs under RE = XXX0, when all households used ρ_{market} and selected TS3:GB2. Note that we ignore that the LTC period of different TSs might not yet be complete (see Figures 4.4 and 4.5 for the years in which TSs were initially adopted).

As discussed in Section 4.5.1, we confirmed that the heating costs of the transition were higher than the heating costs of using natural gas. In spite of fiscal policy interventions, disconnecting a dwelling from natural gas was never financially advantageous. Figure 4.7 also confirms that, when there was a transition (XXXD), heating costs were lower when all households used ρ_{market} than when all used ρ_{bnd}.

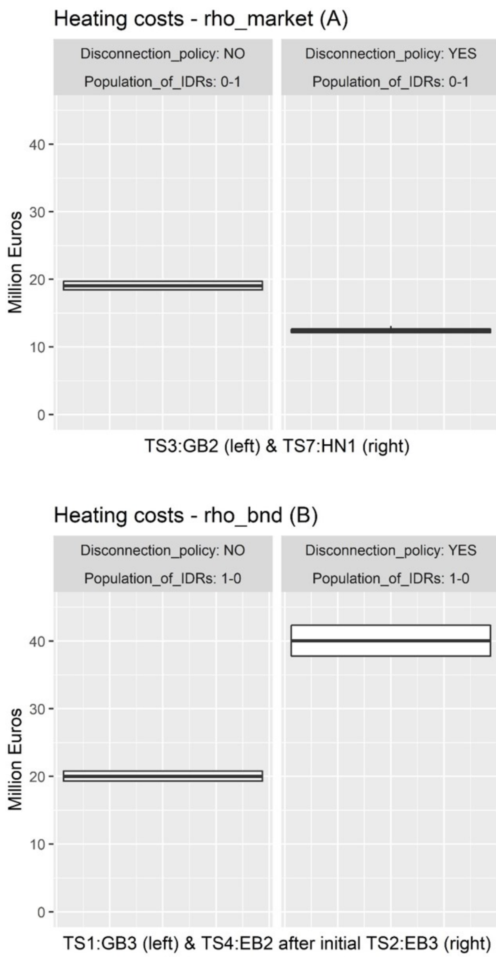

Figure 4.7: Heating costs when all households had ρ_{market} (A) or ρ_{bnd} (B), after 30 years.

4.5.5. MODELLING DECISIONS BY TERRACED HOUSES

A clarification regarding our ABM with respect to the version of this chapter that is published in Nava-Guerrero et al. [2021] is necessary. In the simulations, when a heat network could not be realised because there were not sufficient households that wished to join the project, households that preferred the heat network no longer tried to realise a project at the level of an HOA. Instead, they selected an alternative among the individual options without natural gas.

In Table 4.4, heat pumps (TS6:HP1) were conceptually considered to be individual technologies for self-standing dwellings. However, in the ABM, for implementation purposes, households in self-standing dwellings were modelled as members of an HOA with a single member. Because (in the ABM) technologies that required an HOA decision were excluded from the options that a household considered after the heat network could not be realised, terraced houses that preferred a heat network no longer considered heat pumps. Instead, they preferred electric boilers with high insulation.

A different approach to modelling terraced houses and their decisions would have been to allow them to consider heat pumps. Having done this would have changed the number of households that adopted electric boilers in Figure 4.6. This was not the case in the work reported in Chapter 5, where households in self-standing dwellings did consider heat pumps after their preferred heat network could not be realised.

4.6. VALIDATION

In the following subsections we discuss the sensitivity analysis and consultation of expert publications and newspaper articles as forms of validation.

4.6.1. SENSITIVITY ANALYSIS

We conducted one-factor-at-a-time [ten Broeke et al., 2016] sensitivity analysis on the four variables from Table 4.10. The new values for the sensitivity analysis were determined as 10% lower or higher than the nominal value.

Parameter	Units	Nominal value	New values	Population of IDRs	Repetitions
HOA Quorum	%	70	63, 77	0.25–0.75	10
HN Quorum	%	75	67.5, 82.5	0.25–0.75	10
ρ_{market}	%	2.33	2.1, 2.56	0–1	1
ρ_{bnd}	%	36	32.4, 39.6	1–0	1

Table 4.10: Values for the sensitivity analysis.

HN QUORUM AND HOA QUORUM

We explored different percentages for the HN Quorum and HOA Quorum when 75% of households used ρ_{market}. HN Quorums of 67.5% and 82.5% did not qualitatively affect the ways in which the transition could happen: under the disconnection policy, heat networks were sometimes but not always adopted by some households. In contrast, HOA Quorum variations did have a qualitative effect. When the HOA Quorum was 63%, heat networks were always adopted by some households, and when it was 77%, only in some random repetitions.

MARKET DISCOUNT RATE

A 10% decrease or increase in ρ_{market} (2.1% or 2.56% instead of 2.33%) did not change households' individual preferences nor their choices over time. However, the actual value of ρ_{market} could vary beyond the range that we explored. We assumed that households could receive a loan for energy renovations with the same interest rate as their mortgage. Other loans for house renovations can have higher interest rates, e.g. 4.2% on the basis of 15 years [Green Loans] or 4.5% or higher on the basis of 8 years [ING].

Therefore, we explored 18 additional values of ρ_{market} by further increasing and decreasing its nominal value in intervals of 0.233, i.e. from 0.23% to 4.66%. We only explored scenarios in which all households used ρ_{market}. The sensitivity results that were qualitatively different from the nominal results are summarised in Table 4.11.

Household choices	RE	ρ_{market} (%)
Households adopted TS7:HN1 towards the end of the simulation.	G0H0	0.23, 0.47, 0.7
	GEH0	0.23, 0.47, 0.7, 0.93
By the end of the second year, households adopted TS5:HN2.	XXHD	2.8, 3.03, 3.26, 3.5, 3.73, 3.96, 4.19, 4.43, 4.66
	0X0D	3.26, 3.5, 3.73, 3.96, 4.19, 4.43, 4.66
By the end of the second year, households adopted TS5:HN2, maintained it for one or more years, and adopted TS7:HN1.	GX0D	3.96, 4.19, 4.43, 4.66

Table 4.11: Changes in household preferences when 0.23% < ρ_{market} =< 4.66%.

4.6.2. EXPERT PUBLICATIONS AND NEWSPAPER ARTICLES

Whether disconnecting dwellings from natural gas can be cost neutral, i.e. recovering investments via savings in the energy bill, is a known concern in the Netherlands. In August 2020, Schilder and van der Staak [2020] reported that such cost neutrality is often not feasible. Although their study excluded collective solutions, this conclusion is in line with our own: in our ABM, the transition took place only under the disconnection policy. Furthermore, they highlighted the importance of the interest rate in the calculations: alternatives to the status quo became attractive for most of the households that they modelled under a hypothetical interest rate of 0% instead of 2%. These findings are also in line with ours: we found that under discount rates lower than or equal to 0.93% and under certain RE, the disconnection policy was no longer necessary. Furthermore, they also expect interest rates related to future building-related financing to be higher, as we discuss in 4.6.1.

Moreover, Schilder and van der Staak [2020] explain that even if savings compared to the status quo could be achieved over the lifetime of the alternatives, those savings would not necessarily justify the large upfront investment. In other words, cost neutrality might not be a sufficient incentive for households to transition. We represent this possibility by using a discount rate of 36%. They explain that although neighbourhood-oriented approaches could lead to cost-reduction due to economies of scale, such approaches pose coordination challenges.

Newspaper articles describe examples of such challenges. In Het Financieele Dagblad, McDonald [2020] reported that after two years of consultation, residents of owner-occupied dwellings in an Amsterdam neighbourhood preferred to postpone the decision to phase out natural gas. According to van den Berg [2021], an inventory conducted by De Volkskrant showed that only 206 houses in four of 27 testing grounds had been disconnected from natural gas. In the same year, McDonald [2021] discussed examples of dwellings that did phase out natural gas, and their costs varied. Our representation of group decisions is a step towards accounting for coordination challenges by using ABMs.

Our choice to model a disconnection policy is validated by McDonald [2020] reporting of potential future obligations to disconnect from natural gas in Het Financieele Dagblad. According to Verhelst [2019] in the same newspaper, a mandatory connection was described by the director of a Danish heat network as the most important condition for project success; otherwise, the necessary investments would not be possible. In our ABM, the transition was indeed achieved only with the disconnection policy. However, experts have raised concerns regarding such a potential obligation in the context of the Netherlands and about potential legislation [Huygen and Akerboom, 2020, van Vlerken, 2019].

4.7. CONCLUSIONS AND POLICY IMPLICATIONS

4.7.1. CONCLUSIONS

The main research question of this work is: How could individual and group decisions between building owners, and within HOAs in strata buildings, influence the course of the heat transition in a neighbourhood in the Netherlands, under different policy interventions? To answer this question, we took an agent-based approach and applied it to an illustrative example of a residential neighbourhood. We modelled three fiscal policies and a disconnection policy and explored how they would influence the adoption of alternatives to natural gas by households that make group decisions, under a set of specific assumptions.

We found that no combination of the fiscal policies that we explored incentivised households to disconnect from the natural gas network. The fiscal policies were based on the Climate Agreement [Rijksoverheid, 2019d], an amendment to The Dutch Crisis and Recovery Act [2020], and the potential disconnection of a testing ground [PAW, 2019]. The disconnection policy was the only necessary and sufficient condition for households to stop consuming natural gas.

Notably, under the disconnection policy, uncoupling the price of heat from networks from the price of natural gas decreased the incentive for households to further insulate their dwellings and decrease their energy demand. Households with bounded financial rationality preferred an electric boiler, and only later improved dwelling insulation. Households with perfect financial rationality preferred a low temperature heat network with high insulation. Because the heat price remained constant, the savings that households would have had by adopting a low temperature heat network with high insulation, compared to a medium temperature heat network with medium insulation, were smaller.

Group decisions influenced choices in the neighbourhood when there was a mix of households with perfect and bounded financial rationality. Although there were in principle sufficient households that preferred a heat network, group decisions sometimes resulted in unmet quorums. In those cases, households had to adopt their best individual option, i.e. an electric boiler with either low or medium dwelling insulation, depending on their implicit discount rate.

We found that our results were qualitatively sensitive to changes in two variables. First, the percentage of households that need to agree to a project within a homeowner association for that project to be realised. Second, to the discount rate that was used in lifetime-cost calculations. When discount rates were equal or lower than 0.93%, and in combination with taxes on natural gas that continued to increase after 2026 and a cap on the price of heat from networks, the transition was possible without the disconnection policy, but only towards the end of the simulation.

It must be noted that the quantitative power of our ABM is limited. Our conclusions should not be used to select specific policy interventions or changes in technology because the nature of this work is exploratory. Instead, this work paves the way for future research in two directions. First, regarding the application of our approach to specific case studies. Second, regarding how to include group decisions between and within home owner associations in agent-based modelling studies of heat transitions and other types of transitions that involve group decisions between heterogeneous actors.

To use or adapt our agent-based model to study a neighbourhood, we recommend the following. Use input data specific to the neighbourhood. Consider the inclusion of decreased efficiency of heating systems due to ageing, reinforcement of the electricity network, and relevant transaction costs. Explore the sensitivity of the lifetime-cost sub-model to the financial data.

Future research to improve our agent-based model includes the following. Account for uncertainties in future prices. Use empirically determined implicit discount rates, different implicit discount rates for competing technologies and for different households, and model non-financial preferences of households explicitly. Account for heterogeneous quorums between and within homeowner associations, and for factors that influence group decisions. Account for the energy performance gap. Model policy interventions in more detail; in particular, the regulated heat price and the disconnection policy.

4.7.2. POLICY IMPLICATIONS

Under the assumptions of our agent-based model, we make the following observations.

A cost-neutral transition towards heating without natural gas would require additional policy intervention. We recommend to further explore potential subsidies for upfront costs, much higher taxes on natural gas, or relatively higher taxes on natural gas in combination with interest rates approaching zero and a cap on the price of heat from networks. However, their implications for affordability should also be considered.

Assuming financial rationality, policies that target upfront rather than operation costs could be more effective, e.g. initial subsidies rather than subsequent taxes. The fiscal policies that we modelled could, in theory, incentivise households to replace their natural gas-based heating systems or to choose one heating system over another. These policies artificially increase or decrease the operation costs associated to energy consumption. However, in our model, the difference between the lifetime costs of a heat network with medium insulation and one with high insulation was less than 5%, and the upfront costs of the former were about a third lower than those of the latter. Because future cash flows are discounted in a lifetime-cost assessment, a change of X€ in the upfront costs would have a greater impact in the value of the project than a change of X€ in the operation costs over time.

Fiscal policies could have unexpected consequences, such as reducing the attractiveness of an option that might be desirable at a system level. In our model, uncoupling the heat price reduced the incentive for households to join a low rather than a medium temperature heat network. Therefore, policy makers should account for the interaction effects of policies that aim at enabling the transition. In particular, we recommend policy analysts and policy makers to focus on the interaction between incentives for insulation and incentives to phase-out natural gas.

Finally, because group decisions can influence adoption decisions, group decisions within and between homeowner associations should be taken into consideration in the design of policies.

4.8. ACKNOWLEDGEMENTS

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4.9. APPENDIX A. INPUT DATA

In this Appendix, we describe input data regarding (1) technical specifications of TSs, (2) costs of TSs, (3) annual costs of TSs, and (4) energy taxes for 2019 and 2020. Input data is based on desk research, estimates, and assumptions.

4.9.1. TECHNICAL SPECIFICATIONS OF TSS

Each TSs is further described by cooking demand (kWh/year), thermal efficiency (fraction), lifetime of the heating system (years), heat demand of apartments, and heat demand of row houses. We consider the following:

- Cooking demand is assumed to be 361.47 kWh/year for natural gas, and 175 kWh/year for electrical appliances. See for example the website of Milieu Centraal.

- Heat demand is expressed as the natural gas demand for apartments and row houses that have a natural gas boiler. It is based on CBS [2019] and Milieu Centraal and Rijksoverheid [n.d.], and depends on insulation levels, as summarised in Table 4.12.

- We define insulation levels in the following way, with a dwelling with a natural gas boiler as a reference:

    1. Level 3: lowest level; equivalent to energy label C to D.
    2. Level 2: medium level; equivalent to Level 3 plus windows with HR++ glass.

3. Level 1: highest level; equivalent to Level 2 plus façade, floor, and roof insulation.

- We assume the following values for thermal efficiency of heating systems: 87% for natural gas boilers, based on ACM [2019], which we also assume for electric boilers; 100% for heat networks, based on ACM [2019], and 3.81 for heat pumps, based on Hoogervorst et al. [2020]. However, in the ABM, we use thermal efficiency of heating systems relative to natural gas boilers and use the following values: 100% for natural gas and electricity boilers, 1.15% for heat networks, and 4.38 for heat pumps.

- The lifetime (τ) of heating systems is assumed to be 30 years for heat networks and 15 years for all other heating systems.

Type of dwelling	Units	Level 3	Level 2	Level 1
Apartments	kWh/year	9574	8235	4269
Terraced houses	kWh/year	12,993	11,176	5793

Table 4.12: Assumptions for heat demand in kWh/year per insulation level.

4.9.2. UPFRONT AND REINVESTMENT COSTS OF TSS

For each dwelling, changing or maintaining their TSs has upfront costs (UC) and reinvestment costs (RC), as described in 4.4.2 Individual preferences sub-model. UC is the sum of the costs of appliances (AP), insulation (IN), and heating systems (HS). RC is equivalent to HS. These costs are described in Equation 4.6.

$$UC = AP + IN + HS \tag{4.6}$$

Equation 4.6: Upfront costs.

To parameterise the model, we make the following assumptions:

- That the costs of a collective heat pump are proportional to those of an individual heat pump. For example, that a collective heat pump for an HOA of 6 members would be 6 times more expensive than an individual heat pump for one of its members.

- That the costs for apartments are approximately 74% of the costs for terraced houses, based on the differences in their heat demands from Table 4.5.

- That replacing a natural gas stove for an electric or induction stove costs 2500€ (AP).

- The values of IN for all TSs and HS for TS6:HP1 are loosely based on data from a publicly available tool to estimate renovation options and costs in the Netherlands [Milieu Centraal and Rijksoverheid, n.d.], as summarised in Table 4.13, Table 4.14.

- The value of HS for TS5:HN2 and TS7:HN1 is assumed to be 12000€ linked to an assumed HN Quorum of 75%. Note that, in practice, we expect both numbers to vary, with the former in the order of thousands of Euros [ACM, GreenHome, 2019, Vereniging Eigen Huis]. We selected a value of 12000€ to represent a situation in which HS for TS7:HN1 are lower than those of TS6:HP1, and both TS5:HN2 and TS7:HN1 are financially attractive options over their lifetime compared to other TSs that do not use natural gas.

- For TS1:GB3 and TS3:GB2, we base HS on the costs of natural gas boilers reported by Homedeal [2015]. Similarly, we base the costs of HS of TS2:EB3 and TS4:EB2 on Feenstra [2018], Fleiter et al. [2016].

- An overview of RC and UC is provided in Table 4.16.

Change in insulation level	IN
Level 3 to Level 1	12,801
Level 3 to Level 2	3957
Level 2 to Level 1	8844

Table 4.13: Assumptions for the costs of changing insulation level (IN).

Heating system	HS
Natural gas boiler	2400
Electric boiler	5000
Heat network	12,000
Heat pump	12,501

Table 4.14: Assumptions for the costs of heating systems (HS).

Heating system	RC
Natural gas boiler	2400
Electric boiler	5000
Heat network	0
Heat pump	12,501

Table 4.15: Assumptions for reinvestment costs (RC).

		TS'						
		1:GB3	2:EB3	3:GB2	4:EB2	5:HN2	6:HP1	7:HN1
TS	1:GB3	0	7500	3957	11,457	18,457	27,802	27,301
	2:EB3	NA[a]	0	NA[a]	3957	15,957	25,302	24,801
	3:GB2	NA[a]	NA[a]	0	7500	14,500	23,845	23,344
	4:EB2	NA[a]	NA[a]	NA[a]	0	12,000	21,345	20,844
	5:HN2	NA[a]	NA[a]	NA[a]	5000	0	21,345	20,844
	6:HP1	NA[a]	NA[a]	NA[a]	NA[a]	NA[a]	0	12,000
	7:HN1	NA[a]	NA[a]	NA[a]	NA[a]	NA[a]	12,501	0

NA[a] = Not applicable.

Table 4.16: Assumptions for UC of changing from TS to TS'.

4.9.3. ANNUAL COSTS OF TSS

Households have annual costs (AC) that are linked to their TS. AC are the sum of fixed costs (FC) and variable costs (VC). FC is the sum of an annual connection fee (CoF) and measuring fee (MeF). We exclude a maintenance fee (MaF) which in the case of heat networks, would include a rental fee for the equipment in the dwelling. VC is the product of the energy price and the annual heat demand of the dwelling. These costs are described in Equation 4.7 to Equation 4.9.

$$AC = FC + VC \tag{4.7}$$

Equation 4.7: Annual costs.

$$FC = CoF + MeF \tag{4.8}$$

Equation 4.8: Fixed costs.

$$VC = energy\_price * annual\_heat\_demand \tag{4.9}$$

Equation 4.9: Variable costs.

FC are summarised in Table 4.17, and we considered the following:

- For TS1:GB3 and TS3:GB2, connection and measuring fees are based on the fees from a natural gas supplier in the Netherlands for 2020, for a consumption between 500 < 4000 m^3/year [Stedin]. The connection fee includes periodical and transport fees, which in turn, includes fixed and capacity fees.
- For the electric TSs, TS2:EB3, TS4:EB2, TS6:HP1, connection and measuring fees are also based on the fees from an electricity supplier in the Netherlands for 2020 [Stedin]. However, we assumed that regardless of their TS, households would have

a connection to the electricity network, but if they adopted an electric TSs, they would have to have a different and more expensive connection. We assume that a non-electric TS requires a connection of type 1X35A, while an electric TS requires a connection of type 3X35A. However, the necessary connection is case specific, and in reality, a connection smaller than 3X35A and with a lower connection fee could be sufficient. Such change would result in lower annual costs for TS2:EB3, TS4:EB2, and TS6:HP1.

- For the heat network TSs, TS5:HN2 and TS7:HN1, connection and measuring fees are based on a heat supplier in the Netherlands for 2020 [HVC, n.d.].

	Units	TS						
		1:GB3	2:EB3	3:GB2	4:EB2	5:HN2	6:HP1	7:HN1
CoF	€/year	159.56	656.78	159.56	656.78	371.73	656.78	371.73
MeF	€/year	22.39	24.20	22.39	24.20	26.63	24.20	26.63

Table 4.17: Assumptions for annual connection and measuring fees.

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Energy prices are an input for VC. Natural gas and electricity prices for 2019 are based on the estimated average prices for the second half of 2019 [9]: 0.04806824 €/kWh and 0.1218 €/kWh, respectively. After 2019, these prices remain constant in the model. Heat price is based on the fees of a heat supplier in the Netherlands for 2020, with a value of 24.77 €/GJ, equivalent to 0.089172 €/kWh [HVC, n.d.].

4.9.4. ENERGY TAXES FOR 2019 AND 2020

Taxes for natural gas and electricity for 2019 and 2020 were based on real data for the Netherlands [Rijksoverheid, 2019a]. The taxes for natural gas were 0.2931 €/m^3 and 0.333 €/m^3, equivalent to 0.030002 and 0.034086 €/kWh, respectively. The taxes for electricity were 0.0986 €/kWh and 0.0977 €/kWh, respectively.

4.10. APPENDIX B. RESULTS OF INDIVIDUAL PREFERENCES SUB-MODEL

In this appendix, we provide the results of the individual preferences sub-model in year 2020, for 2021 to 2050. Table 4.18 is an overview of estimates for each TS under each RE, in k€. The remaining tables contain the LTC estimates for each TS, per RE. All tables contain LTC estimates for both apartments and terraced houses when houses used (ρ_{market}) (ideal estimates) and (ρ_{bnd}) (bounded estimates). In Table 4.19, Table 4.20, Table 4.21, Table 4.22, Table 4.23, Table 4.24, Table 4.25, Table 4.26, the colour gradient in each column shows the TS with the highest (red) and lowest (green) LTC, and the underlined number in bold indicates the TS without natural gas with the lowest LTC.

As explained in Section 4.4.2, we modelled 16 regulatory environments (REs). Each RE is a combination of four assumed policy interventions, which in turn have two models: reference and alternative. In the name of each RE, the alternative mode of each policy intervention is indicated with a suggestive letter: G for an annual linear increase in taxes on natural gas; E for an annual linear decrease in taxes on electricity; H for a regulated price of heat from networks in the form of heat prices that are coupled to natural gas prices; D for a disconnection policy. The reference mode is always indicated with 0. We fix the order of the policy interventions as just mentioned. For instance, we denote by GEHD the RE where all policy interventions are in alternative mode, and we denote by GE00 the RE where the first two policy interventions follow the alternative mode, but the last two policy interventions follow the reference modes. A letter "X" indicates that the outcomes apply to the reference and alternative mode of that policy alike.

Source	TS	RE	Apartments		Terraced houses	
			Ideal Estimates (k€)	Bounded Estimates (k€)	Ideal Estimates (k€)	Bounded Estimates (k€)
Natural gas	1:GB3	GXXX	28.0	5.7	36.3	7.5
		0XXX	26.1	5.7	33.7	7.4
	3:GB2	GXXX	26.3	6.4	34.0	8.4
		0XXX	24.7	6.4	31.8	8.4
Electricity	2:EB3	XEXX	53.9	15.1	67.5	19.5
		X0XX	60.5	15.3	76.5	19.7
	4:EB2	XEXX	52.6	17.1	65.7	22.2
		X0XX	58.3	17.2	73.5	22.4
	6:HP1	XEXX	45.7	24.1	56.3	31.6
		X0XX	46.5	24.1	57.3	31.6
Heat	5:HN2	GE0X	39.3	17.8	50.0	23.5
		G00X	39.5	17.8	50.1	23.5
		0E0X	37.9	17.8	48.0	23.5
		000X	38.0	17.8	48.1	23.5
		XEHX	36.9	17.7	46.7	23.4
		X0HX	37.0	17.7	46.8	48
	7:HN1	GE0X	38.0	23.1	48.1	30.7
		G00X	38.1	23.1	48.2	30.7
		0E0X	37.2	23.1	47.1	30.7
		000X	37.3	23.1	47.2	30.7
		XEHX	36.7	23.1	46.4	30.6
		X0HX	36.9	23.1	46.5	30.6

Table 4.18: Assumptions for annual connection and measuring fees.

TS		TS1:GB3	TS2:EB3	TS3:GB2	TS4:EB2	TS5:HN2	TS6:HP1	TS7:HN1
Apartments	Ideal estimates	28.0	53.9	26.3	52.6	39.3	45.7	38.0
	Bounded estimates	5.7	15.1	6.4	17.1	17.8	24.1	23.1
Terraced houses	Ideal estimates	36.3	67.5	34.0	65.7	50.0	56.3	48.1
	Bounded estimates	7.5	19.5	8.4	22.2	23.5	31.6	30.7

Table 4.19: LTC estimates in 2020, for 2021 to 2050, when RE = GE0X.

TS		TS1:GB3	TS2:EB3	TS3:GB2	TS4:EB2	TS5:HN2	TS6:HP1	TS7:HN1
Apartments	Ideal estimates	28.0	60.5	26.3	58.3	39.5	46.5	38.1
	Bounded estimates	5.7	15.3	6.4	17.2	17.8	24.1	23.1
Terraced houses	Ideal estimates	36.3	76.5	34.0	73.5	50.1	57.3	48.2
	Bounded estimates	7.5	19.7	8.4	22.4	23.5	31.6	30.7

Table 4.20: LTC estimates in 2020, for 2021 to 2050, when RE = G00X.

TS		TS1:GB3	TS2:EB3	TS3:GB2	TS4:EB2	TS5:HN2	TS6:HP1	TS7:HN1
Apartments	Ideal estimates	26.1	53.9	24.7	52.6	37.9	45.7	37.2
	Bounded estimates	5.7	15.1	6.4	17.1	17.8	24.1	23.1
Terraced houses	Ideal estimates	33.7	67.5	31.8	65.7	48.0	56.3	47.1
	Bounded estimates	7.4	19.5	8.4	22.2	23.5	31.6	30.7

Table 4.21: LTC estimates in 2020, for 2021 to 2050, when RE = 0E0X.

TS		TS1:GB3	TS2:EB3	TS3:GB2	TS4:EB2	TS5:HN2	TS6:HP1	TS7:HN1
Apartments	Ideal estimates	26.1	60.5	24.7	58.3	38.0	46.5	37.3
	Bounded estimates	5.7	15.3	6.4	17.2	17.8	24.1	23.1
Terraced houses	Ideal estimates	33.7	76.5	31.8	73.5	48.1	57.3	47.2
	Bounded estimates	7.4	19.7	8.4	22.4	23.5	31.6	30.7

Table 4.22: LTC estimates in 2020, for 2021 to 2050, when RE = 000X.

TS		TS1:GB3	TS2:EB3	TS3:GB2	TS4:EB2	TS5:HN2	TS6:HP1	TS7:HN1
Apartments	Ideal estimates	28.0	53.9	26.3	52.6	36.9	45.7	36.7
	Bounded estimates	5.7	15.1	6.4	17.1	17.7	24.1	23.1
Terraced houses	Ideal estimates	36.3	67.5	34.0	65.7	46.7	56.3	46.4
	Bounded estimates	7.5	19.5	8.4	22.2	23.4	31.6	30.6

Table 4.23: LTC estimates in 2020, for 2021 to 2050, when RE = GEHX.

TS		TS1:GB3	TS2:EB3	TS3:GB2	TS4:EB2	TS5:HN2	TS6:HP1	TS7:HN1
Apartments	Ideal estimates	28.0	60.5	26.3	58.3	37.0	46.5	36.9
	Bounded estimates	5.7	15.3	6.4	17.2	17.7	24.1	23.1
Terraced houses	Ideal estimates	36.3	76.5	34.0	73.5	46.8	57.3	46.5
	Bounded estimates	7.5	19.7	8.4	22.4	23.4	31.6	30.6

Table 4.24: LTC estimates in 2020, for 2021 to 2050, when RE = G0HX.

TS		TS1:GB3	TS2:EB3	TS3:GB2	TS4:EB2	TS5:HN2	TS6:HP1	TS7:HN1
Apartments	Ideal estimates	26.1	53.9	24.7	52.6	36.9	45.7	36.7
	Bounded estimates	5.7	15.1	6.4	17.1	17.7	24.1	23.1
Terraced houses	Ideal estimates	33.7	67.5	31.8	65.7	46.7	56.3	46.4
	Bounded estimates	7.4	19.5	8.4	22.2	23.4	31.6	30.6

Table 4.25: LTC estimates in 2020, for 2021 to 2050, when RE = 0EHX.

TS		TS1:GB3	TS2:EB3	TS3:GB2	TS4:EB2	TS5:HN2	TS6:HP1	TS7:HN1
Apartments	Ideal estimates	26.1	60.5	24.7	58.3	37.0	46.5	36.9
	Bounded estimates	5.7	15.3	6.4	17.2	17.7	24.1	23.1
Terraced houses	Ideal estimates	33.7	76.5	31.8	73.5	46.8	57.3	46.5
	Bounded estimates	7.4	19.7	8.4	22.4	23.4	31.6	30.6

Table 4.26: LTC estimates in 2020, for 2021 to 2050, when RE = 00HX.

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5

EXPLORING THE EFFECT OF MULTI-CRITERIA DECISIONS ON HEAT TRANSITIONS

ABSTRACT

Natural gas for heating is widespread in the built environment of the Netherlands, where the government aims at limiting heat demand and reducing natural gas consumption over the coming decades. In the owner-occupied residential sector, this transition is complex and requires cooperation and coordination of individuals and groups that make investment decisions. We use agent-based modelling to explore the effect that various financial policies could have in an illustrative neighbourhood, given that households make multi-criteria and group decisions. In the scientific literature, this type of energy model seldom focuses on the adoption of competing technologies by households as individual and collective agents grouped in homeowner associations in multi-family buildings. To address the problem and knowledge gaps, we model households' preferred combinations of heating system and insulation level as the outcomes of multi-criteria perceived lifetime utility computations, and decisions, as outcomes of those individual computations and a threshold voting system. We explore energy taxes (natural gas and electricity), regulated price of heat from networks, and subsidies (insulation and heat pumps). Under our assumptions, we found that combinations of fiscal policies and regulated heat prices can sometimes create incentives for households to disconnect from natural gas, but that steering the transition mainly with financial policies could prove ineffective. We also found that, in terms of collective CO_2 reduction, some transitions in

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Parts of this chapter refer to article Moncada et al. [2017]; the author of this dissertation and Prof.dr.ir. Zofia Lukszo (one of her promotors) are two of the authors of such article.

which only some households phase out natural gas could have results similar to some scenarios in which households only improve their dwellings' insulation levels.

Keywords: agent-based modelling and simulation; multi-criteria decisions; group decisions; homeowner associations; socio-technical systems.

SUPPLEMENTARY MATERIAL

- **Nava-Guerrero, G. D. C.**, Hansen, H. H., Korevaar, G., & Lukszo, Z. (2022). Agent-based model described in journal article "An agent-based exploration of the effect of multi-criteria decisions on complex socio-technical heat transitions". Publisher of agent-based model: 4TU Repository. DOI of agent-based model: `https://doi.org/10.4121/18865433`.

- **Nava-Guerrero, G. D. C.**, Hansen, H. H., Korevaar, G., & Lukszo, Z. (2022). Supplementary data for journal article "An agent-based exploration of the effect of multi-criteria decisions on complex socio-technical heat transitions". Publisher of supplementary data: 4TU Repository. DOI of supplementary data: `https://doi.org/10.4121/18865406`

5

5.1. INTRODUCTION

In the Netherlands, where natural gas for heating is widespread in the built environment [Beurskens and Menkveld, 2009], a complex energy transition is taking place. The national government has set goals to reduce heat demand and limit natural gas consumption over the coming decades [Rijksoverheid, 2019b]. Municipalities and regions are proposing ways to phase out natural gas in documents known as "Heat transition visions" [RVO] and "Regional Energy Strategies" [Rijksoverheid, 2019b], and the public sector has implemented and continues to explore policies to enable this transition. These policies include, for example, subsidies for insulation [Rijksoverheid, 2016] or heat pumps [Rijksoverheid, 2017b], changes in the taxes of electricity and gas [Rijksoverheid, 2019a,b], and changes in the implementation and management of heat networks [den Dekker et al., 2020, Huygen and Akerboom, 2020, Voortgangsoverleg Klimaatakkoord, 2019].

Phasing out natural gas in the residential built environment is a multi-actor challenge. Homeowners are responsible for energy renovations in their individual dwellings [Filippidou et al., 2017]. However, as explained in our previous work [Nava-Guerrero et al., 2021], coordination and cooperation are specially relevant in owner-occupied multi-family or strata buildings, which have more than one dwelling and potentially more than one owner. In strata buildings, households are required to organise in homeowner associations (HOA). HOAs are governed by rules and regulations [Rijksoverheid, 2019c] and group decisions within HOAs are relevant for energy transitions [Roodenrijs et al., 2020]. Moreover, because the feasibility and affordability of projects such as heat networks depends, among others, on density of demand or numbers of users [Lund et al., 2014, Mahapatra and Gustavsson, 2009], group decisions between HOAs and individual homeowners are also relevant. HOAs are also present in other countries, where they are also relevant to energy transitions [Economidou et al., 2018].

Agent-based models (ABMs) are often used for exploring energy transitions [Li et al., 2015]; however, few works have explored the heat transition [Hansen et al., 2019], and few works have focused on competing technologies [Hesselink and Chappin, 2019]. These limitations are not exclusive to case studies of the Netherlands; they extend to international literature on ABMs. Some exceptions include the works by de Wildt et al. [2021], Faber et al. [2010], Friege [2016], Maya Sopha et al. [2011, 2013], Snape et al. [2015]; the technologies studied in these works include micro-cogeneration, natural gas boilers, heat pumps, electric and wood-pellet heating, insulation measures, district heating, geothermal heat, and electric boilers.

Moreover, in their agent-based models and simulations, Busch et al. [2017] and Fouladvand et al. [2020] incorporate the notion of a necessary minimum density of demand or number of households for heat projects to be feasible. However, organisations that instigate projects, instead of active individual household agents, are included in the work by Busch et al. [2017], and in the work by Fouladvand et al. [2020], HOAs are not mentioned. Further, Pagani et al. [2020] propose a framework to assess scenarios to extend a heat network; they account for household behaviour to predict heat demand, and for a building's likelihood to connect to a heat network. Although they consider multi-family buildings and private or public ownership, HOAs are not discussed. In Nava-Guerrero et al. [2021] we explore the effect of group decisions on heat transitions. To the best of our knowledge at the time of writing, this study was the only ABM work of energy transitions that explicitly represented and focused on group decisions within and between HOAs.

Scientific literature concerning agent-based studies of adoption of alternatives to natural gas in the Netherlands is also limited. A search in the engine Scopus [Elsevier, n.d.] retrieved only 11 publications[1]; in addition to these publications, our work Nava Guerrero et al. [2019] also addresses this topic. From these publications, only Faber et al. [2010], Fouladvand et al. [2020], and our works Nava Guerrero et al. [2019], Nava-Guerrero et al. [2021] study the adoption of alternatives to natural gas, and two additional publications [Bloemendal et al., 2018, de Wildt et al., 2021] study adjacent topics.

In this chapter, we continue our line of research from Moncada et al. [2017], Nava Guerrero et al. [2019], Nava-Guerrero et al. [2021]. In the ABM in Nava-Guerrero et al. [2021], households are decision-makers with bounded financial rationality and they determine their preferences via net present value (NPV) calculations using implicit discount rates (IDRs). IDRs are a quantitative way of representing financial and non-financial factors that influence preferences [Schleich et al., 2016]. Because non-financial factors are implicit in the discount rate in Nava-Guerrero et al. [2021], the possibilities to explore the performance of various financial policies on multi-criteria decisions were limited. Therefore, the work presented in this chapter was guided by the following research question, which is an addition with respect to the version of this chapter published as Nava-Guerrero et al. [2022]:

[1] We searched for entries with the following keywords in the publication's title, abstract, or keywords: (heat OR heating OR thermal) AND (netherlands or dutch) AND (energy) AND (agent-based).

How could multi-criteria decisions by households influence the course of the heat transition in a neighbourhood in the Netherlands, under different policy interventions?

In line with our research question, the objective of this chapter is to address the following knowledge gap. Based on the aforementioned literature, an agent-based study that focuses on heat transitions, incorporates multiple competing alternatives to the incumbent heating system, explicitly represents individual and group decisions within and between HOAs, and explores the performance of financial policies while representing multi-criteria decisions by households, is still missing from the international scientific literature.

Thus, our present work is novel due to the combination of the following aspects, which are relevant to the Netherlands and also to energy transitions in other countries:

- Focus on the emerging challenge of a heat transition in which natural gas is to be phased out from the residential built environment and various combinations of insulation and heating systems compete to replace incumbent natural gas boilers.

- Representation of an illustrative neighbourhood with both single-family and multi-family buildings, in which each agent represents one household in one dwelling, households in multi-family buildings are grouped in HOAs, and there are explicit group constraints and decisions both within and between HOAs.

- Exploration of the performance of financial policies for the phase out of natural gas while explicitly representing multi-criteria decisions by households.

By integrating these aspects in an ABM, we explored a heat transition in an illustrative neighbourhood. We found that under our assumptions, combinations of fiscal policies and regulated heat prices can sometimes create opportunities to incentivise households to disconnect from natural gas. Furthermore, we found that steering the transition mainly with financial policies could prove ineffective, and that not all transitions are equal as they can have different costs and benefits. This approach can be applied to international case studies in which energy transitions are taking place.

The remaining parts of this chapter are structured as follows. In Section 5.2, we specify our materials and methods. Then, we describe our ABM and simulation work in Section 5.3. In Section 5.4, we present and discuss our results, and in Section 5.5, our conclusions.

5.2. Materials and methods

In line with our previous work [Moncada et al., 2017, Nava Guerrero et al., 2019, Nava-Guerrero et al., 2021], we use an approach that integrates the perspectives of STS [Cooper and Foster, 1971, Herder et al., 2008, Trist, 1981] and CAS [Holland, 1988, 1995, Waldorp, 1993]. We describe the problem with the concepts of actors, technology, and institutions. Actors include individuals or organizations [Enserink et al., 2010], and their rationality can be bounded [March, 1978, Simon, 1997]. Interactions between and within actors and technology, which form networks [Herder et al., 2008], are complex and involve institutions, i.e. rules and regulations [North, 1991]. Based on these concepts, we formalise the problem in an ABM. Agent-based modelling builds on CAS and STS, and in this method, actors can be seen as individual components that shape the system as a whole [Dam et al., 2013].

As explained in our previous works [Nava Guerrero et al., 2019, Nava-Guerrero et al., 2021], ABMs have agents, environment, and time [Dam et al., 2013]. The environment contains the agents [Dam et al., 2013]. Agents have parameters, known as “state variables”, which describe them at each point in time [Grimm et al., 2010, Wooldridge and Jennings, 1995], and agents and environment influence each other over time. The behaviour of the system, including interactions between agents, is based on knowledge or assumptions regarding individual agents [Borshchev and Filippov, 2004, Grimm and Railsback, 2005, North and Macal, 2007, Railsback and Grimm, 2019].

Our ABM represents households' adoption of technology states (defined as combinations of heating systems and insulation) in an illustrative neighbourhood under different socio-technical conditions. These conditions, described in Section 5.3, are household preference profiles (HPPs, defined as combinations of criteria and associated weights that each household uses to decide which technology state the household prefers) and regulatory environments (RE, defined as combinations of policies). Our selection of financial policies is based on previous or existing financial energy measures (see Chapter 2); namely, taxation for electricity and gas, price regulation for heat from networks, and subsidies for insulation and heating systems.

In the remainder of this chapter, we use a household's "preference" to refer to the most-preferred technology state of the household, based on a multi-criteria computation in which the household uses its HPP.

We observe the effects of HPPs and REs on five key performance indicators (KPIs): number of households using natural gas (HwNG), natural gas consumption (NG), CO_2 emissions from heating systems' operation (CO_2 emissions), household costs (HC) as cumulative investment (IC) and operation costs (OC) by households, and subsidy costs (SC) as cumulative costs of subsidies for insulation and heat pumps.

We use our ABM to simulate developments in the neighbourhood under experimental scenarios, i.e. combinations of an HPP and a RE that define the input conditions for the simulation. For simplicity, we only explore instances of the neighbourhood in which all households have the same profile. To compare initial preferences with simulation outcomes, we study which combinations of heating systems and insulation levels households preferred at the beginning of the simulation as well as the actual combinations of heating systems and insulation levels present in the illustrative neighbourhood after 30 simulated years.

We use the following modelling questions to guide our work:

1. *Which combinations of heating systems and insulation levels did households prefer at the beginning of the simulation?*

2. *Under which socio-technical conditions, i.e. household preference profiles and regulatory environments, were heat transitions possible?*

3. *How did heat transitions influence CO_2 emissions and costs?*

We analyse output data with R Project 3.2.6 [R Core Team, 2018] via R Studio 1.1.463 [RStudio Team, 2018] with ggplot2 3.2.1 [Wickham, 2016], sqldf 0.4-11 [Grothendieck, 2017], and car 3.0-2 [Weisberg and Fox, 2019]. Our methods are visual inspection and non-parametric statistical tests due to lack of normality and presence of outliers.

We address validation in two ways: a sensitivity analysis based on the One-factor-at-a-time (OFAT) method [ten Broeke et al., 2016], and a reflection on publications regarding the heat transition.

We use desk research to parameterise our ABM; estimates and assumptions for input data are described in Appendix A (Section 5.7). We use some elements and parameters that we also used in Nava Guerrero et al. [2019], Nava-Guerrero et al. [2021].

To identify relevant decision-making criteria, gather information to conceptualise an illustrative neighbourhood, and gather data for some parameters, we conducted a research project at Delft University of Technology. As part of the project, two of the authors supervised a graduate thesis [Wessels, 2020] on a multi-criteria assessment; methods included literature reviews, desk research, and interviews. We use four criteria that were selected by Wessels [2020]: finances, environment, space (occupy by the heating system in the dwelling), and duration (of the works in the dwelling required to install the new technology). In Wessels [2020], reliability of experts to support the change of TS was also included; however, we exclude this criterion to represent a situation in which, by 2030, there are reliable experts in each of the TSs. The literature that was consulted in Wessels [2020] included, among others, Bjørneboe et al. [2018], Ebrahimigharehbaghi et al. [2019, 2020], Wilson et al. [2015].

The neighbourhood that we simulate is illustrative, i.e. while it contains elements of the residential built environment in the Netherlands, it does not represent any specific neighbourhood. For example, the cost-effectiveness of different heating systems can vary as it depends on multiple factors [ECW, Hoogervorst et al., 2020a]; here, we represent heat networks as having higher upfront costs than heat pumps. We make this choice to explore tensions between heating systems that may be preferred on the basis of finances, and other heating systems that may be preferred on the basis of environment, space, or duration of the works.

5.3. DESCRIPTION OF THE AGENT-BASED MODEL

Our ABM represents an illustrative neighbourhood. It expands our previous work in [Nava-Guerrero et al., 2021] by explicitly representing households' multi-criteria decisions under combinations of policies. In this section, we present our ABM's overview and initialization, based on the ODD protocol that is commonly used to describe ABMs [Grimm et al., 2010].

5.3.1. MODEL OVERVIEW

PURPOSE

The purpose of our ABM was described in Section 5.1, i.e. to explore the effect of various financial policies on the heat transition given that household decisions are multi-criteria. We use the KPIs from Table 5.1.

KPI	Abbreviation	Units	Description
Natural gas consumption	NG	MWh	Annual natural gas consumption; computed before households make technology changes.
CO_2 emissions	CO_2	Ton	Cumulative CO_2 emissions from the operation of heating systems; computed before households make technology changes.
Households with natural gas	HwNG	Number of households	Number of households connected to the natural gas network; computed after households make technology changes.
Household costs	HC	Million Euros	Cumulative investment costs (IC) (which include reinvestment) and operation costs (OC) by all households; computed after households make technology changes.
Subsidy costs	SC	Thousands of Euros	Cumulative costs of subsidies for insulation and heat pumps; computed after households make technology changes.

Table 5.1: KPIs used in the agent-based model.

ENTITIES, VARIABLES, AND SCALES

Agents are households, the environment has market conditions and policies, and time consists of annual time steps. We study 30 simulation years, from 2019.

Households - Households have technology and actor components. The technology is the dwelling with its heating system, insulation, and appliances. The actor represents residents and their preferences.

State variables (Table 5.2) describe a household. A household's "type of dwelling" describes whether its dwelling is self-standing (semi-detached or terraced house) or in a strata building (apartments); the type of dwelling is linked to an energy demand and, potentially, group constraints. Households are part of the building's HOA, which have one member for self-standing dwellings. Each household has a technology state ("TS"), i.e. a combination of heating system and insulation, and appliances. Each household remembers its own "previous TS" and has a "profile" representing the combination of criteria and associated weights that the household uses to decide which TS the household prefers.

5

Subject	State variable	Type	Description
Dwelling (technology)	Type of dwelling	Static	Apartment, semi-detached, or terraced house.
	TS	Variable	TS from the TS available (see Table 5.3).
	Previous TS	Variable	TS that the household had before its current TS.
Resident (actor)	Profile	Variable	4-tuple of numbers representing the relative quantitative importance of each decision-making criterion for a household.

Table 5.2: State variables of household agents in the agent-based model.

The ABM has nine TSs (Table 5.3). Three TSs have natural gas boilers and four TSs have alternative heating systems. We assume that hydrogen and green gas become available only from 2030 onwards. The website of the Expertise Center for Heat in the Netherlands states that hydrogen is not expected to play a significant role in the Dutch built environment until 2030 [ECW, 2020b]. The website also states that the availability of green gas (which is processed biogas or syngas [Hoogervorst et al., 2020b]) is limited, and that the green gas sector has the ambition of having increased its production by 2030 [ECW, 2020a]; however, that for hydrogen and green gas, the future remains uncertain [ECW, 2020a,b].

The TS of a household is dynamic. Households consider changing their TS annually. There are two restrictions based on a household's current TS (Figure 5.1). First, insulation levels can only improve. Second, after being disconnected, a dwelling cannot reconnect to natural gas.

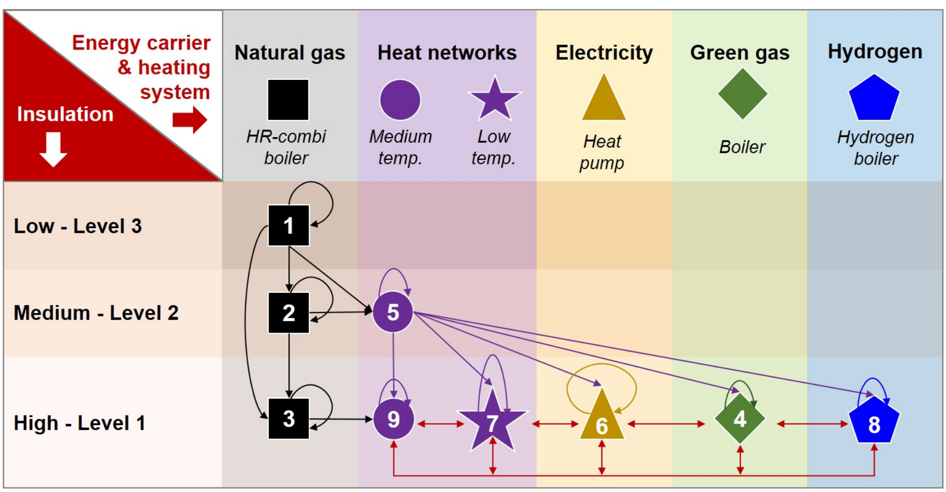

Figure 5.1: TSs that are available to households based on their current TS.

TS	Type	Heating system	Insulation	Appliances
1:GB3	Individual[a]	Natural gas boiler	3:Low	Natural gas
2:GB2	Individual[a]	Natural gas boiler	2:Medium	Natural gas
3:GB1	Individual[a]	Natural gas boiler	1:High	Natural gas
4: BN1[b]	Collective: Neighbourhood[c]	Green gas network and an individual hybrid heat pump	1: High	Electric
5:medHN2	Collective: Neighbourhood[c]	Medium temperature heat network	2:Medium	Electric
6:HP1	Collective: HOAs[d]	Heat pump	1:High	Electric
7:lowHN1	Collective: Neighbourhood[c]	Low temperature heat network and an individual heat pump	1:High	Electric
8: HH1[b]	Collective: Neighbourhood[c]	Hydrogen network and an individual hybrid heat pump	1: High	Electric
9:medHN1	Collective: Neighbourhood[c]	Medium temperature heat network	1:High	Electric

[a] In the ABM, changes in insulation are treated as individual decisions for apartments too; in practice, renovation projects may require approval from an HOA. See the website of the municipality of The Hague [Gemeente Den Haag, n.d.] as an example.
[b] In the ABM, TS4:BN1 and TS8:HH1 are available to households only after 2030.
[c] We assume that all collective projects at the level of the neighbourhood require changes in buildings that need approval from the building's HOA.
[d] In the ABM, TS1:HP6 are treated as collective TSs for HOAs also for self-standing houses, which are modelled as part of an HOA with a one member, i.e. themselves.

Table 5.3: Conceptualization of the TS available in the illustrative neighbourhood.

Five TSs (TS4:BN1, TS5:medHN2, TS6:HP1, TS7:HN1, and TS8:HH1) are simplified representations of combinations of heating systems and insulation that have already been represented in energy models in the Netherlands [Hoogervorst et al., 2020a, Wessels, 2020].

We conceptualised the remaining TSs as follows. A study by Faber et al. [2010], which explored competition between incumbent natural gas boilers and micro-cogeneration that also uses natural gas, found that the adoption of the alternative could be inhibited if demand for natural gas decreased, for example, via insulation. Therefore, we include TSs that only require changes in insulation while maintaining a natural gas boiler (TS2:GB2 and TS3:GB1). This allows us to explore combinations of policies that aim at reducing heat demand, such as subsidies for insulation, and policies that aim at phasing out natural gas, such as subsidies for heat pumps. Similarly, we include a TS in which households would join a medium temperature heat network but would also insulate their dwelling and reduce their heat demand (TS9:medHN1).

The decision-making criteria are operationalised as follows. “Finances” is the lifetime-cost of adopting and using a TS. “Environment” is the CO_2 emissions from operation of a TS, based exclusively on the amount of energy carrier used by the TS during its lifetime. “Space” is the area of the dwelling (in m2) that a TS would occupy. “Duration” is the number of hours required to change TSs. Details on these calculations are provided in Appendix B (Section 5.8).

Profiles are 4-tuples of numbers with values 0, 25, 50, or 100. Each number represents the relative importance that a household gives to each decision-making criterion. The sum of all numbers in a profile is always 100. Each household uses its profile to determine its preferred TS relative to each current TS. To do this, households use the numbers in their profiles as the weights of the four decision-making criteria when computing a weighted average over the normalised criteria scores. The resulting weighted average or score is considered to be the multi-criteria perceived lifetime utility of each TS relative to the current TS. This computation is defined as the Sub-model: Individual multi-criteria perceived lifetime utility from Appendix B (Section 5.8).

Market conditions – We include sales prices (retail price plus tax) of energy and prices of changing TSs. Energy prices include gas, electricity, and heat from networks. To focus on the effect of fiscal policies, we maintain retail prices constant during the simulation, with the exception of the regulated price of heat from networks. Taxes change based on REs. Input data for this and other variables in the ABM are presented in Appendix A (Section 5.7).

Policies – Regulatory environments (REs) are combinations of five policies; each policy can be active or inactive. These policies are an annual increase in natural gas tax after 2026 (G), annual decrease in electricity tax after 2026 (E), cap on the price of heat from networks (H), insulation subsidy (I), and heat pump subsidy (S). When a policy is inactive, it means that the annual increase or decrease is zero, that there is no price cap, or that there is no subsidy, respectively. We represent a RE as a string of length five; if a policy is active, we represent it with a letter (as just indicated), and if it inactive, with a zero. For example, in RE=GEHIP all policies are active; in RE=GEH0P there is no insulation subsidy but the other policies are active; in RE=00000 all policies are inactive. We write RE=GXXXX to denote the collection of all REs where the increase in natural gas tax after 2026 is active and each of the remaining policies is either active or inactive.

Our policies are simplified representations of existing measures and expectations for future policies. Taxes on gas and electricity have increased and decreased, respectively [Rijksoverheid, 2019a]. Based on the Climate Agreement, further increases and decreases until 2026 can be expected [Rijksoverheid, 2019b]. The price of heat from networks is regulated [ACM, 2019] and alternative forms of regulation are also expected [Voortgangsoverleg Klimaatakkoord, 2019]. Subsidies for insulation [Rijksoverheid, 2016] and heat pumps [Rijksoverheid, 2017b] have been available.

Group decisions – Households’ preferences are constrained by group decisions via a system of thresholds [2]. In our ABM, if households are part of an HOA, a threshold

[2] The word “threshold” replaces the word “quorum” from our previous work in Nava-Guerrero et al. [2021].

percentage of households must first approve such project within the HOA. If the threshold is met, the TS becomes the preferred TS of all households in the HOA, and if the threshold is not met, the households that preferred the project no longer pursue it. Note that this is a simplified representation of the legal systems and decision-making processes in place, which are more intricate and varied. In the Netherlands, HOAs are regulated by Book 5 of the Civil Code [2018] and by their deed of division and rules [Rijksoverheid, 2017a]. See Roodenrijs et al. [2020] for a tentative framework to describe group decisions within HOAs in energy transitions.

In our ABM, collective TSs for HOAs also require a percentage of households in the neighbourhood to be willing to join the project in order for the project to be realised. This reflects the fact that the costs or feasibility of energy infrastructure such as heat networks are linked to number of users or density of demand [den Dekker et al., 2020, Lund et al., 2014, Mahapatra and Gustavsson, 2009]. We define these percentages as “HN Threshold” for heat networks (including TS5:medHN2, TS7:lowHN1, and TS9:medHN1); “HH Threshold” for TS8:HH1; and “BN Threshold” for TS4:BN1.

We represent an additional prerequisite for hydrogen and green gas projects. Based on ECW [2020a,b], we assume that there is only one network infrastructure for gas and that it can only transport either hydrogen or other types of gas. We do not account for a mix of natural gas and green gas. In our ABM, the corresponding threshold must be met and households with one of the other energy carriers must prefer to change their TS to a TS that uses the energy carrier in question.

5

PROCESS OVERVIEW AND SCHEDULING

The main processes in our ABM are as follows (see Table 5.1 with KPIs).

1. In every time step, market conditions are updated based on the RE. In the first time step, HwNG is computed. In every subsequent time step, heating systems age, households consume heat, NG and operation costs are recorded, and the procedures below take place.

2. Households determine their preferred TSs using the sub-model 1 from Appendix B (Section 5.8).

3. Thresholds for collective projects are assessed and projects for which thresholds are met are built and become operational the following year. The steps below are followed for heat networks, heat pumps, green gas networks, and hydrogen networks, in that order.

   (a) The ABM determines if the HOA Threshold for a collective project in each building is met. In each HOA, if the HOA Threshold was met for a neighbourhood project, either all households in the HOA count towards the required threshold in the neighbourhood, or none of them does (winner-takes-all). For heat networks, votes for TS5:medHN2, TS7:lowHN1, and TS9:medHN1 are counted together; only later is it determined which TS with a heat network each household implements.

   (b) The ABM determines if the neighbourhood threshold is met (HN Threshold, HH Threshold, or BN Threshold).

(c) If a neighbourhood threshold is met or a neighbourhood project of that type exists from a previous tick, the households in HOAs in which the HOA threshold was met for that type of neighbourhood project maintain their current TS if they had already adopted that type of neighbourhood project or replace their current TS if they had not. If the HN Threshold is met, each HOA determines whether a low and medium temperature network is implemented, based on which type is preferred by most households in the HOA. The constraints from Figure 5.1 are also considered when determining whether a household will install TS5:medHN2 or TS9:medHN1.

4. Individual TSs are implemented as follows.

   (a) Households that preferred collective TSs that were not feasible determine their preferred individual TS (including TS6:HP1 for self-standing houses) and implement it.

   (b) Households that initially preferred TSs with natural gas and who did not join a collective project in that time step adopt their preferred TS.

5. Each household replaces its heating system if such heating system has reached the end of its lifetime.

6. HwNG is updated and CO_2, HC and SC are computed.

5.3.2. INITIALIZATION

Our illustrative neighbourhood has 500 dwellings and one household per dwelling. The neighbourhood has a new and an old area where dwellings initially have high and low insulation, respectively. There are three types of dwellings: terraced and semi-detached houses, and apartments. The energy demand is determined by the dwelling type and insulation. The type of dwelling and insulation are based on a set of dwellings conceptualised in Wessels [2020]. At the beginning of the simulation, all dwellings are connected to natural gas and their boilers are 14 years; their expected lifetime is assumed to be 15 years. Old boilers are a known problem in the European Union [European Commission, 2016].

The initial configuration of the neighbourhood is summarised in Table 5.4. Moreover, we use an HOA Threshold of 70% and HN Threshold, HH Threshold, and BN Threshold of 75%.This initialization is constant across experimental scenarios. We point out that this is not meant to correspond to any specific real-world neighbourhood.

Area	Type of dwelling	Number	TS
Old	Semi-detached	50	TS1:GB3
	Terraced	150	
New	Semi-detached	22	TS3:GB1
	Terraced	50	
	Apartments	228	

Table 5.4: Initialization of dwellings in the neighbourhood.

We use experimental scenarios that differ in terms of household HPPs and REs. There are 32 REs resulting from all combinations of the five policies. We study 23 HPPs, summarised in Table 5.5. Four HPPs are single-criterion. To explore the effect of financial policies, in the remaining 20 HPPs finances has at least 25% weight. For simplicity, we only explore instances of the neighbourhood in which all households have the same profile.

Profile	Finances	Environment	Space	Duration
A	25	50	0	25
B	25	50	25	0
C	25	25	25	25
D	25	25	50	0
E	25	25	0	50
F	25	75	0	0
G	25	0	50	25
H	25	0	25	50
I	25	0	75	0
J	25	0	0	75
K	50	50	0	0
L	50	0	50	0
M	50	0	0	50
N	50	25	25	0
O	50	25	0	25
P	50	0	25	25
Q	75	25	0	0
R	75	0	25	0
S	75	0	0	25
T	100	0	0	0
U	0	100	0	0
V	0	0	100	0
W	0	0	0	100

Table 5.5: Household preference profiles with weights per criterion.

5.4. RESULTS AND DISCUSSION

This section is structured as follows. In Section 5.4.1, we discuss households' preferred TSs at the beginning of the simulation, and in Section 5.4.2, results from the entire simulation. In 5.4.3, we discuss the effect of heat transitions on the KPIs, and in Section 5.4.4, we address validation. Finally, we discuss limitations and future work in Section 5.4.5. Simulation data and agent-based model are available as supplementary material (see page 112).

Throughout the section we use three concepts to classify simulation runs. First, *partial transitions*, in which some but not all households disconnected from natural gas. Second, *full transitions*, in which all households disconnect from natural. Third, *insulation-only*, in which all households remained connected to natural gas and a positive nonzero number of households improved their insulation level.

5.4.1. HOUSEHOLDS' PREFERRED TSS AT THE BEGINNING OF THE SIMULATION

We use households' preferred TSs at the beginning of the simulation as a baseline to understand the effect of our dynamic simulation on the TSs that were adopted in the neighbourhood. Table 5.6 is an overview of the most preferred TS of households with single-criterion household preference profiles (HPPs). As illustrated in the row with HPP=100-0-0-0, a cost-neutral transition was not possible under the initial conditions. All households preferred to remain connected to natural gas and only households in old semi-detached dwellings preferred to improve their insulation to level 2 when a subsidy for this purpose was available. Similarly, when households based their decisions on duration, they preferred to maintain their existing TS. In contrast, when households based their decisions on a single criterion other than finances and duration, they preferred medium temperature heat networks with varying levels of insulation.

Results differed when households had multi-criteria HPPs. Under most HPPs, households preferred natural gas, with varying insulation levels. There were six exceptions in which all households preferred medium temperature heat networks, summarised in Table 5.7. In those HPPs, environment is weighted at least as much as finances, and duration is weighted 25% or 0%.

<table>
<tr><th rowspan="3">Criterion</th><th colspan="5">Type of dwelling</th></tr>
<tr><th colspan="2">Old</th><th colspan="3">New</th></tr>
<tr><th>Semi-detached</th><th>Terraced</th><th>Semi-detached</th><th>Terraced</th><th>Apartments</th></tr>
<tr><td rowspan="2">Finances HPP=100-0-0-0</td><td>RE=XXXIX, TS2:GB2</td><td rowspan="2">TS1:GB3</td><td colspan="3" rowspan="2">TS3:GB1</td></tr>
<tr><td>RE=XXX0X, TS1:GB3</td></tr>
<tr><td>Environment HPP=0-100-0-0</td><td colspan="5">TS9:medHN1</td></tr>
<tr><td>Space HPP=0-0-100-0</td><td colspan="2">TS5:medHN2</td><td colspan="3">TS9:medHN1</td></tr>
<tr><td>Duration HPP=0-0-0-100</td><td colspan="2">TS1:GB3</td><td colspan="3">TS3:GB1</td></tr>
</table>

Table 5.6: Preferred TSs at the beginning of the simulation.

<table>
<tr><th rowspan="2">Preferred heating system</th><th rowspan="2">Are HPPs sufficient?</th><th rowspan="2">Profile</th><th colspan="4">Criterion (%)</th><th colspan="3">Preferred TS per dwelling</th></tr>
<tr><th>Finances</th><th>Environment</th><th>Space</th><th>Duration</th><th>Old semi-detached</th><th>Old terraced</th><th>New area</th></tr>
<tr><td rowspan="6">Medium temperature heat network</td><td rowspan="6">Yes</td><td>A</td><td>25</td><td>50</td><td>0</td><td>25</td><td colspan="2" rowspan="2">TS5:mHN2</td><td rowspan="2">TS9:mHN1</td></tr>
<tr><td>C</td><td>25</td><td>25</td><td>25</td><td>25</td></tr>
<tr><td>B</td><td>25</td><td>50</td><td>25</td><td>0</td><td rowspan="4">TS5:mHN2</td><td colspan="2" rowspan="4">TS9:mHN1</td></tr>
<tr><td>D</td><td>25</td><td>25</td><td>50</td><td>0</td></tr>
<tr><td>F</td><td>25</td><td>75</td><td>0</td><td>0</td></tr>
<tr><td>K</td><td>50</td><td>50</td><td>0</td><td>0</td></tr>
</table>

Table 5.7: Sufficient HPPs for households to prefer a disconnection from natural gas at the beginning of the simulation.

5.4.2. HEAT TRANSITIONS OVER 30 YEARS

Partial and full transitions were possible over 30 years. HPPs were the single most influential condition enabling transitions. While no RE was a sufficient condition for a partial transition, the same six HPPs from Table 5.7 were sufficient conditions for full transitions. The remaining HPPs under which either type of transition took place had to be combined with specific REs. Conditions are summarised in Table 5.8.

Transition?	HPPs as condition	Profile	Criterion (%)				Additional REs required
			Finances	Environment	Space	Duration	
Partial	Necessary	T	100	0	0	0	GEXXX or G0XXP
		Q	75	25	0	0	GXXXX
		O	50	25	0	25	GXHIX or GE0IP
Full	Sufficient	A	25	50	0	25	None
		B	25	50	25	0	
		C	25	25	25	25	
		D	25	25	50	0	
		F	25	75	0	0	
		K	50	50	0	0	
	Necessary	E	25	25	0	50	GXHXX
Insulation	Sufficient	N	50	25	25	0	None
	Necessary	T	100	0	0	0	0XXIX or G0XX0
		I	25	0	75	0	GXXXX or 0XXIX
		L	50	0	50	0	
		P	50	0	25	25	G0HIX or GEHI0
		O	50	25	0	25	G00IX or GE0I0
		S	75	0	0	25	GXXIX
		R	75	0	25	0	0XXIX or GXXXX
		Q	75	25	0	0	0XXXX

Table 5.8: Household profiles that were sufficient or necessary conditions for full transitions after 30 years in the set of nominal results, according to our ABM.

PARTIAL TRANSITIONS

Partial transitions took place under three HPPs (T, Q, or O). No HPP was a sufficient condition; they always required RE=GXXXX, and in some cases, additional policies. In those HPPs, finances had the highest weight, followed by environment in multi-criteria HPPs.

The number of households that disconnected from natural gas varied, as well as the TSs that they adopted. In most cases, households adopted heat pumps. As shown in Figure 5.2, the median of the number of disconnected households was highest with HPP=50-25-0-25. The median (428) occurred for RE=G0HIX: households joined a medium temperature heat network, and in the old area, households made only small insulation improvements. Outliers when HPP=50-25-0-25 occurred under RE=GE0IP: 150 households adopted heat pumps. In the other HPPs households also adopted heat pumps, with higher outliers for HPP=100-0-0-0 and RE=GEX0P, and HPP=75-25-0-0 and RE=GEXXP. REs in which outliers occurred had favourable conditions for heat pumps: increasing natural gas taxes, decreasing electricity taxes, and heat pump subsidy.

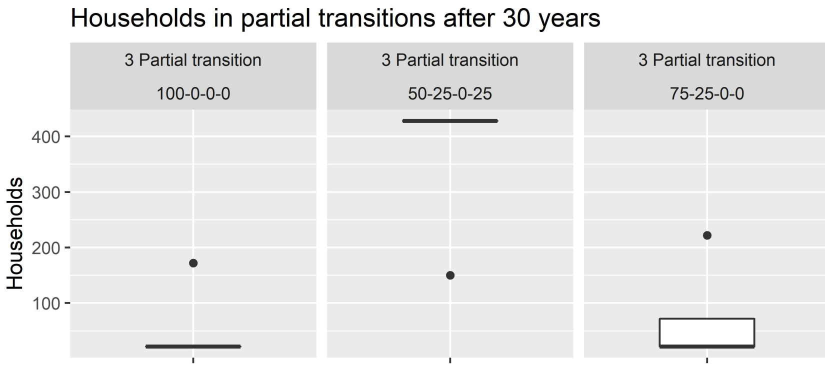

Figure 5.2: Boxplot of the number households that disconnected from natural gas by the end of the simulation, when the simulation run was classified as a partial transition.

During partial transitions, households disconnected from natural gas over the last two thirds of the simulation; the earliest ones occurred under HPP=75-25-0-0. Changes in insulation preceding a natural gas disconnection were also possible. For example, Figure 5.3 illustrates two types of transitions when HPP=50-25-0-25. Under GXHIX, households that disconnected from natural gas adopted heat networks towards the end of the simulation (note that the changes in G0HIX and GEHIX took place one year apart). Under GE0IP, they adopted heat pumps.

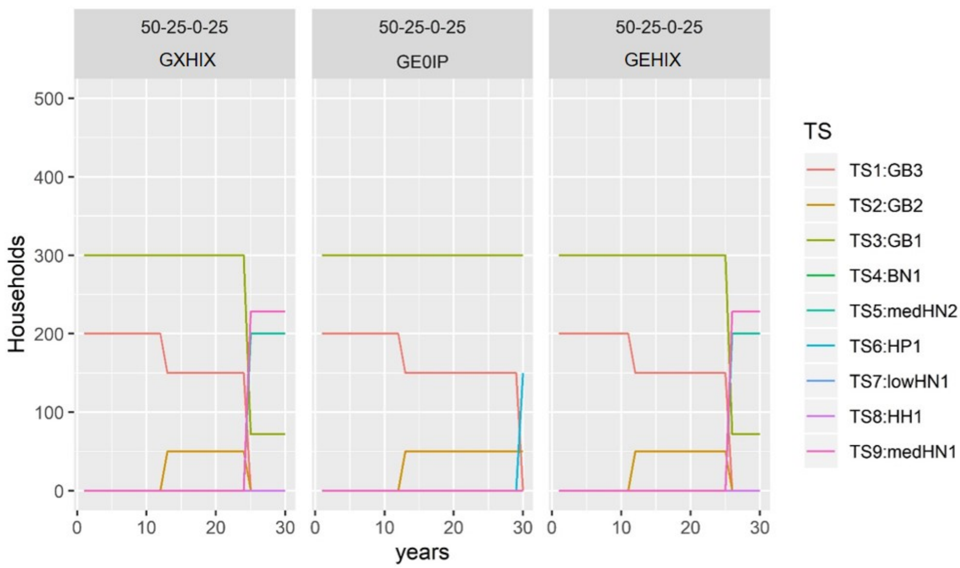

Figure 5.3: TSs of households in partial transitions when HPP=50-25-0-25 per RE.

FULL TRANSITIONS

In most full transitions, disconnections took place at the beginning of the simulation, when varying numbers of households adopted medium temperature heat networks. Under HPP=25-25-25-25 and 25-50-0-25, households in old dwellings made only small insulation improvements (TS5:medHN2). Under HPP=25-25-50-0, 25-50-25-0, 25-75-0-0, and 50-50-0-0, most households improved their insulation further (TS9:medHN1), except for households in old semi-detached dwellings (TS5:medHN2). However, under 50-50-0-0 and RE=GX0XX, the 22 households in new semi-detached houses that had adopted TS9:medHN1 changed to TS6:HP1; this change occurred in the second half of the simulation, as illustrated in the two examples from Figure 5.4. Under HPP=25-25-0-50, disconnections occurred in the last third of the simulation and all households adopted a heat network, as shown in Figure 5.5.

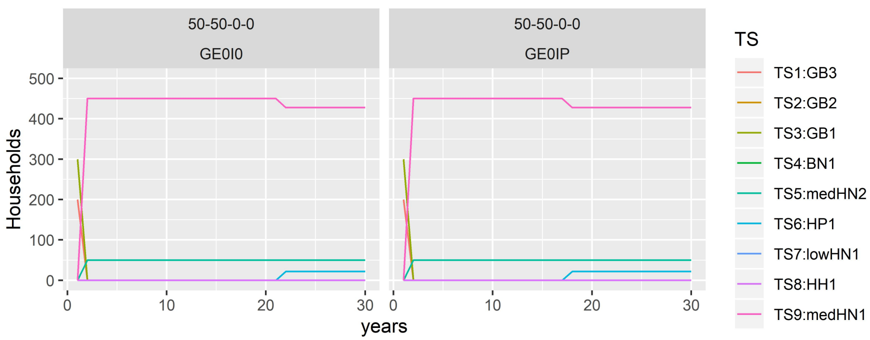

Figure 5.4: TSs of households in full transitions when HPP=50-50-0-0 per RE.

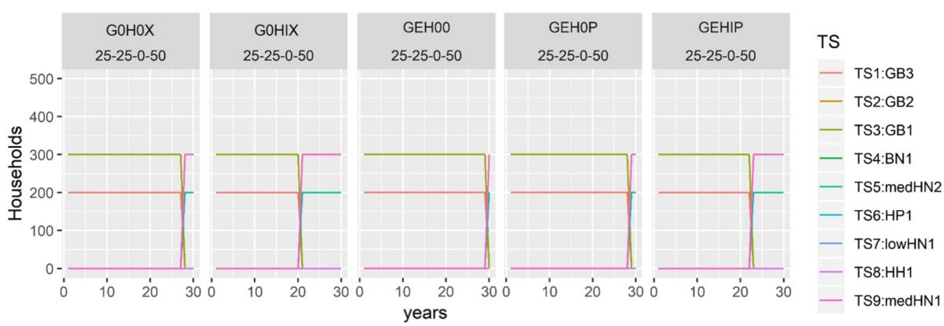

Figure 5.5: TSs of households in full transitions when HPP=25-25-0-50 per RE.

INSULATION-ONLY

Households that never disconnected from natural gas sometimes improved their insulation. Figure 5.6 shows the following. Under RE=0XXXX, by the end of the second year, 250 households improved their insulation to level 3, and 50 households, to level 2. Figure 5.7 illustrates that when RE=GXXXX, changes took place in different years.

Changes were at the beginning of the simulation for HPP=50-25-25-0, towards the middle for 50-25-0-25, and towards the end for 75-0-0-25 and 50-0-25-25. For the remaining HPPs, changes were at the beginning when there was an insulation subsidy, and when such a subsidy was not available, changes occurred towards the end. In Figure 5.7, empty boxes indicate that this was not an insulation-only run.

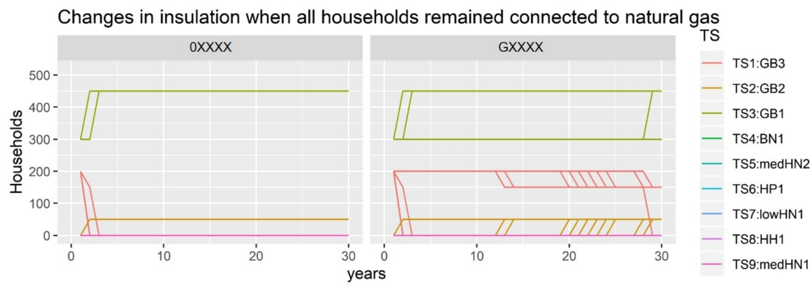

Figure 5.6: TSs of households when only changes in insulation took place, by increase in natural gas tax.

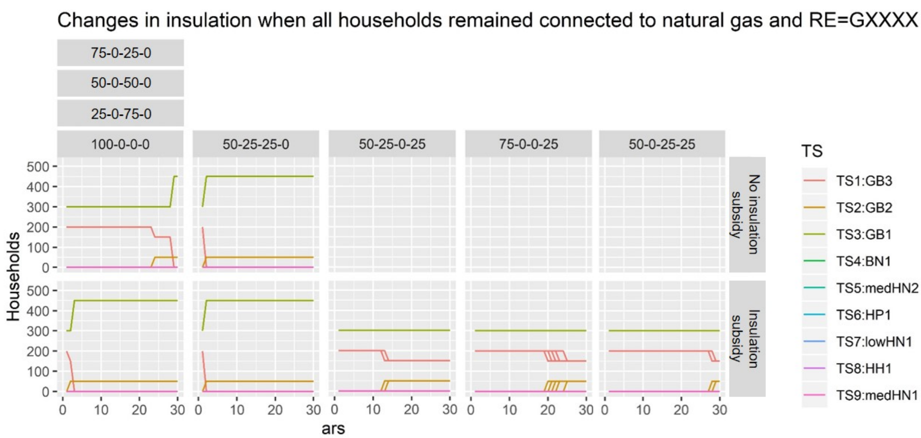

Figure 5.7: TSs of households when only changes in insulation took place and RE=GXXXX.

5.4.3. EFFECTS OF TRANSITIONS ON NATURAL GAS CONSUMPTION, CO_2 EMISSIONS, AND COSTS

We normalised the KPIs and classified simulation runs in four groups (“1 No changes”, “2 Insulation only”, “3 Partial transition”, and “4 Full transition”), as illustrated in Figure 5.8.

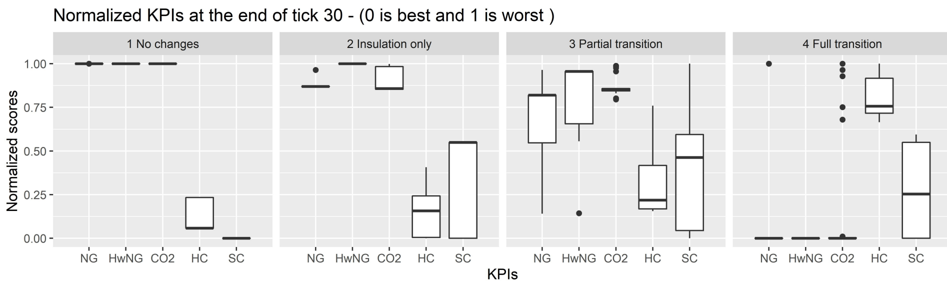

Figure 5.8: Normalised KPIs in the ABM nominal results.

In Figure 5.8, the medians of NG, HwNG and CO_2 appear at their lowest in “4 Full transition”. By definition, when the entire neighbourhood disconnected, no natural gas was consumed. Moreover, all households changed to TSs with the lowest emissions. In “4 Full transition”, outliers for NG indicate that changes in TSs took place at the end of the last year and they would only influence heat consumption on the following year. Outliers in CO_2 correspond to transitions under HPP=25-25-0-50, which took place in the last third of the simulation. Notably, the median of CO_2 appears to be similar for “3 Partial transition” than for “2 Insulation only”; in spite of their small difference, the distributions are different (see Table 5.9).

Variable compared	Levene's[a] (p-value)	Shapiro-Wilk[b] (p-value)	Kruskal-Wallis rank sum[c] (p-value)	Wilcoxon rank sum (summary of findings)
Normalised CO_2 emissions	0.00	0.00	0.00	Differences between all groups
Annual CO_2 emissions	0.00	0.00	0.00	Differences between all groups
Subsidy costs per annual CO_2 reduction after 30 years	0.00	0.00	0.00	Differences between most groups, except for 2&3.

[a] We assume homogeneity of variances only if p-values are higher than the significance level of 0.05.
[b] We assume normality only if values are higher than the significance level of 0.05.
[c] We use this test as a non-parametric alternative to one-way ANOVA. A p-value lower than the significance level of 0.05 indicates significant differences between groups.

Table 5.9: Results for statistical tests to assess the effect of heat transitions on CO_2 emissions between four groups: “1 No changes”, “2 Insulation only”, “3 Partial transition”, and “4 Full transition”.

The median of HC was higher for “4 Full transition” than for “1 No changes”. However, as described in Table 5.1, NG and HwNG are annual measures, and CO_2, HC, and SC are cumulative measures. When households made changes in TSs in different years, the lifetime of some TSs was not finished by the end of the simulation. As a result, a comparison of CO_2 and HC between groups that include “2 Insulation only” and “3 Partial transition” is incomplete. In those cases, investment costs would be overrepresented in HC and CO_2 emissions could be either under- or overrepresented. This indicates that, unless households changed their TSs from the beginning of the simulation, a horizon of 30 years would be insufficient to observe the effects of partial transitions and changes in insulation on KPIs without using annualised measures.

Therefore, we further examined the effect of transitions on CO_2 emissions after 30 years as follows. Firstly, we compared the expected annual CO_2 emissions of different groups, based on the final state of households (Figure 5.9). Here too was the median for “3 Partial transition” close to that of “2 Insulation only”; nonetheless, the distributions were statistically different (see Table 5.9). Secondly, we estimated the subsidy costs of annual CO_2 reduction after 30 years with respect to the initial conditions. Figure 5.10 illustrates no used subsidies for “1 No changes”, and otherwise, the lowest median for “4 Full transition” and the highest for “2 Insulation only” and “3 Partial transitions”; the difference in the distributions of groups 2 and 3 was not statistically significant (see Table 5.9).

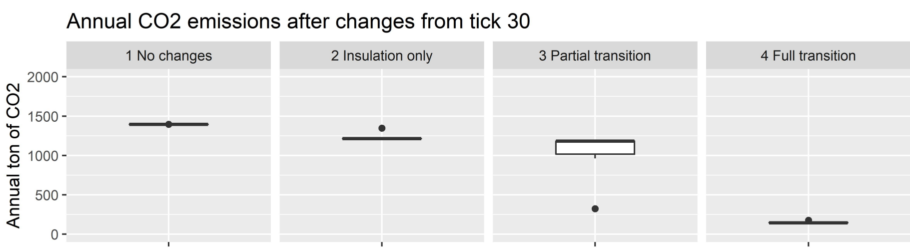

Figure 5.9: Annual CO_2 after changes from tick 30, according to our ABM.

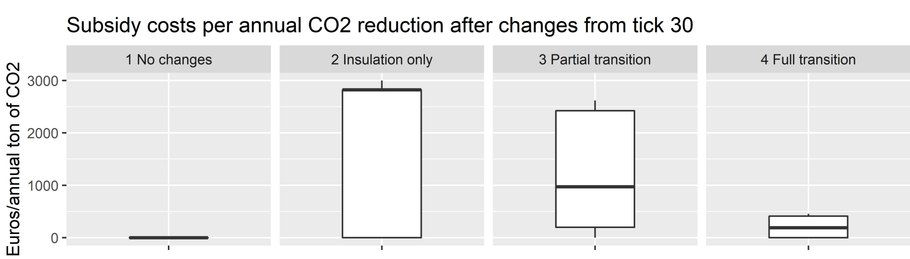

Figure 5.10: Subsidy costs per annual CO_2 emissions reduction, according to our ABM.

Finally, since HC were not annualised, we compared the average annual OC per household at the end of the simulation for every group (Figure 5.11), and the average IC per household (Figure 5.12). Not all groups had significant differences between each other in terms of the distribution of average annual OC (Table 5.10). Differences in IC were greater, as illustrated in Figure 5.12, and were the cause of “4 Full transition” having higher HC that the other groups; differences in their distributions were statistically significant (see Table 5.10).

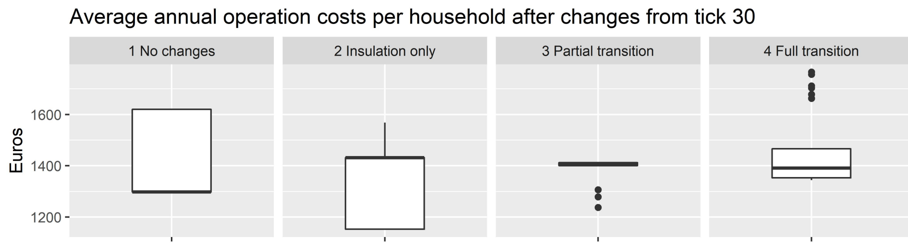

Figure 5.11: Annual OC after changes from tick 30, according to our ABM.

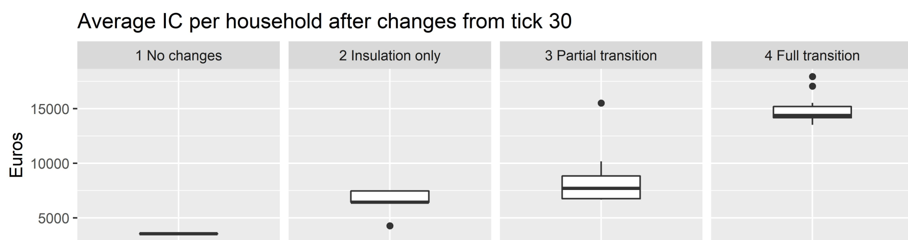

Figure 5.12: Average IC after changes from tick 30, according to our ABM.

Variable compared	Levene's[a] (p-value)	Shapiro-Wilk[b] (p-value)	Kruskal-Wallis rank sum[c] (p-value)	Wilcoxon rank sum (summary of findings)
Annual OC after changes in tick 30	0.00	0.00	0.00	Differences between: 1&2, 1&4, 2&4. No differences between: 1&3, 2&3, 3&4
Average IC per household after changes in tick 30	0.00	0.00	0.00	Differences between all groups.

[a] We assume homogeneity of variances only if p-values are higher than the significance level of 0.05.
[b] We assume normality only if values are higher than the significance level of 0.05.
[c] We use this test as a non-parametric alternative to one-way ANOVA. A p-value lower than the significance level of 0.05 indicates significant differences between groups.

Table 5.10: Results for statistical tests to assess the effect of heat transitions on costs between four groups: "1 No changes", "2 Insulation only", "3 Partial transition", and "4 Full transition".

5.4.4. VALIDATION

The heat transition is ongoing and possibilities for validation with historical data or with experiments are limited. Therefore, in this section, we address validation in the form of a sensitivity analysis (Section 5.4.4), and a discussion of our results in the light of expert reports and news (Section 5.4.4).

SENSITIVITY ANALYSIS

The insulation subsidy influenced the preferred TS of some households with HPP=100-0-0-0 at the beginning of the simulation. When the insulation subsidy was 110% of its nominal value, households in old terraced houses preferred TS3:GB1 instead of the TS1:GB3 from Table 5.6. In contrast, the conditions under which households preferred to disconnect from natural gas at the beginning of the simulation, reported in Table 5.7, did not change.

In the simulations, partial transitions still took place under HPP=T, C, or O; however, changes in each policy except for the decrease in the electricity tax resulted in some changes in the REs that were necessary for partial transitions. The required REs that differed from the nominal results are summarised in Table 5.11. For example, in the nominal results, RE=GXXXX was necessary for partial transitions when HPP=Q; in contrast, in the sensitivity analysis, the transition was also possible if the increase in natural gas tax was only 90% of the nominal value, as long as RE=GEXXXX or G0XXP. Overall, as the values of the policies increased or decreased, partial transitions were possible under more or less REs, and the number of households that disconnected from natural gas sometimes varied. Results were robust with respect to changes in the value of the electricity tax, but they were often influenced by changes in the value of natural gas tax, and less often, by changes in the value of the remaining policies.

For full transitions, only HPP=25-25-0-50 was sensitive to changes in the values of policies, and only to increases in the natural gas tax and in the regulated price of heat from networks. If the increase in the natural gas tax was smaller or the price cap on heat from networks was higher, the transition only took place when an insulation subsidy was in place. These findings are summarised in Table 5.12. Overall, results were robust with respect to changes in all policies except for a decrease in the natural gas tax and an increase in the regulated price of heat from networks.

<table>
<tr><th rowspan="2">Profile</th><th colspan="4">Criterion (%)</th><th rowspan="2">Nominal REs that were required</th><th colspan="4">Change in the variable with respect to its nominal value</th><th rowspan="2">REs required in the sensitivity analysis</th></tr>
<tr><th>Finances</th><th>Environment</th><th>Space</th><th>Duration</th><th>GAS</th><th>INS</th><th>INS</th><th>HPS</th></tr>
<tr><td rowspan="2">T</td><td rowspan="2">100</td><td rowspan="2">0</td><td rowspan="2">0</td><td rowspan="2">0</td><td rowspan="2">GEXXX or G0XXP</td><td>0.9</td><td colspan="3">1</td><td>GEXXX</td></tr>
<tr><td colspan="3">1</td><td>0.9</td><td>GEXXP</td></tr>
<tr><td>C</td><td>75</td><td>25</td><td>0</td><td>0</td><td>GXXXX</td><td>0.9</td><td colspan="3">1</td><td>GEXXX or G0XXP</td></tr>
<tr><td rowspan="5">O</td><td rowspan="5">50</td><td rowspan="5">25</td><td rowspan="5">0</td><td rowspan="5">25</td><td rowspan="5">GXHIX or GE0IP</td><td>0.9</td><td colspan="3">1</td><td>GXHIX</td></tr>
<tr><td>1.1</td><td colspan="3">1</td><td>G0HXX or GE0IP or GEH0P or GEHIX</td></tr>
<tr><td>1</td><td>2026</td><td colspan="2">1</td><td>GEHIP</td></tr>
<tr><td colspan="2">1</td><td>0.9</td><td>1</td><td>GXHIX</td></tr>
<tr><td colspan="3">1</td><td>0.9</td><td>GXHIP</td></tr>
</table>

Table 5.11: Conditions for partial transitions that differed from the nominal results in the sensitivity analysis.

<table>
<tr><th rowspan="2">Profile</th><th colspan="4">Criterion (%)</th><th rowspan="2">Nominal REs that were required</th><th colspan="2">Change in the variable with respect to its nominal value</th><th rowspan="2">REs required in the sensitivity analysis</th></tr>
<tr><th>Finances</th><th>Environment</th><th>Space</th><th>Duration</th><th>GAS</th><th>DHN</th></tr>
<tr><td rowspan="2">E</td><td rowspan="2">25</td><td rowspan="2">25</td><td rowspan="2">0</td><td rowspan="2">50</td><td rowspan="2">GXHXX</td><td>0.9</td><td>1</td><td rowspan="2">GXHIX</td></tr>
<tr><td>1</td><td>2026</td></tr>
</table>

Table 5.12: Conditions for full transitions that differed from the nominal results in the sensitivity analysis.

REFLECTION ON PUBLICATIONS REGARDING THE HEAT TRANSITION

As explained in our previous work [Nava-Guerrero et al., 2021], the heat transition in the Netherlands is complex. Schilder and van der Staak [2020] found that, under their assumptions, the costs of disconnecting from natural gas would seldom be recovered via energy savings. Moreover, although the government has supported areas known as "testing grounds" to explore ways to disconnect from natural gas [PAW, n.d.], national numbers indicate that the percentage of dwellings that did not use natural gas at the beginning of 2019 was 5.7% [CBS, 2021].

However, heat transition projects are yielding lessons [Dignum et al., 2021, Participatiecoalitie, 2021] and some testing grounds are in an implementation phase [PAW]. The challenge of actor heterogeneity and the resulting need to customise projects and measures to disconnect from natural gas was noted by an alderman in the testing ground of Garyp [PAW, 2019a] and by a project leader in the testing ground of Loppersum [PAW, 2019b]. Furthermore, Dignum et al. [2021] higlights, among other points, that working at the level of neighbourhoods makes both problems and solutions identifiable; moreover, that customization is necessary, that social preferences may not always lead to the lowest social costs, and that structural national solutions to potential bottlenecks will be needed. According to a dashboard from the testing grounds which we consulted on October 6, 2021, 29 testing grounds are in a planning phase and 17 testing grounds are in an implementation phase [PAW].

Our work echoes some of the previously mentioned situations. Firstly, that a cost-neutral transition was not possible under the initial conditions of the simulation (see Section 5.3.1). Secondly, that actor heterogeneity, in our case in the form of HPPs, is a determining factor for successful transitions. This resonates with the need to consider customization and multiple factors in the testing grounds, which is mentioned in PAW [2019a,b]. Furthermore, in some testing grounds, differences have been found between dwellings with different ages. Namely, in Loppersum and Nagele, heat networks have been found to be interesting in older areas [PAW, 2019b, 2020]. Our results also showed situations in which different TSs were attractive to different types of dwellings. See variations in initial preferred TSs in Section 5.4.1, and variations in TSs at the end of the simulation for partial and full transitions in Section 5.4.2.

5.4.5. LIMITATIONS AND FUTURE WORK

For simplicity, we only explore situations in which all households had the same HPP. Although we represent different types of dwellings, we also expect the preferences of households to vary. Therefore, it would be more realistic to simulate a neighbourhood in which households also have different HPPs. However, the present study allows us to identify HPPs under which households would prefer to change their initial state. Future work can build on this identification to explore combinations of HPPs and type of dwellings in neighbourhoods.

We incorporate elements of the Dutch built environment, decisions by households, and relevant policies in our ABM. However, since our work is exploratory, we use simplified representations of policies, group and multi-criteria decisions, and input data based on desk research, as well as assumptions. For instance, we expect our results to be different for neighbourhoods in which heat networks are more cost-effective than heat pumps: Multi-criteria decisions might more often lead to disconnections from natural gas, provided that heat networks are preferred based on non-financial criteria. We also exclude effects of TSs on public space or infrastructure. Future studies can incorporate empirically validated representations and parameters –including for example of group decisions and varying energy prices-, quantitative models that are technologically accurate, study specific neighbourhoods and their alternatives to natural gas, adopt broader perspectives, and incorporate stakeholder participation.

The following changes can improve our ABM. Firstly, as described by Busch et al. [2017], infrastructure requires a development process rather than instantaneous adoption. Our ABM could incorporate more realistic timelines and decision processes. For example, when comparing TSs, our households decide whether to change their TS on an annual basis and they do not take into account the age of their heating system, whether they have recovered previous investments, or whether they have sufficient capital to make a new investment. In reality, households are more likely to make an investment decision during dwelling renovation, change of residents, or breakdown of heating systems [Dignum et al., 2021]. Secondly, a dynamic sub-model for the business case of collective infrastructure depending on the number of users or heat demand -such as the model in ECW, Hers et al. [2020]- could be used to determine costs for households.

5

Finally, our work is exploratory and our quantitative findings are only valid under the assumptions of our model. Therefore, instead of providing quantitative conclusions, with this work we seek to advance the study of the heat transition while accounting for group and multi-criteria decisions and to provide directions for future research in these lines. Our approach can be applied further to case studies concerning energy transitions in which various technologies compete to replace an incumbent technology, and in which both individual and collective decisions play a role in their adoption. This is for example relevant to the challenge of improving the energy performance of buildings and reducing greenhouse gas emissions in the built environment in the European Union, as described in [European Commission, 2016].

5.5. CONCLUSIONS

Household preference profiles were more influential in the transition than financial policies; while no combination of financial policies was sufficient to enable the transition, six household preference profiles were sufficient conditions. Moreover, our results showed that combinations of policies can have different outcomes depending on household preference profiles, and transitions may require specific combinations of financial policies.

In simulations over 30 years, full transitions occurred when household preference profiles were as follows. Environment and finances were each weighted 50%. All criteria were weighted 25%. Finances and environment had nonzero weights but environment was weighted higher than finances. Finances and environment were weighted 25%, duration was weighted 50%, natural gas tax increased, and there was a cap on the price of heat from networks.

Partial transitions occurred under specific household preference profiles and policies, and the number of households that disconnected from natural gas varied: it could be as low as 22 and as high as 428. Moreover, the benefits of partial transitions were debatable.

When comparing medians, annual CO_2 emissions at the end of the simulation were lower for partial transitions than for simulation runs in which only changes in insulation took place; however, the difference was small. Moreover, the difference between the distributions of the subsidy costs per annual CO_2 reduction of partial transitions and of simulation runs with only changes in insulation was not statistically significant. In other words, in terms of collective CO_2 emissions and subsidy costs relative to the reduction in CO_2 emissions, some transitions in which only some households phased out natural gas could have results similar to some scenarios in which households only improved their dwellings' insulation levels.

Full transitions also posed challenges. In terms of medians, although they led to lower CO_2 emissions, they also led to higher investment costs. Heat networks were often adopted by households in full transitions and our assumptions represented a situation in which heat networks had high costs. However, full transitions did not have the highest average annual operation costs per household. Lower upfront costs and other ratios between the costs of different alternatives could reveal different favourable socio-technical conditions for full transitions.

The nature of our work is exploratory and it should not be used as a quantitative analysis nor to select specific technologies or policy interventions. However, we make the following recommendations for policy analysis. These recommendations are intended for heat transitions in the built environment in which various technologies compete to replace an incumbent technology, and in which both individual and collective decisions play a role in their adoption.

Firstly, combinations of ex-ante regulation of heat prices and the fiscal policies for other energy carriers are relevant for the transition; theoretically, they could incentivise households to disconnect from natural gas. Therefore, we recommend to further explore interaction effects of these policies.

Secondly, full transitions might not happen with financial policies alone; instead, only some households might disconnect from natural gas. In case of partial transitions, the difference in CO_2 emissions with insulation-only scenarios might be small. For these reasons, in analyses and discussions, we recommend to include scenarios in which households maintain natural gas and different levels of insulation, as well mixes of dwellings with and without natural gas.

Thirdly, we encourage authors and decision-makers to also consider non-financial measures. To this aim, we recommend to continue to explore criteria that are relevant for households, the impact of heterogeneity on the performance of financial policies, and the influence of natural moments in which households may decide to improve their insulation or replace their heating system.

Finally, we recommend to continue to explore the costs that the transition and its financial policies could have for different actors, implications for energy poverty and vulnerability, for the business case of energy projects, and for public expenditures.

5.6. ACKNOWLEDGEMENTS

This research was funded by the Dutch Research Council (NWO, for its initials in the Dutch language), as part of project number 14183 "Modeling Lab for smart grids, smart policies, smart entrepreneurship". This project is Project E from the Smart Energy Systems in the

Built Environment (SES-BE) Programme.

5.7. APPENDIX A. INPUT DATA

In this appendix we summarise input data used in the ABM. Some of the content of this appendix is similar to our previous work in [Nava-Guerrero et al., 2021] because our ABM is an expansion of the previous one. Other assumptions and input data are based on the work by Wessels [2020].

5.7.1. CONSIDERATIONS

In line with the exploratory purpose of our ABM, input data was gathered via desk research and includes estimates and assumptions. Developing a quantitative model to compare combinations of heating systems and insulation measures was not a purpose of our work. See Henrich et al. [2021] for an overview of energy models used for decision making in the heat transition in the Netherlands.

Our compilation does not represent a specific neighbourhood. To apply our ABM to a case study, input data needs to be validated in order to improve its quantitative accuracy.

We summarise some of our modelling choices as follows.

- We use the higher heating value (HHV=35.17MJ/m^3) for natural gas and an ideal heat capacity for hydrogen gas (see Table 5.13). Future work can use different values or explore the sensitivity of our calculations to these values.

- Input data was consolidated from different sources and we did not standardise the costs that are included in the estimates. For instance, upfront costs based on Hoogervorst et al. [2020a] do not include value-added tax, while sources such as Wessels [2020] do not discuss value-added tax. Standardizing costs to include or exclude value-added tax, or using existing models that are already validated, can be part of future work. Similarly, the estimated costs that we use are not detailed estimates, but general assumptions for our exploratory purposes. See sources such as Hoogervorst et al. [2020a] and Schepers et al. [2019] for a technical and financial model.

- We focus on the costs, duration, and space of TSs that directly affect users in their dwellings during the lifetime of the TSs. See Hoogervorst et al. [2020a], Schepers et al. [2019] and Wessels [2020] for broader perspectives.

- We simulate 30 years, and assume that heat networks do not require reinvestment during this time and that other heating systems require one reinvestment. A lifetime of 30 years with reinvestments after 15 years is often the starting point of business cases for heat networks [den Dekker et al., 2020]. A lifetime of 30 years has also been used in the scientific literature [Kim and Weidlich, 2017, Persson and Werner, 2011]; however, Kim and Weidlich [2017] explain that different lifetimes are expected depending on the specifications of the technology. See Kim and Weidlich [2017] for an overview of various estimated lifetimes.

Energy carrier	Heat capacity	Source
Natural gas	35.17 MJ/m^3	Gasunie
Green gas	We assume that it has the same heat capacity than natural gas.	
Hydrogen gas	0.03 kgH2/kWh	Christensen [2020]
		A similar value of 33.33 kWh/kg was discussed in WaterstofNet.

Table 5.13: Assumptions for the heat capacity used for the calculation of CO_2-equivalents per energy carrier in $kgCO_2/kWh$.

5.7.2. TECHNICAL SPECIFICATIONS

We study nine TSs, described in 5.3.1. TSs have a heating system (defined as "primary heating system"), insulation level, and appliances. We conceptualise the primary heating system of TS4:BN1 and TS8:HN1 as boilers. We assume that TS4:BN1, TS7:lowHN1, and TS8:HN1 require additional heat pumps (defined as "secondary heating system"), in line with Hoogervorst et al. [2020a]. We do not account for separate heat demand or systems for space heating and tap water; we only make a difference between heat demand for cooking and for space heating.

Each TS is associated with the following parameters: thermal efficiency, lifetime of the heating system, and heat demand (cooking, primary, and secondary). Thermal efficiency and lifetime of the heating system are summarised in Table 5.14 to Table 5.16. To represent situations in which insulation measures are improved but natural gas is maintained, we assume that the heat demand of TS2:GB2 and TS5:medHN2 are equal, as well as the heat demand of TS1:GB1 and of TSs without natural gas and with the highest insulation.

TS	Thermal efficiency [fraction]	Sources	Thermal efficiency relative to natural gas boilers [fraction]
1:GB3	0.87	ACM [2019]	1.00
2:GB2	0.87	ACM [2019]	1.00
3:GB1	0.87	ACM [2019]	1.00
4:BN1	0.87	We assume the same value than natural gas boilers.	1.00
5:medHN2	1	ACM [2019]	1.15
6:HP1	3.81	Hoogervorst et al. [2020a]	4.28
7:lowHN1	1	ACM [2019]	1.15
8:HH1	0.87	We assume the same value than natural gas boilers.	1.00
9:medHN1	1	ACM [2019]	1.15

Table 5.14: Assumptions for thermal efficiency the primary heating system of each TS.

<table>
<tr><th>TS</th><th>Thermal efficiency [fraction]</th><th>Sources</th><th>Thermal efficiency relative to natural gas boilers [fraction]</th></tr>
<tr><td>4:BN1</td><td rowspan="2">4.4</td><td rowspan="3">Hoogervorst et al. [2020a]</td><td rowspan="2">5.06</td></tr>
<tr><td>8:HH1</td></tr>
<tr><td>7:lowHN1</td><td>6.1</td><td>7.01</td></tr>
</table>

Table 5.15: Assumptions for thermal efficiency of the secondary heating system.

<table>
<tr><th>TS</th><th>Lifetime of primary heating systems [years]</th><th>Lifetime of secondary heating systems [years]</th><th>Source</th></tr>
<tr><td>1:GB3</td><td>15</td><td>Not applicable</td><td rowspan="9">Assumptions. See Hoogervorst et al. [2020b] for heat pumps and natural gas boilers. See Section 1 in this Appendix for heat networks.</td></tr>
<tr><td>2:GB2</td><td>15</td><td>Not applicable</td></tr>
<tr><td>3:GB1</td><td>15</td><td>Not applicable</td></tr>
<tr><td>4:BN1</td><td>15</td><td>15</td></tr>
<tr><td>5:medHN2</td><td>30</td><td>Not applicable</td></tr>
<tr><td>6:HP1</td><td>15</td><td>Not applicable</td></tr>
<tr><td>7:lowHN1</td><td>30</td><td>15</td></tr>
<tr><td>8:HH1</td><td>15</td><td>15</td></tr>
<tr><td>9:medHN1</td><td>30</td><td>Not applicable</td></tr>
</table>

Table 5.16: Assumptions for the lifetime of heating systems.

Demand is summarised in Table 5.17 to 5.20. The values of the heat demand of the three insulation levels were based on Milieu Centraal and Rijksoverheid [n.d.] and Wessels [2020]. Wessels [2020] used theoretical estimates from Liander and adjusted those estimates to account for the energy performance gap described in Filippidou et al. [2019], in which actual energy consumption after a renovation tends to be higher than theoretically estimated. The resulting demand consisted of cooking demand (when natural gas is used) and demand for heating to be fulfilled by the primary and, if applicable, secondary heating systems. The heating demand that is to be fulfilled by the primary heating system for TS4:BN1 and TS8:HN1 was determined using the fraction 0.525 from Hoogervorst et al. [2020a], as used by Wessels [2020]. For TS7:lowHN1 we used the fraction 0.75, which is mentioned by Hoogervorst et al. [2020a] as the fraction of the heat demand delivered by the individual heating system rather than the heat network. Note that we assume that all the demand after subtracting cooking demand is demand for space heating, and do not consider tap water demand.

<table>
<tr><th>TS</th><th>Cooking demand</th><th>Sources</th></tr>
<tr><td>1:GB3</td><td rowspan="3">37m^3/year</td><td rowspan="9">Based on the average consumption of stoves natural gas and induction stoves by Milieu Centraal</td></tr>
<tr><td>2:GB2</td></tr>
<tr><td>3:GB1</td></tr>
<tr><td>4:BN1</td><td rowspan="6">175 kWh/year</td></tr>
<tr><td>5:medHN2</td></tr>
<tr><td>6:HP1</td></tr>
<tr><td>7:lowHN1</td></tr>
<tr><td>8:HH1</td></tr>
<tr><td>9:medHN1</td></tr>
</table>

Table 5.17: Assumptions for cooking demand of TSs.

<table>
<tr><th>TS</th><th>Heat demand from the primary heating system [kWh/year]</th><th>Heat demand from the secondary heating system</th><th>Sources</th></tr>
<tr><td>1:GB3</td><td>20936</td><td>Not applicable</td><td rowspan="9">See description in text.</td></tr>
<tr><td>2:GB2</td><td>15963</td><td>Not applicable</td></tr>
<tr><td>3:GB1</td><td>15358</td><td>Not applicable</td></tr>
<tr><td>4:BN1</td><td>7295</td><td>8063</td></tr>
<tr><td>5:medHN2</td><td>15963</td><td>Not applicable</td></tr>
<tr><td>6:HP1</td><td>15358</td><td>Not applicable</td></tr>
<tr><td>7:lowHN1</td><td>3839</td><td>11518</td></tr>
<tr><td>8:HH1</td><td>7295</td><td>8063</td></tr>
<tr><td>9:medHN1</td><td>15358</td><td>Not applicable</td></tr>
</table>

Table 5.18: Semi-detached houses: assumptions for heat demand.

TS	Heat demand from the primary heating system [kWh/year]	Heat demand from the secondary heating system	Sources
1:GB3	16794	Not applicable	See description in text.
2:GB2	14029	Not applicable	
3:GB1	12378	Not applicable	
4:BN1	5879	6498	
5:medHN2	14029	Not applicable	
6:HP1	12378	Not applicable	
7:lowHN1	3094	9283	
8:HH1	5879	6498	
9:medHN1	12378	Not applicable	

Table 5.19: Terraced houses: assumptions for heat demand.

5

TS	Heat demand from the primary heating system [kWh/year]	Heat demand from the secondary heating system	Sources
1:GB3	Not applicable	Not applicable	See description in text.
2:GB2	Not applicable	Not applicable	
3:GB1	9984	Not applicable	
4:BN1	4743	5242	
5:medHN2	Not applicable	Not applicable	
6:HP1	9984	Not applicable	
7:lowHN1	2496	7488	
8:HH1	4743	5242	
9:medHN1	9984	Not applicable	

Table 5.20: Apartments: assumptions for heat demand.

5.7.3. MARKET CONDITIONS

Annual costs (AC), fixed costs (FiC), and variable costs (VC) are expressed in Equation 5.1 to Equation 5.4. In Equation 5.2, CoF is a connection fee for both primary and secondary heating systems, and MeF is a measuring fee. In Equation 5.4, d, e, and f are the prices (including taxes) of the corresponding energy carrier, HD is heat demand, and CD is cooking demand.

$$AC = FiC + VC \tag{5.1}$$

Equation 5.1: Annual costs.

$$FiC = CoF + MeF \tag{5.2}$$

Equation 5.2: Fixed costs.

$$CoF = CoF_{\text{primary}} + CoF_{\text{secondary}} \tag{5.3}$$

Equation 5.3: Measuring fee for primary and secondary heating systems.

$$VC = d * HD_{primary} + e * HD_{secondary} + f * CD \tag{5.4}$$

Equation 5.4: Variable costs.

We assume that all households have a connection to the electricity network regardless of their TS and pay a measuring fee for this energy carrier. Therefore, we exclude MeF for electricity from our analysis. However, we assume that when households adopt a TS with an electric component (TS4:BN1, TS6:HP1, TS7:lowHN1, or TS8:HH1) they require a larger connection to the electricity network, which requires higher CoF. As mentioned in our previous work Nava-Guerrero et al. [2021], in practice, a smaller connection without higher CoF could be sufficient. We only include the difference between the CoF of a larger connection (assumed to be 3x35A) and the CoF that households already had (assumed to be between 1x35A). The values for MeF and CoF are summarised in Table 5.21 and Table 5.22.

TS	Primary heating system		Secondary heating system	
	CoF	Source	CoF	Source
1:GB3	159.56	Based on the 2020 fees of a natural gas supplier in the Netherlands [Stedin].	NA*	NA*
2:GB2	159.56			
3:GB1	159.56			
4:BN1	159.56	We assume the same cost as for natural gas.	656.78	Based on the 2020 fees of an electricity supplier in the Netherlands [Stedin].
5:medHN2	371.73	Based on the 2020 fees of a district heating supplier [HVC, n.d.].	NA*	NA*
6:HP1	656.78	Based on the 2020 fees of an electricity supplier in the Netherlands [Stedin].	NA*	NA*
7:lowHN1	371.73	Based on the 2020 fees of a district heating supplier [HVC, n.d.].	656.78	Based on the 2020 fees of an electricity supplier in the Netherlands [Stedin].
8:HH1	159.56	We assume the same cost as for natural gas.	656.78	Based on the 2020 fees of an electricity supplier in the Netherlands [Stedin].
9:medHN1	371.73	Based on the 2020 fees of a district heating supplier [HVC, n.d.].	NA*	NA*

*NA = Not applicable.

Table 5.21: Assumptions for Connection fee for primary and secondary heating systems.

TS	MeF	Source
1:GB3	22.40	Based on the 2020 fees of a natural gas supplier in the Netherlands [Stedin].
2:GB2		
3:GB1		
4:BN1	22.40	Assumed to be the same as for natural gas.
5:medHN2	26.63	Based on the 2020 fees of a district heating supplier [HVC, n.d.].
6:HP1	0.00	Excluded because all households use electricity.
7:lowHN1	26.63	Based on the 2020 fees of a district heating supplier [HVC, n.d.].
8:HH1	22.40	Assumed to be the same as for natural gas.
9:medHN1	26.63	Based on the 2020 fees of a district heating supplier [HVC, n.d.].

Table 5.22: Assumptions for Measuring fee.

UPFRONT AND REINVESTMENT COSTS

We define upfront costs (UC) in Equation 5.5, where HeC are the costs of heating systems, InC are the costs of insulation measures, IS are the insulation subsidies, HS are the heat pump subsidies, and RE is the regulatory environment. Assumptions for HeC, RC, and InC are summarised in Tables 5.23 to 5.27, and for IS and HS, in 5.7.4 and 5.7.4.

$$UC(s, s', RE) = HeC(s, s') + InC(s, s') - IS(s, s', RE) - HS(s, s', RE) \tag{5.5}$$

Equation 5.5: Upfront costs.

TS	HeC [Euros]	Source
1:GB3	NA*	NA*
2:GB2	1775.8	Hoogervorst et al. [2020a] for HR boilers, which we assume to be applicable to natural gas, green gas, and hydrogen.
3:GB1		
4:BN1		
8:HH1		
6:HP1	7458.0	Adapted from Wessels [2020], which was based on Schepers et al. [2019] and Hoogervorst et al. [2020a] for a 6kW heat pump.
5:medHN2	12000.0	Assumption selected to represent a situation in which the upfront costs of heat networks are higher than those of other TSs.
7:lowHN1		
9:medHN1		

*NA = Not applicable

Table 5.23: Assumptions for HeC of the primary heating system.

TS	HeC [Euros]	Source
4:BN1	6638.0	Adapted from Wessels [2020], which was based on Schepers et al. [2019] and Hoogervorst et al. [2020a] for a 4kW heat pump.
8:HH1		
7:lowHN1	4500.0	Assumption based on Hoogervorst et al. [2020a].

Table 5.24: Assumptions for HeC of the secondary heating system.

TS	RC [Euros]	Source
1:GB3	1775.8	Equal to UC of the primary heating system.
2:GB2		
3:GB1		
4:BN1	8413.8	Equal to sum of UCs of primary and secondary heating systems.
8:HH1		
6:HP1	7458.0	Equal to UC of the primary heating system.
5:medHN2	0.0	We assume that no reinvestments are necessary.
9:medHN1		
7:lowHN1	4500.0	Equal to UC of the secondary heating system.

Table 5.25: Assumptions for RC.

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Change in insulation level	Type of dwelling	
	Semi-detached houses	Terraced houses
Low to medium	HR++ glass Roof insulation Cavity wall insulation	HR++ glass Roof insulation
Low to high	HR+++ glass Roof insulation Floor insulation Cavity wall insulation	HR++ glass Roof insulation Floor insulation Cavity wall insulation
Medium to high	HR+++ glass Roof insulation Floor insulation Cavity wall insulation	Floor insulation Cavity wall insulation
Source	Based on Wessels [2020].	

Table 5.26: Assumptions for the insulation measures required by each type of old dwelling. Adapted from Wessels [2020].

Change in insulation level	Type of dwelling	
	Semi-detached houses	Terraced houses
HR++ glass	3770	3103
HR+++ glass	6240	NA*
Roof insulation	2768.5	2005.5
Floor insulation	2640	1880
Cavity wall insulation	1956	846
Source	Based on Wessels [2020].	

* NA = Not applicable.

Table 5.27: Assumptions for the cost of insulation measures per type of old dwelling. Adapted from Wessels [2020].

ENERGY PRICES

We define energy (sales) prices as the sum of retail prices and energy taxes. Retail prices of natural gas, electricity, hydrogen and green gas were constant throughout the simulation. This allowed us to focus our analysis on the effects that financial policies, including taxes and regulated price of heat from networks, could have on the transition. We represent a situation in which there are no taxes on green gas and hydrogen and their prices are low. Our assumptions for the sales prices of energy carriers are summarised in Table 5.28. Energy taxes, and the regulated price of heat from networks, are described in 5.7.4.

Energy carrier	Assumption [Euros/kWh]	Source
Natural gas	0.04	Estimated value for 2019 and 2020 [Eurostat, 2021b].
Electricity	0.14	Estimated value for 2019 and 2020 [Eurostat, 2021a].
green gas	0.07	Based on an estimated low price in Hoogervorst et al. [2020a].
Hydrogen	0.06	Based on estimated low prices when produced with energy carriers other than natural gas, as discussed by Weeda and Niessink [2020].

Table 5.28: Assumptions for sales prices of energy carriers.

5.7.4. FINANCIAL POLICIES

NATURAL GAS AND ELECTRICITY TAXES

The taxes for the first two time steps, corresponding to 2019 and 2020, were based on data from the Netherlands [Rijksoverheid, 2019a]. The natural gas tax was rounded to 0.030€/kWh for 2019 and 0.034€/kWh for 2020. The electricity tax was rounded to 0.099€/kWh for 2019 and 0.098 for 2020€/kWh. After 2020 and before 2027, changes in taxes were based on the content of the Climate Agreement [Rijksoverheid, 2019b].

Natural gas tax increased by 0.01€/m^3-year (0.001€/ kWh-year). Electricity tax decreased about 0.05€/kWh, a decrease that we implemented linearly: 0.0083€/year.

After 2026, energy taxes depended on the RE. When G was inactive (RE=0XXXX), natural gas taxes remained constant. When E was inactive (RE=X0XXX), electricity taxes remained constant. When G was active (G=GXXXX), natural gas taxes continued to increase by 0.001€/ kWh-year. When E was active (E=0EXXX), electricity taxes continued to decrease by 0.0083€/year until they reached zero.

REGULATED PRICE OF HEAT FROM NETWORKS

The regulated price of heat from networks for 2019 and 2020 is 0.09 Euros/kWh, based on the price of a heat supplier for 2020 [HVC, n.d.]. After 2020, if the policy is active (RE=XXHXX), the price remains constant. After 2020, when the policy is inactive (RE=XX0XX), the price continues to increase in proportion to the sales price of natural gas, as expressed in Equation 5.6. In Equation 5.6, RHP is the regulated price of heat from networks, t is the time step, and SPG is the sales price of natural gas. This is a simplified representation of a price cap.

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$$RHP(t) = \left(1 + \frac{SPG(t) - SPG(t-1)}{SPG(t-1)}\right) * RHP(t-1) \tag{5.6}$$

Equation 5.6: Regulated price of heat from networks under RE=XX0XX.

INSULATION SUBSIDY

Our insulation subsidy is based on the former policy SEEH (Subsidie energiebesparing eigen huis) that was in place until the end of 2020 [RVO, 2021b, n.d.]. Currently, insulation subsidies are available via a different policy. Following our conceptualization, we assume that old dwellings, which have low insulation, can improve to medium or high level, and that new dwellings already have the highest insulation. Our assumptions for the insulation subsidies are summarised in Table 5.29.

Change in insulation level	Type of dwelling	
	Semi-detached houses	Terraced houses
Low to medium	2981	1895
Low to high	5133	2436
Medium to high	2152	541
Source	Based on Wessels [2020].	

Table 5.29: Assumptions for the available insulation subsidies. Adapted from Wessels [2020].

HEAT PUMP SUBSIDY

Our heat pump subsidy is based on the existing policy ISDE (Investeringssubsidie Duurzame Energie) [RVO, 2021a]. We assume that a subsidy of 1700 Euros is granted for hybrid heat pumps (TS4:BN1 and TS8:HH1) and a subsidy of 1900 Euros for regular heat pumps (TS6:HP1). These assumptions are based on online examples such as Hage [2021], Warmtepomp Revolutie, and Saman Groep. We assume that the subsidy is granted only for the first time that a heat pump is installed and not for future reinvestments.

5.7.5. FACTORS FOR THE MULTI-CRITERIA COMPUTATION

ENVIRONMENTAL COMPUTATION

We limit the environmental computation to an estimate of the CO_2-equivalents linked to the energy carrier during the operational phase of the heating system. The factors are summarised in Table 5.30.

Energy carrier	Factor	Source	Factor in $kgCO_2/kWh$
Natural gas	56.6 $kgCO_2/GJ$	Zijlema [2019]	0.20
Electricity	0.475 $kgCO_2/kWh$	Stichting Stimular	0.48
green gas	0.723 $kgCO_2/m^3$	Stichting Stimular	0.07
Hydrogen gas	1.5 $kgCO_2/kg$	Wessels [2020] assumed that 50% is produced from wind and 50% is produced from PVs, and used factors from Bhandari et al. [2014].	0.05
Low temperature heat network	8.60 $kgCO_2/GJ$	Schepers and Scholten [2016], assuming a geothermal source and including only direct emissions from the main source.	0.03
Medium temperature heat network	5.7 $kgCO_2/GJ$	Schepers and Scholten [2016], assuming residual heat and including direct emissions only from the main source.	0.02

Table 5.30: Factors used for the calculation of CO_2-equivalents per energy carrier. Adapted from Wessels [2020].

SPACE COMPUTATION

The space computation required a space factor (s') for each TS, summarised in Table 5.31.

TS	1:GB3	2:GB2	3:GB1	4:BN1	5:medHN2	6:HP1	7:lowHN1	8:HH1	9:medHN1
Space factor	0.584	0.584	0.584	1.83	0.584	5.746	5.49	1.83	0.584
Source	Based on Wessels [2020].								

Table 5.31: Space factor (s') in m^3.

DURATION COMPUTATION

The duration computation required a duration factor (s') for each TS, summarised in Table 5.32 to Table 5.34. When a reinvestment was necessary, we used the values of Table 5.35.

TS	TS'								
	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	TS9
1:GB3	0	26	46	54	26	54	54	54	46
2:GB2	NA	0	46	54	4	54	54	54	46
3:GB1	NA	NA	0	12	NA	12	12	12	4
4:BN1	NA	NA	NA	0	NA	12	12	12	4
5:medHN2	NA	NA	NA	54	0	54	54	54	42
6:HP1	NA	NA	NA	12	NA	0	12	12	4
7:lowHN1	NA	NA	NA	12	NA	12	0	12	4
8:HH1	NA	NA	NA	12	NA	12	12	0	4
9:medHN1	NA	NA	NA	12	NA	12	12	12	0
Source	Based on Wessels [2020].								

*NA = Not applicable.

Table 5.32: Duration factor (s') for semi-detached houses in hours.

TS	TS'								
	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	TS9
1:GB3	0	20	38	46	20	46	46	46	38
2:GB2	NA	0	22	30	4	30	30	30	22
3:GB1	NA	NA	0	12	NA	12	12	12	4
4:BN1	NA	NA	NA	0	NA	12	12	12	4
5:medHN2	NA	NA	NA	30	0	30	30	30	18
6:HP1	NA	NA	NA	12	NA	0	12	12	4
7:lowHN1	NA	NA	NA	12	NA	12	0	12	4
8:HH1	NA	NA	NA	12	NA	12	12	0	4
9:medHN1	NA	NA	NA	12	NA	12	12	12	0
Source	Based on Wessels [2020].								

*NA = Not applicable.

Table 5.33: Duration factor (s') for terraced houses in hours.

TS	TS'								
	TS1	TS2	TS3	TS4	TS5	TS6	TS7	TS8	TS9
1:GB3	NA	NA	NA	NA	NA	NA	NA	NA	NA
2:GB2	NA	NA	NA	NA	NA	NA	NA	NA	NA
3:GB1	NA	NA	0	12	NA	12	12	12	4
4:BN1	NA	NA	NA	0	NA	12	12	12	4
5:medHN2	NA	NA	NA	NA	NA	NA	NA	NA	NA
6:HP1	NA	NA	NA	12	NA	0	12	12	4
7:lowHN1	NA	NA	NA	12	NA	12	0	12	4
8:HH1	NA	NA	NA	12	NA	12	12	0	4
9:medHN1	NA	NA	NA	12	NA	12	12	12	0
Source	Based on Wessels [2020].								

*NA = Not applicable.

Table 5.34: Duration factor (s') for apartments in hours.

TS	1:GB3	2:GB2	3:GB1	4:BN1	5:medHN2	6:HP1	7:lowHN1	8:HH1	9:medHN1
Space factor	4	4	4	12	0	12	12	12	0
Source	Based on Wessels [2020].								

Table 5.35: Duration factor (s') in hours for all dwellings, when a reinvestment was necessary.

5.8. APPENDIX B. DESIGN CONCEPTS AND SUB-MODEL

In this appendix, we discuss the design concepts of our ABM and the sub-model for individual multi-criteria perceived lifetime utility.

5.8.1. DESIGN CONCEPTS

Our ABM has three basic principles:

- Multi-criteria decisions in the form of households having profiles with their preferences.
- Group decisions in the form of a system of thresholds.
- Heterogeneity in the form of dwellings with different characteristics.

Further, our ABM has the following design concepts:

- Objectives: households try to maximise their utility by preferring the TS with highest score.

- Prediction: households have imperfect prediction of future financial policies and use current prices and taxes in their estimates.
- Sensing: households in an HOA know whether the HOA Threshold was met and all households know whether the HN Threshold was met. No other interactions are formalised.
- Observation: takes place via the computation of KPIs.
- Collectives: households are grouped into HOAs, which condition their decisions.

5.8.2. SUB-MODEL: INDIVIDUAL MULTI-CRITERIA PERCEIVED LIFETIME UTILITY

Households use this sub-model to determine the score of each TS with respect to the household's current TS. It consists of five computations: four single-criterion computations that are later normalised (finances, environment, space, duration), and the computation of a score or weighted average based on the single-criterion computations and the household's profile. We first proposed and used the finances computation in Nava-Guerrero et al. [2021] as a lifetime-cost (LTC) calculation. The remaining computations are based on the static multi-criteria assessment model by Wessels [2020].

The financial cost (FC) is the lifetime-cost (LTC) of changing from the current TS (s) to a new TS (s'), discounted with a market discount rate (ρ) to account for differences in present and future cash-flows, and starting on the current time step (t). The FC and the LTC, which we defined in our previous work Nava-Guerrero et al. [2021], is expressed in Equation 5.7, where UC are upfront costs, AC and RC are annual costs and reinvestment costs, β is a uniform horizon equal to the lifetime of the heating system with the longest lifetime, and τ is the lifetime of the heating system of s' for which Equation 5.7 is being used. Input data is presented in Appendix A (Section 5.7).

$$FC_{s,s'} = LTC(s,s',\rho,t) = UC(s,s') + \sum_{k=0}^{\beta} \frac{AC(s',t+k)}{(1+\rho)^k} + \sum_{j=1}^{\left\lfloor \frac{\beta-1}{\tau} \right\rfloor} \frac{RC(s')}{(1+\rho)^{j\tau}} \tag{5.7}$$

Equation 5.7: Financial cost.

Note that households do not consider the lifetime of their current heating system in the calculation of UC and RC. For instance, if s' uses the same heating system as s, regardless of the age of s, households consider the standard: no investment costs required for heating system of s' and only one reinvestment throughout 30 years. This is however only accurate when the heating system of s is at the beginning of its lifetime. Therefore, households could be underestimating RC of s' that use the same heating system as s does. A more accurate representation would have households consider the age of their current heating system in the calculation of UC and RC.

The environmental cost (EC) is the CO_2 emissions of the energy carrier used during the lifetime of a TS. It is expressed in Equation 5.8, where a, b, and c are emission factors in kg of CO_2/kWh, HD is heat demand, CD is cooking demand, nH is the efficiency of heating systems, and the energy demands are expressed in kWh/year (see Appendix A in Section 5.7 for their specific values). See Section 5.4.5 for a discussion of the limitations of our definition of EC. Note that we use the concept "environmental cost" in a rather narrow sense.

$$EC = \left(a * \frac{HD_{primary}}{nH_{primary}} + b * \frac{HD_{secondary}}{nH_{secondary}} + c * CD\right) \tag{5.8}$$

Equation 5.8: Environmental cost.

We assume that the space that the heating system occupies in the dwelling does not change over time, and the works to install the TSs take place only once. Therefore, the spatial cost (SpC) and the duration cost (DC) are equal to a constant space factor or duration factor for every TS. As expressed in Equation 5.9, the value of the space factor depends only on s', and the value of the duration factor depends on both s and s', as expressed in Equation 5.10 (see Appendix A in Section 5.7 for their specific values).

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$$SpC_{s'} = spacefactor(s') \tag{5.9}$$

Equation 5.9: Space computation.

$$DC_{s,s'} = durationfactor(s,s') \tag{5.10}$$

Equation 5.10: Duration computation.

After the FC, EC, SpC, and DC are computed for all TSs, results are normalised as expressed in Equation 5.11, where N stands for normalised, X is a placeholder for F, E, S, or D, and minimums (min) and maximums (max) are taken over the values of s'.

$$NXC = \frac{XC - XC_{min}}{XC_{max} - XC_{min}} \tag{5.11}$$

Equation 5.11: Normalization computation.

Finally, for each TS, a score is calculated as expressed in Equation 5.12, where FW, EW, SW, and DW indicate the weights given to each criterion in the HPP. The TS with the highest score becomes the most preferred TS by the household.

$$Score_{s,s'} = FW * NFC_{s,s'} + EW * NEC_{s,s'} + SW * NSC_{s,s'} + DW * ND_{s,s'} \tag{5.12}$$

Equation 5.12: Normalization computation.

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6

CONCLUSIONS

In this chapter, we present our conclusions in terms of research outcomes, discussion and reflection, and recommendations.

6.1. OVERVIEW OF RESEARCH OUTCOMES

In this section, we answer the main research question and the sub-questions of this dissertation. Each sub-question was the focus of Chapter 3, 4, and 5, respectively.

Main research question

How could the heat transition in the Netherlands be influenced by homeowners' individual and group decisions regarding investment in heating systems and insulation measures?

Research sub-questions

1. *How to explore the influence of homeowners' decisions regarding investment in heating systems and insulation measures on the heat transition in the Netherlands?*

2. *How could individual and group decisions between building owners, and within HOAs in strata buildings, influence the course of the heat transition in a neighbourhood in the Netherlands, under different policy interventions?*

3. *How could multi-criteria decisions by households influence the course of the heat transition in a neighbourhood in the Netherlands, under different policy interventions?*

Parts of this chapter are adapted from Nava Guerrero et al. [2019], Nava-Guerrero et al. [2021, 2022]. The first author, who is also the author of this dissertation, conceptualised and performed the research. The other authors have performed an advisory role.
Parts of this chapter refer to article Moncada et al. [2017]; the author of this dissertation and Prof.dr.ir. Zofia Lukszo (one of her promotors) are two of the authors of such article.

In Chapters 3, 4, and 5, we modelled illustrative neighbourhoods as groups of households living in owner-occupied dwellings that are connected to the natural gas network. Dwellings were either single-family buildings or were part of multi-family buildings, and had an insulation level and a heating system with corresponding appliances. Households in the models had the option to replace their heating system, their insulation level, or both; their decisions were based on single or multiple criteria, and their financial rationality could be perfect or bounded.

6.1.1. RESEARCH SUB-QUESTION 1

How to explore the influence of homeowners' decisions regarding investment in heating systems and insulation measures on the heat transition in the Netherlands?

Throughout this dissertation, we used a complex systems engineering (CSE) approach [Moncada et al., 2017] with a conceptual framework based on the perspectives of socio-technical systems and complex adaptive systems to the development of agent-based models. This framework allows us to explore combinations of technological, economic, legal, and social interventions. As explained on page 2 of Moncada et al. [2017], CSE "*addresses not only the challenges and possibilities of technical artefacts but also multi-actor complexity of socio-technical systems*". This approach relies on modelling and simulation methods to explore technological and institutional challenges of energy transitions. We first demonstrated how to use the conceptual framework via an illustrative example of a neighbourhood's transition to heating without natural gas in Chapter 3.

In our illustrative example, we aimed at answering the question: *Which socio-technical conditions support the Dutch neighbourhoods' transition from natural gas-based to natural gas-free heat supply until 2040 while meeting the neighbourhoods' heat demand?* To answer this question, we observed natural gas consumption and cumulative costs in an illustrative residential neighbourhood. The neighbourhood's natural gas consumption and cumulative costs changed as a function of individual decisions of households. Households could improve their dwellings' insulation or replace their heating system. Further, households could be environmentally-oriented, socially-oriented, or financially-oriented. They considered specific time horizons when comparing investments. Institutions were implicit in changes in energy prices, the sunsetting of natural gas boilers, and households' ability to compare combinations of heating systems and insulation levels, which was a proxy for the impact of an information campaign about cost-effective investments. We found that natural gas-free heating was achieved by 2040 when all households were environmentally-oriented, or when three conditions were met; namely, the time horizon was 5 or 10 years, electricity price decreased, and natural gas price increased. Further, the ability to compare combinations of insulation and heating systems made room for more cost-effective decisions. In other words, the transition could happen when all households were driven only by environmental concerns. Otherwise, the transition was not guaranteed and more elaborate combinations of factors were necessary.

While the illustrative example and its model were intentionally simple and its results were straightforward, they contained key elements of agent-based modelling. They allowed us to demonstrate how to develop and use ABMs from the perspective of STS and CAS, in order to gain insights regarding the interactions between actors, institutions, and technology. Further, this illustrative example paved the way for answering the remaining research sub-questions.

6.1.2. RESEARCH SUB-QUESTION 2

How could individual and group decisions between building owners, and within HOAs in strata buildings, influence the course of the heat transition in a neighbourhood in the Netherlands, under different policy interventions?

We modelled the combinations of insulation and heating systems that individual households preferred as the outcomes of a lifetime-cost calculation with a discount rate. Households with perfect financial rationality used a market discount rate. Households with bounded financial rationality used an implicit discount rate, which had a higher value than the market discount rate. To represent group decisions, we used a voting system with two layers of thresholds: one layer for decisions within buildings and their homeowners associations, and a second for decisions between HOAs and self-standing households in the neighbourhood. Further, we modelled three financial policies and a disconnection policy. The financial policies included higher natural gas taxes, lower electricity taxes, and a cap on the price of heat from networks.

Group decisions influenced choices in the neighbourhood when there was a mix of households with perfect and bounded financial rationality. In our illustrative example, we modelled heat networks as the most cost-effective option from the perspective of perfect financial rationality. In simulation runs with a mix of households with perfect and bounded rationality, although there were in principle sufficient households that preferred a heat network, decisions at the level of homeowner associations sometimes resulted in unmet thresholds at the level of the neighbourhood. In those cases, the emergence of a heat network was blocked and households had to adopt their best individual option.

Further, we found that no combination of the fiscal policies that we explored incentivised individual households to disconnect from the natural gas network. The disconnection policy was the only necessary and sufficient condition for households to stop consuming natural gas. Under the disconnection policy, uncoupling the price of heat from networks from the price of natural gas decreased the incentive for households to further insulate their dwellings and decrease their energy demand. However, according to experts in the Netherlands [Huygen and Akerboom, 2020, van Vlerken, 2019], a top-down approach, specifically for heat networks, could prove problematic.

6.1.3. RESEARCH SUB-QUESTION 3

How could multi-criteria decisions by households influence the course of the heat transition in a neighbourhood in the Netherlands, under different policy interventions?

We modelled the combinations of insulation and heating systems that individual households preferred as the outcomes of a multi-criteria perceived lifetime utility sub-model, and decisions as outcomes of individual preferences and a threshold voting

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system in the same two-level manner as for sub-question 2. Each household had a household preference profile, which contained the weights that the household assigned to each of four decision criteria: environment, finances, duration of the works to install a combination of heating system and insulation, and the space that the heating system would occupy in the dwelling. At the beginning of the simulation, we explored the combinations of technology that households with 23 different profiles preferred, including four single-criterion profiles in which one criterion had 100% weight. In simulations over 30 years, we only explored household preference profiles in which finances had a non-zero weight. As policies, we included energy taxes (natural gas and electricity), regulated price of heat from networks, and subsidies (insulation and heat pumps).

We found that household preference profiles were more influential than financial policies. In simulations of 30 years, full transitions required household preference profiles with non-zero weight on non-financial criteria. While no combination of financial policies was sufficient to enable a full transition, six multi-criteria household preference profiles were sufficient conditions. In these profiles, finances had at most 25% weight, environment had at least 25% weight and together with space at least 50% weight. At the beginning of the simulation, in addition to the previous six multi-criteria household preference profiles, when households had profiles in which environment or space had 100% weight, households preferred heat networks; otherwise, households preferred to remain connected to natural gas. In other words, non-financial criteria were necessary for the entire illustrative neighbourhood to disconnect from natural gas. Under the combinations of policies that we explored, decisions made only with the financial criterion did not result in full transitions.

Further, simulation runs could result in full or partial transitions, but those transitions posed challenges. In terms of medians, although full transitions led to lower CO_2 emissions, they also led to higher investment costs. Lower upfront costs and other ratios between the costs of different alternatives could constitute more favourable techno-economic conditions for full transitions. In partial transitions, the number of households that disconnected from natural gas varied: it could be as low as 22 and as high as 428 out of 500. Further, the benefits of partial transitions were debatable. In terms of collective CO_2 emissions and subsidy costs relative to the reduction in CO_2 emissions, some transitions in which only some households phased out natural gas could have results similar to some scenarios in which households only improved their dwellings' insulation levels. Note that the illustrative neighbourhood and the set of alternatives to natural gas as well as their costs were different from those discussed in Section 6.1.2 and the results are therefore not directly comparable. In the work discussed in Section 6.1.2, we modelled heat networks as the most cost-effective alternative to natural gas, and in the work discussed in this section, we modelled heat pumps as the most cost-effective alternative.

Overall, our results illustrated that household preference profiles with financial and non-financial criteria, and the resulting multi-criteria decisions, could influence the outcomes of the combinations of financial polices that we explored, and as a consequence, the course of the heat transition in the illustrative neighbourhood. Even when certain combinations of financial policies were in place, multi-criteria decisions were necessary for full transitions to occur. Transitions, full or partial, could sometimes pose challenges, i.e. higher investment costs or contestable reductions in CO_2 emissions.

6.1.4. MAIN RESEARCH QUESTION

How could the heat transition in the Netherlands be influenced by homeowners' individual and group decisions regarding investment in heating systems and insulation measures?

Our agent-based studies illustrate that group decisions and multi-criteria decisions could influence the heat transition in the Netherlands as follows. Group decisions can enable or block collective projects such as heat networks or other decisions at the level of buildings or neighbourhoods; they can lead to a different outcome than when only individual decisions are made. This can affect which alternatives to natural gas are implemented, and as a result, the costs of the heat transition. Based on our modelling results, we expect the phasing out of natural gas to be more expensive for households than remaining connected to natural gas. Although financial policies could be used to shift this balance, given that decisions by households are also influenced by non-financial factors, we expect that stimulating the transition with financial policies alone would not be effective; instead, a multi-actor and multi-criteria perspective would be necessary.

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6.2. RECOMMENDATIONS FOR POLICY-ANALYSIS

We make the following recommendations for policy-analysis.

Account for the occurrence of group decisions in heat transitions. Individual decisions are not the only decisions that are required from households in heat transitions. Because group decisions can influence adoption decisions, group decisions within and between homeowner associations should be taken into consideration in the analysis and design of policies.

Account for the limited effect of financial policies to enable heat transitions. In our analyses, when we assumed that households made decisions solely based on finances, the effect of financial policies to enable heat transitions was limited. In Chapter 4, no combination of financial policies was sufficient to achieve the heat transition. In Chapter 5, specific combinations of policies were often required. Therefore, we expect financial policies to be only one of the factors influencing the success of heat transitions. To mention a few, as reported by Dignum et al. [2021], there would be specific moments in which households would be more likely to undergo changes in their dwellings, and as reported by Roodenrijs et al. [2020], leadership and information processing within groups also play a role. We expect knowledge generation from heat transition initiatives, such as the testing grounds and other projects, to be crucial in the design of policies to phase-out natural gas in other parts of the country.

Include scenarios with natural gas and demand reduction in the discussions of alternatives to the current situation of heat provision. Households are currently able to insulate their dwellings without replacing their natural gas boilers. Among other purposes, subsidies are in principle available for insulation. In our ABMs, unless there was a requirement to disconnect from natural gas, or specific combinations of non-financial motivations, disconnections of all households could happen later in the simulated time, and they could be preceded by changes in insulation. Therefore, we consider relevant to explore the effect that insulation could have on the heat transition, and to incorporate the findings of such exploration in policy discussions.

Account for the different effects that heat transitions could have on households depending on their income level, and on other parties. As a thought experiment, in our work (Chapter 4), we explored which financial policies could sufficiently change the NPVs of different combinations of heating systems and insulation levels in order to make alternatives to natural gas more attractive than their counterparts. Our findings suggest that large changes would be necessary to change the NPVs; for example, a continued increase in the natural gas tax and a cap on the price of heat from networks. However, our research did not analyse the consequences of those increases on the finances of households, nor the consequences of a price cap on heat utilities. A recent study [Vollebergh et al., 2021] suggests that taxes for households are already disproportionate to the emissions that they generate. Furthermore, changes in the cap of the price of heat from networks are already considered to be necessary and are already in motion. Therefore, we recommend to explore the effects that potential fiscal policies, subsidies, and other measures could have on different households.

6.3. DISCUSSION AND REFLECTION

6.3.1. USING AGENT-BASED MODELS TO STUDY HEAT TRANSITIONS

In light of the broad and fast-evolving heat transition in the Netherlands, our work has an exploratory scope. We structured the challenge of the heat transition using the perspectives of STS and CAS, and proposed how to explore it with ABMs. We used desk research and validation via sensitivity analysis, expert reports, and news. The novelty of our contribution rests on using ABMs to explore the heat transition, including competing rather than single technologies, focusing on group decisions within and between HOAs in addition to individual decisions, relaxing assumptions of perfect financial rationality, and having an explicit focus on the analysis of potential policies.

Nevertheless, it must be noted that the quantitative power of our ABMs is limited. Input data for market conditions and technical specifications can influence the combinations of heating systems and insulation measures that households in our models prefer. Variations in input data could lead to households preferring a different combination of heating systems and insulation measures. Our selection of prices of natural gas and electricity also introduce uncertainties in our calculations: we assume them to be constant but can in reality fluctuate. Similarly, the quantification of energy demand can vary when phenomena such as the rebound effect of the energy performance gap occur and are represented.

As a result, our conclusions should not be used to select specific policy interventions or changes in technology. Instead, this work paves the way for future research in the form of case studies, model refinement, and even multi-modelling studies.

6.3.2. REPRESENTATION OF GROUP DECISIONS

Our work in Chapter 5 makes explicit the relevance of group decisions for heat transitions. To explore the effect of group decisions in our models, we use a simplification of actual formal systems and informal processes at play. However, actual decisions can be more intricate and varied, and the conditions that could enable or block heat transition projects could be different. Since our ABMs can be customised, they offer an opportunity to replace our representations with validated conceptual models of group decisions.

Further, our research regarding group decisions has common elements with the body of literature concerning energy communities, which we consider to be outside the scope of this project. In our ABMs, decisions by individual households can result in the emergence of collective projects, but we do not explore the "how" or the "why". Instead, we use a higher level of abstraction and explore the effect of group decisions, whether they lead to energy communities or not. Our models can be modified to explicitly represent energy communities.

6.3.3. REPRESENTATION OF MULTI-CRITERIA DECISIONS

Our representations of non-financial factors that influence the decisions of households have limitations. In Chapter 4, we used an illustrative value for the implicit discount rate; however, the preferences of households could be better represented with a variety of implicit discount rates rather than a homogeneous value. Moreover, our use of implicit discount rates limits the exploration of the effect that policies could have on the disconnection from natural gas. To address this last limitation, in Chapter 5, we modelled the preferences of households with decision criteria and weights. The selection of the multiple criteria that households take into consideration in their decisions was based on a literature review and an expert interview, as reported by Wessels [2020]. However, in practice, different households may consider criteria or weights that we did not include. Further, we operationalised the multiple criteria in a simplified manner: for the financial and environmental criteria we focused on the lifetime rather than the life-cycle; for duration of the works, following Wessels [2020], we focused on inconvenience in the private sphere and excluded the inconvenience in public spaces; we also assumed that their values remained constant throughout the simulation.

An additional limitation concerns the period following the adoption of a technology. The implicit discount rates and the multiple criteria are ways of conceptualizing the preferences of households when adopting a given technology. However, after the technology is adopted, different dynamics concerning their use and maintenance might be at play. As a result, representing the maintenance of a technology as a series of adoption decisions might not be accurate and a different approach might be necessary.

Therefore, our modelling of multi-criteria decisions can be expanded to represent specific case studies or more realistic situations based on empirical research.

6.3.4. REPRESENTATION OF POLICIES

Due to the exploratory nature of our work, we made the following choices when representing policies in our models. Firstly, we used a simplification of existing policies. This is the case for the quantitative calculation of the regulated price of heat for networks and the quantitative value of subsidies and taxes. Secondly, we used a simplification of future uncertainties. This is the case for the increase in the electricity tax until 2026, increases in natural gas and electricity taxes after that year, and the disconnection policy. Finally, our selection of policies is a non-exhaustive representation of the policies that are currently in place to enable the heat transition. Our work can be expanded by including more detailed representation of policies, as well as a wider selection of existing and potential policies.

6.3.5. ACCOUNTING FOR POTENTIAL INEQUALITIES

Exploring the effect that different changes in technology and policies could have on the finances of households was outside of the scope of our work. In our ABMs, we assume that households are always able to pay for a change in heating systems and insulation, regardless of their financial situation and of whether they made a change in the recent past. Furthermore, we explore theoretical increases in taxes and in the regulated price of heat from networks, but we do not account for the effect that such increases would have on household finances. This is an important topic that should be addressed in future research.

6.4. SUGGESTED FUTURE RESEARCH

In this section, we propose various lines of work to expand and use the ABMs, and we provide recommendations for decision-makers.

6.4.1. MODEL REFINEMENT AND EXPANSION

As explained in Chapter 2, as the heat transition in the Netherlands evolves, the literature on this topic is increasing. This increase creates opportunities to integrate our work and models with other research. Therefore, we propose some directions for improving the ABMs.

Incorporate new decision-making models and interactions between households. The literature describing the dynamics of HOAs in energy transitions is limited [Roodenrijs et al., 2020]. As more empirical literature regarding group decision-making becomes available, we suggest to adapt the threshold rules for different types of decisions and different sizes and types of HOAs. We also suggest to incorporate interactions between households in the form of social networks.

Further, although we focused on the owner-occupied share of the housing sector, our work can be expanded to other shares of this sector. For example, group decisions and majority systems also play a role in buildings with tenant-occupied dwellings. Currently, landlords who wish to connect buildings that use natural gas to a heat network may require the support of a percentage of the tenants. According to ACM ConsuWijzer, approval from 70% of tenants is required in two situations. Firstly, if the change to a heat network would require adjustments in at least 10 dwellings. Secondly, if a group of tenants would be forced to change to a heat network and their service costs would change as a result.

A collaborative approach could also be adopted to collect empirical data to fine-tune different parts of the models, such as the threshold system, implicit discount rates, and household preference profiles. These improvements would make the representation of households' decisions over time more realistic. A more realistic representation would enable further exploration and design of financial and non-financial policies to enable the heat transition.

Integrate validated quantitative calculation models. This dissertation lays the foundation to inform or even pair our ABMs with calculation models that have been explicitly built to compare combinations of heating systems and insulation levels. As explained by Brouwer [2019] and Henrich et al. [2021], various parties have already built calculation models to compare alternatives to natural gas. A validated selection of alternative technologies to natural gas boilers, including their technical specifications and costs, would enhance the quantitative power of our models and make them more suitable for the design and selection of policy interventions.

One specific suggestion is to incorporate a dynamic model to calculate the business case of a heat network. Among other factors, it could include the number of connections and the heat demand of households willing to join the project. See a template for the business case of heat networks in ECW. Instead of the current representation of only one heat network that requires a fixed percentage of households to be implemented, using a dynamic model would enable the representation of different heat networks with different number of households and associated costs.

A complementary approach would be to incorporate participatory model building and validation. See, for example, the companion modelling approach by Bousquet et al. [2014]. Further, as qualitative reports regarding the challenges of disconnecting neighbourhoods from natural gas increase, opportunities arise to refine our ABMs with empirical findings. These findings can then replace current assumptions.

Incorporate non-instantaneous decisions. According to Busch et al. [2017], ABMs of adoption of technology often contain instantaneous decisions, instead of representations of technology adoption as a multi-actor process over time. This is one of the limitations of our work: when households make a decision, the combination of heating system and insulation that they chose is functional in the following year. Moreover, we assumed that households made decisions every year, but we do not expect this to be the case in practice.

Representing a process, as described by Busch et al. [2017], would be a more accurate way to represent decision processes and implementation of technology. The new representation could include adaptation and learning by households over time, which are design elements of ABMs [Grimm et al., 2010]. Moreover, the representation of individual preferences and decisions can be refined, for example, by including the natural decision moments reported by Dignum et al. [2021] (e.g. moving houses, renovation, or replacement of boilers).

Expand our models by coupling them with related models. Literature regarding ABMs of heat transitions has increased in recent years. We suggest to connect our ABMs with other related ABMs that have been developed for similar purposes but with different features. This could reduce the time required to develop new code in order to improve the representations of technology, actors, and institutions.

In particular, we propose to connect our research with lines of work regarding building retrofit and the emergence of energy communities. For example, a conceptual ABM of neighbourhood-level building retrofits based on the Energiesprong approach was presented in a recent conference by Akhatova et al. [2021]. Another example is the work by Schiera et al. [2019], which explores the diffusion of rooftop photo-voltaic cells in an area with both single-family and multi-family buildings. Among other aspects, their model represents a hypothetical scenario in which a majority of apartments can adopt the technology together and have a single connection to the grid. In our ABMs, we focus on the phase-out of natural gas and our households do not adopt photo-voltaic cells nor explicitly become prosumers. Connecting our ABMs to this line of research could improve the impact of our results by producing use-cases not only about the Netherlands and the heat transition, but also about other countries trying to achieve a decarbonization of the built environment and integrated energy systems with prosumers.

We also propose to connect our research with lines of work regarding the acceptance and acceptability of energy projects. A lack of social acceptance of heating systems may occur over time when there are value conflicts, explain de Wildt et al. [2021]; they propose an approach for their ex-ante assessment. Our work centered on households' decision to adopt a heating system and treated the process of maintaining a heating system as a sequence of adoption decisions. Connecting our models with models of acceptance would enable the exploration of the factors that drive households to decision moments in which they would consider to maintain or replace their heating system.

6.4.2. MODEL USE

We recommend to use the ABMs for the following purposes.

Explore system behaviour under different neighbourhood configurations. Our illustrative examples were limited by the layout of the neighbourhood that we selected. Different number, types, and densities of dwellings, as well as the types of households, could lead to different results. One avenue of research would be to apply our work to a series of individual case studies. A second option would be to conduct a parameter sweep and explore the different results that the models are able to produce, and their implications for actual neighbourhoods. We expect the first option to require more empirical research than the second one. We expect that the parameter sweep could be conducted mainly with desk research.

Explore system behaviour under various uncertainties. In addition to the neighbourhood configuration, various factors in our ABMs are in reality uncertain. For example, market conditions or the way in which households interact with each other. A wide uncertainty analysis, in addition to sensitivity analyses, would build confidence on the findings linked to the ABMs.

Explore potential policy measures in a participatory setting. The policies that we modelled, although based on existing or potential policies, were illustrative. The effects of future policies could be explored by using the ABM in a participatory setting. Such an exercise could be used to support learning and decision-making processes, build confidence in the outcomes, and account for factors that we did not consider.

Explore potential inequalities between households. We used our ABMs to explore which combinations of financial policies could lead to heat transitions. Our outcomes could be further analysed by comparing how the resulting costs would affect the expenses of households. In particular, we recommend analyzing, ex-ante, the impact that it would have on households with different income levels. The outcomes of such an analysis can then serve as input to decide whether an increase in taxes is at all possible, whether subsidies will be offered, or which combination of policies would be implemented.

6.5. FINAL REMARKS

The implementation of heat transition projects in the Netherlands is challenging. Robust techno-economic assessments of combinations of heating systems and insulation measures in the built environment are indispensable for heat transition projects. In addition to these assessments, actor analyses with a focus on heterogeneity as well as institutional analysis, both from a socio-technical perspective, are also indispensable.

Agent-based modelling and simulation is a well-suited method to explore the complexities of the heat transition. As shown in our studies, with an ABM it is possible to integrate techno-economic descriptions with institutional context, with decentralised decisions, and with actor heterogeneity in order to explore their influence on the heat transition. This dissertation takes the application of this method to explore the heat transition one step further.

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Curriculum Vitae

Graciela del Carmen Luteijn-Nava Guerrero

Graciela was born on the 22nd of September 1990, in Zapopan, Mexico. Motivated by the many challenges to sustainable development, in 2013, Graciela obtained a Bachelor in Environmental Engineering from ITESO, in Mexico. Afterwards, in 2016, she obtained a Master of Science in Engineering and Policy Analysis from Delft University of Technology, in the Netherlands; she graduated *cum laude* and with the annotation Technology in Sustainable Development. In 2016, Graciela pursued the doctoral research project that led to this dissertation.

Graciela conducted her PhD research at the Faculty of Technology, Policy and Management at the Delft University of Technology. She was part of the Energy and Industry Group at the Department of Engineering Systems and Services. Her doctoral research was part of the NWO Project “Modeling Lab for smart grids, smart policies, smart entrepreneurship”. This project was Project E from the Smart Energy Systems in the Built Environment (SES-BE) Programme. In addition to research, her tasks involved interactions with industrial, academic, and public stakeholders, as well as education. Throughout her project she assisted in various bachelor and master courses, delivered two guest lectures in the master course "Design of Integrated Energy Systems", and co-supervised two master graduation projects. She co-authored scientific works concerning complex systems engineering for energy transitions. Her works include workshop and conference presentations, and journal articles.

Since September 2021, Graciela is a researcher at the Netherlands Environmental Assessment Agency (PBL, for its initials in the Dutch language).

List of Publications

1. **Nava-Guerrero, G.D.C.**, Hansen, H. H., Korevaar, G., & Lukszo, Z. (2022) An agent-based exploration of the effect of multi-criteria decisions on complex socio-technical heat transitions. Applied Energy, 306(Part B), 118118. `https://doi.org/10.1016/j.apenergy.2021.118118`.

2. **Nava-Guerrero, G.D.C.**, Hansen, H. H., Korevaar, G., & Lukszo, Z. (2021). The effect of group decisions in heat transitions: An agent-based approach. Energy Policy, 156(112306). `https://doi.org/10.1016/j.enpol.2021.112306`.

3. **Nava Guerrero, G.D.C.**, Korevaar, G., Hansen, H. H., & Lukszo, Z. (2019). Agent-Based Modeling of a Thermal Energy Transition in the Built Environment. Energies, 12(5), 856. `https://doi.org/10.3390/en12050856`.

4. Moncada, J.A., Park Lee, H.K., **Nava Guerrero, G.D.C.**, Okur, Ö., Chakraborty, S.T., & Lukszo, Z. (2017). Complex Systems Engineering: Designing in sociotechnical systems for the energy transition. EAI Endorsed Transactions on Energy Web 17. `https://doi.org/10.4108/eai.11-7-2017.152762`

Other materials

1. **Nava-Guerrero, G. D. C.**, Hansen, H. H., Korevaar, G., & Lukszo, Z. (2022). Agent-based model described in journal article “An agent-based exploration of the effect of multi-criteria decisions on complex socio-technical heat transitions”. Publisher of agent-based model: 4TU Repository. DOI of agent-based model: `https://doi.org/10.4121/18865433`.

2. **Nava-Guerrero, G. D. C.**, Hansen, H. H., Korevaar, G., & Lukszo, Z. (2022). Supplementary data for journal article "An agent-based exploration of the effect of multi-criteria decisions on complex socio-technical heat transitions". Publisher of supplementary data: 4TU Repository. DOI of supplementary data: `https://doi.org/10.4121/18865406`

3. **Nava-Guerrero, G. D. C.**, Hansen, H. H., Korevaar, G., & Lukszo, Z. (2022). Agent-based model described in journal article “The effect of group decisions in heat transitions: An agent-based approach”. Publisher of agent-based model: 4TU Repository. DOI of agent-based model: `https://doi.org/10.4121/18865415`

4. **Nava-Guerrero, G. D. C.**, Hansen, H. H., Korevaar, G., & Lukszo, Z. (2022). Supplementary data for journal article “The effect of group decisions in heat transitions: An agent-based approach”. Publisher of supplementary data: 4TU Repository. DOI of supplementary data: `https://doi.org/10.4121/18865385`

5. **Nava-Guerrero, G. D. C.**, Korevaar, G., Hansen, H. H., & Lukszo, Z. (2022). Agent-based model described in journal article “Agent-based modeling of a thermal energy transition in the built environment”. Publisher of agent-based model: 4TU Repository. DOI of agent-based model: `https://doi.org/10.4121/18865367`.

6. **Nava-Guerrero, G. D. C.**, Korevaar, G., Hansen, H. H., & Lukszo, Z. (2022). Supplementary material from journal article “Agent-based modeling of a thermal energy transition in the built environment”. Publisher of agent-based model: 4TU Repository. DOI of supplementary material: `https://doi.org/10.4121/18865355`

7. **Nava Guerrero, G.D.C.**, Hansen, H. H., Korevaar, G., & Lukszo, Z. An agent-based exploration of individual and collective decisions towards heat transitions. Conference abstract submitted for an oral presentation.

8. Westera, N.M., **Nava Guerrero, G.D.C.**, Hemmes, K., & Lukszo, Z., Ramírez Ramírez, A. Exploring community acceptance of ownership models for district heating as an alternative to natural gas-based residential heating in a city in the Netherlands. Presentation at the 4th International Conference on Smart Energy Systems and 4th Generation District Heating. 13-14 November, 2018. Aalborg, Denmark.

9. **Nava Guerrero, G.D.C.**, Hansen, H.H., Korevaar, G., & Lukszo, Z. Agent-based modelling for the thermal energy transition of natural gas dependent neighborhoods. Presentation at the 4th International Conference on Smart Energy Systems and 4th Generation District Heating. 13 November, 2018. Aalborg, Denmark.

10. **Nava Guerrero, G.D.C.**, Hansen, H.H., Korevaar, G., & Lukszo, Z. Agent-based modelling of a neighborhood’s transition towards gas-free heating. Presentation at the 3rd International Workshop on Agent-Based Modelling of Urban Systems. July 15, 2018. Stockholm, Sweden.