FEASIBILITY OF CARBON NEUTRALITY IN AN URBAN CONTEXT

Evaluating the case of Groningen

Peter Constantijn Osseweijer
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Master Programme Energy and Environmental Sciences, University of Groningen

university of groningen

faculty of science and engineering

energy and sustainability research institute groningen

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Supervised by:
Prof. dr. Klaus Hubacek
Co-supervised by:
Dr. Yuli Shan, PhD

University of Groningen
Energy and Sustainability Research Institute Groningen, ESRIG

Nijenborgh 6
9747 AG Groningen
T: 050 - 363 4760
W: www.rug.nl/research/esrig

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Abstract

An increasing number of cities presents plans to reduce carbon emissions on their municipal grounds in order to limit their contribution to global warming. The Dutch city of Groningen is no exception. The city considers itself as a frontrunner in the energy transition and aims to achieve carbon neutrality before the year 2035. To this end, a clear set of transitioning actions has been formulated. The question that arises is: can it be done?

In this research, a model is developed in Excel to assess the impact of the roadmap proposed by Groningen in three main categories: emissions avoided by the envisioned actions, additional upstream emissions caused by the actions, and the investment costs they require. The aim of this research is twofold: first, evaluating the feasibility of Groningen's goal of achieving carbon neutrality; second, laying the groundwork for an accessible and insightful tool for urban environments to evaluate their own roadmaps.

The actions Groningen has proposed to bring carbon emissions down to zero were found to reduce emissions by 92.6%. Simultaneously, the investments the implementation of the actions require total to €4.4 billion to be spend in the 20 years before 2035. This figure is almost twice as high as the €2.3 Groningen estimated for the transition. On top of that, the implementation of new equipment causes upstream emissions of 1.88 $MtCO_2$. This is more CO_2 than what Groningen currently emits in an entire year.

Technologically, it seems perfectly feasible for Groningen to achieve net zero carbon emissions. The cost involved, however, is considerable. Much of the cost is expected come at the expense of households and businesses. Whether these sectors can and will execute on the proposed actions remains highly questionable.

The stark difference between the transitioning cost estimations of the model and of Groningen itself signals shortcomings in the decision-making process present in municipal leadership. Environmental policy is held back due to a lack of in-house expertise and a limited involvement in underlying research. The model developed in the research can help alleviate these issues for city councils.

List of abbreviations and acronyms

BAG	Basisregistratie Adresgegevens
BEV	Battery electric vehicle
CBS	Centraal Bureau voor de Statistiek
CO_2	Carbon dioxide
DHW	Domestic hot water
EES	Energy and Environmental Sciences
EUA	European allowance
EU ETS	European emissions trading system
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
GDP	Gross domestic product
HHV	Higher heating value
ICE	Internal combustion engine
kW	Kilowatt
kWh	Kilowatt hour
LCA	Life-cycle assessment
LCV	Light commercial vehicle
LHV	Lower heating value
LNG	Liquefied natural gas
$MtCO_2$	Megaton CO_2
MW	Megawatt
MWp	Megawatt peak
NDC	Nationally determined contribution
PV	Photovoltaics
tCO_2	Ton CO_2
TTW	Tank-to-wheels
WTT	Well-to-tank
WTW	Well-to-wheels

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1. Introduction

As a result of human behaviour, the global average temperature has been climbing steadily over the past century. Atmospheric CO_2, being one of the main drivers of this climbing temperature, currently shows a global average concentration of over 414 parts per million (U.S. National Oceanic & Atmospheric Administration, 2021). These events are fuelled by human consumption, and find their culmination in urban areas (Watts, 2017). More cities are starting to formulate their own action plans, not willing to wait for climate commitments of their often-slow national governments. Cities are often close to the sources of pollution. On top of that, cities are involved with their communities, making it easier to include them in the decision-making process. On the other hand, cities struggle with limited funds and limited authority. This raises the question of how a municipality can effectively confront a changing climate.

1.1. Background

Climate change as a result of ever-increasing anthropogenic emissions is a global problem. With the world's population getting richer and continuously reaching new technological highs, we keep increasing the pressure on the planet that facilitates everything. As humans tend to conglomerate together, cities and other urban areas are the main regions anthropogenic emissions can be linked to (Doll *et al.*, 2000; Gurney *et al.*, 2015). Construction, transportation, and just people living their lives; all these activities contribute to the rising levels of carbon dioxide in the atmosphere (Khan *et al.*, 2020). And it goes further: a large part of the production that happens in rural areas is intended to fulfil the needs of the urban population (Hoornweg *et al.*, 2011; Osei-Owusu *et al.*, 2020). Studies assessing the carbon footprints of human settlements throughout the world concluded that for the United Kingdom, 90% of settlements are net importers of CO_2 emissions (Minx *et al.*, 2013), and worldwide, 80% of cities have larger consumption-based emissions than production-based emissions (Doust *et al.*, 2018). At the same time, there tends to be a stark division between cities and rural areas in terms of economic welfare. With 55% percent of the world population living in urban areas and over 80% of the global gross domestic product (GDP) being generated in cities, they have the means to engage in more serious climate action than their rural counterparts (World Bank, 2020). It seems obvious that cities should play a vital role in the race to put a stop to the release of carbon dioxide.

The number of governments, from municipal to federal and beyond, joining the fight against climate change is rising, each with their own set of actions and roadmaps. Still, the augmented amount of carbon dioxide that will be prevented from being released into the atmosphere more often than not falls short of the savings declared in Nationally Determined Contributions (NDCs) (Amundsen *et al.*, 2018; Fuhr *et al.*, 2018). In turn, all these NDCs combined only account for a reduction of the emissions gap, the gap between no further climate actions and the goal of limiting global warming to 1.5°C by 2050, of 35% (Bailey *et al.*, 2019). In other words, actions required to keep the planet liveable and to prevent mass extinction and mass migration need to be significantly more radical than what is being considered by most countries and cities around the world today.

The number of organisations and cooperations between cities aiming to formulate climate actions tailor-made for urban areas is increasing (Acuto, 2013). Both the C40 network and the Global Covenant of Mayors for Climate and Energy are good examples that produce a large amount of literature and data for other urban areas to use. Other cities come up with their own detailed roadmaps that devise a step-by-step guide towards a more sustainable future. However, how ambitious these futures are, varies wildly (Wallaart & Kusse Public Affairs, 2018).

One such city that set out on the quest to become more sustainable is the municipality of Groningen, situated in the eponymous province in the north of the Netherlands. Groningen propagates itself as a frontrunner in climate actions and applauds the sense of urgency that is present within its community. The city has developed a roadmap to becoming carbon neutral by 2035, and the fruits of their labour can already be found in the streets in some forms (Gemeente Groningen, 2018; Dagblad van het Noorden, 2020).

The province of Groningen has long played a vital role in the energy supply in the Dutch market. The region is a source of natural gas and the Netherlands are for a large part dependent on this gas. Groningen, the capital city of the province, houses headquarters of multiple large players in the production of this natural gas. The production is being brought to a halt as a result of a rise in earthquakes related to the gas extraction. The region views this as an opportunity to proliferate the north as a sustainable energy hub in order to maintain its position as an energy producer for the rest of the country throughout the transition to a decarbonised economy (TopDutch, 2020).

1.2. CO_2-neutrality in Groningen

"The Dutch municipality of Groningen wants to be CO_2-neutral by 2035." With this sentence the municipality starts its *Routekaart Groningen CO_2-neutraal 2035*, their roadmap to CO_2-neutrality (Gemeente Groningen, 2018). In this 80-page document, Groningen outlines the steps that need to be taken to reduce the locally emitted carbon dioxide to zero. Prior to the release of this report, the city's ambitions were limited to achieving energy neutrality, as expressed in their report *Masterplan Groningen Energieneutraal* (Gemeente Groningen, 2011). Groningen wishes to be a frontrunner in the energy transition and envisions itself as a future 'Energy City'; however, the city started to realise that their aspirations had grown beyond the goals set in their earlier master plan. Yet, with growing aspirations come greater hurdles to be overcome. To that end, Groningen commissioned an investigation into the achievability of their ambitions that is presented in their *Routekaart* report. This roadmap report is a means to gauge the extent to which the municipality will be able to make the transition to a fully sustainable energy supply within its own municipal borders. The city states that CO_2-neutrality is technologically possible, but that it needs all stakeholders to partake in the transition to get there. That last part is telling. Most of the required actions lie beyond the power of the municipality. As a result, the municipality can only hope to persuade other stakeholders to play their part by offering subsidies and to steer their behaviour by enacting legislation. The city set out to inform and motivate other parties, and to congregate them to stimulate cooperation. What the city *is* able to do, is to lead by example.

For their report, Groningen considered five categories: households, businesses, industry, mobility, and sustainable energy supply. For each category, the city examined how it could contribute to the goal of CO_2 neutrality and what investments will be required. The specific actions presented in the report are included in appendix A. To progress towards CO_2 neutrality, the current situation was mapped out first. The actions for all individual categories were then combined into one plan for Groningen's future presented in the roadmap. Additional investments and energy reductions were computed per category and per type of technology. To not just work towards a goal that might appear as too far into the future for some, Groningen defined intermediate, more specific goals for the year 2023. This year can be seen as a checkpoint towards the end goal.

The envisioned carbon neutrality does not come cheap. In their roadmap, the municipality of Groningen estimates a €140 million yearly investment from 2016 onward to achieve their goals, totalling to €2.3 billion in 2035 (Gemeente Groningen, 2018). Even if Groningen manages to become CO_2-neutral by 2035, leading up to that year carbon dioxide will still have been emitted to the atmosphere. Not just as a result of continued operation of current technologies: consider that the shift to a low-carbon future will come with additional so-called upstream emissions, emissions that are attributed to the production and transportation phase of new infrastructure and technologies.

It must be noted that Groningen bases their carbon neutrality purely on the first two scopes, ignoring the full set of greenhouse gasses emitted while producing goods and products consumed within city borders. This includes the upstream emissions from transitioning actions. On top of that, leading up to the year 2035, Groningen still expects to be carbon positive. In these years, total emissions will stack up. The city currently does not look beyond 2035, and as such has no plans to account for these emissions after carbon neutrality in scopes 1 and 2 has been achieved.

1.3. Motivation and aim

This research evaluates the energy transition that municipality Groningen plans to accomplish. The city intends to implement a vast set of climate actions, while they are not always in the position to force conformity. Groningen has to rely on the readiness of its communities, but the presented figures are limited in their transparency and are difficult to interpret. Their goal, however, is clear: CO_2 neutrality by 2035 (Gemeente Groningen, 2018). This alone already solicits a thorough assessment of the feasibility of these plans.

The city of Groningen is not alone in its ambitions. An increasing number of lower-level governments is joining the energy transition in an effort to hold off climate change (Millard-Ball, 2012). Cities are often the best positioned government bodies to inspire willingness in its communities. The actions implemented by cities have the greatest impact on the direct surroundings of both private individuals and businesses (Boehnke *et al.*, 2019; Hoppe *et al.*, 2014). As such, there is great potential in cities that appropriate a leading role in the energy transition. Simultaneously, the approach cities take often leaves much to be desired. Some cities carry out their own research without asking the proper question, sometimes missing the point entirely; influential decisions can be made without offering communities a proper voice; estimates of required investments tend to underestimate the work and equipment involved (Boehnke *et al.*, 2019). As cities often lack the in-house expertise essential to a solid climate policy, the underlying research is outsourced to external consultancies. The resulting reports are inclined to be non-transparent and sometimes difficult for policy makers to fully understand. Especially in climate policy, the efficacy of specific actions is very much dependent on environmental parameters, and thus differs per city. This brings up significant hurdles in the process of translating external research into adequate actions.

This brings us to the motivation behind this research. In order to aid city councils in integrating environmental criteria into the decision-making process, it is important to have access to a clear overview of the possible impacts of the wide spectrum of available solutions. Such an overview is necessary to be able to compare fundamentally different technologies and to identify and assess the mix of sustainability actions that best fits the respective city. As no city is equal, the effectiveness of technologies such as district heating might differ wildly. A multitude of factors will affect the realisable outcomes of each combination of mitigation strategies. Local climate, available surface area, willingness to adapt, and already present infrastructure are examples of such factors with a significant effect. Access to a transparent and intuitive method to develop tailor-made transitioning actions will not only simplify the lives of counsellors, but it can also be instrumental in the dialogue with communities.

The aim of this study is to be a first step in that direction. I develop an Excel model to assess and analyse the costs and the impacts of the climate actions as proposed by the Dutch municipality of Groningen. As discussed previously, Groningen detailed plans for the municipality to become carbon neutral by the year 2035. The city has formulated specific actions to reduce carbon emissions, supported by an estimation of the economic impact per sector and per technology. The underlying research, however, is opaque. To gain insights in the (cost-)effectiveness of individual transitioning actions in an urban context, I choose to validate the projected outcomes of the case of Groningen. This enables the assessment of the feasibility of the end goal of carbon neutrality, and to quantify the impact each transitioning action has in the context of Groningen.

With this research I aim to answer to following research question:

"What is the ratio between environmental impacts and investment costs of actions required to achieve CO_2-neutrality in Groningen as proposed by the Groningen municipality, and who is accountable for the investments accompanying the proposed actions?"

The ratio between the carbon impacts and the investment cost will give an idea of the effectiveness of each individual mitigation action. This ratio can be used to make a comparison between actions and to find what actions are optimal in which context. The question of accountability is important in order to know what sector is expected to bear the cost of each action and to what extent each sector can contribute to a successful energy transition. Impacts and costs are computed for each action individually. For this, an elaborate model is built in Excel. The conclusion of this study can be the first part of the puzzle to develop an elaborate model to assess the impact of climate actions optimised specifically for a single city.

2. Methods

2.1. Impact assessment

This study aims to index the mitigation strategies proposed by the city of Groningen (Gemeente Groningen, 2018) and the annual emissions that can be avoided by deploying these strategies. Additionally, the upstream emissions and the forthcoming investments to deploy the required technology are determined. To that end, we have developed an Excel model. The impacts the model assesses are categorised as avoided emissions, upstream emissions, and investment costs.

These investment costs include all the extra investments required to install all equipment necessary for a carbon neutral city. This mainly encompasses the cost of purchase, but when available, the cost of labour, required energy and materials, and the cost of transportation are also considered. Costs that can be attributed to the operation phase are at this moment omitted by the model. Furthermore, upstream emissions are the emissions embodied in the equipment and infrastructure that is to be installed. When new products are put into operation, carbon has already been emitted upstream in the product's value chain during its production and transportation. As such, the transition to more carbon efficient technologies brings along some new emissions. Where possible, these emissions should be accounted for. Avoided emissions are the emissions the new equipment and infrastructure, once installed, help to avoid on a yearly basis, as compared to a business-as-usual scenario where Groningen would continue to rely on the polluting energy solutions currently in use. To bring down the emissions in scope 1 and 2 to zero, this is the impact category to focus on (World Resources Institute, 2004, p. 25).

To put it in perspective, if you were to switch from one appliance to a new one that is 10% more efficient in its energy consumption, the direct emissions for which you are responsible for will decrease 10% after you start using the new appliance, assuming a similar usage pattern and an unchanged energy mix. In other words, you avoid 10% of your earlier emissions. However, the production of the appliance and its subsequent transportation to your house has already put an amount of CO_2 in the atmosphere: the upstream emissions. Additionally, to replace the old appliance, you had to purchase a new one, and possibly you also had to pay to get it to your house and to get it installed. These costs are the investment costs.

2.2. System description

The model developed for this research was tailored to the municipality of Groningen. Where possible, it builds on data specific to the city. If such data appears unavailable, external data is scaled towards Groningen; however, this approach increases the error margin of the outcomes. For the model to be applied elsewhere, the city-specific data can be exchanged for more general, national data, or for data optimised for the city in question. As the model was designed with the Groningen roadmap in mind, it only includes the technologies and strategies considered by the city, divided over the sectors the city identifies. The technologies and the sectors they relate to are found in Figure 1.

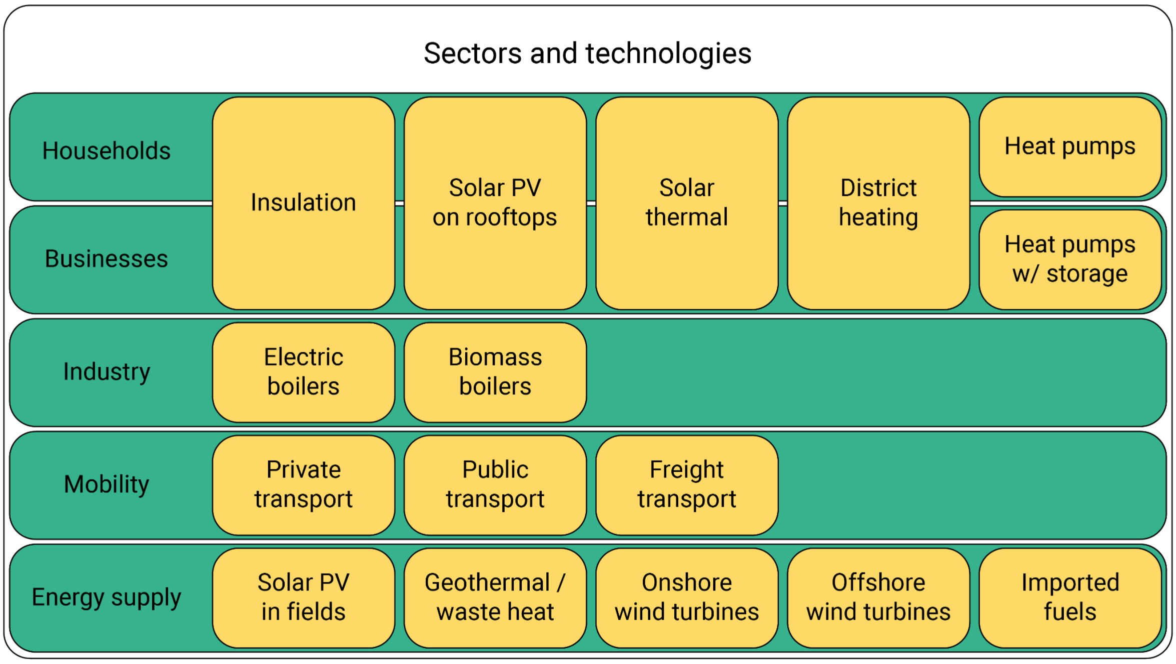

Figure 1: An overview of the technologies the model considers and the sectors they affect.

As this research identifies the municipality as the problem owner, the aim is to limit the deployed measures to what can be done within municipal boundaries and what can be achieved without intervention of higher governments. The possibility of offsetting carbon emissions with foreign investments is ignored for the 2035 carbon neutrality goal; however, it will be discussed as an option to account for historical and upstream emissions. In terms of emission types, only the impact of the greenhouse gas carbon dioxide, or CO_2, will be considered.

The local CO_2 emissions will be tracked over the period 2016-2035. 2035 is the year in which the municipality of Groningen aims to be carbon neutral. 2016 is the year the municipality used as a baseline for its mitigation strategies (Gemeente Groningen, 2018). Investments in low-carbon infrastructure will have to fall in this period and carbon neutrality must be achieved by 2035 at the latest. Avoided emissions and upstream emissions over this period will be tracked. This will help form an idea of the extra emissions stemming from the mitigation strategies. Mitigation of these upstream emissions and other historical emissions will be discussed.

For a large share of the proposed mitigation strategies, the municipality relies on companies and houseowners to contribute financial means and for the actual execution. Therefore, much of the investments will not come from the city itself. In some cases, subsidies from the federal government are available, but they are ignored in this study. This research will only look at the total capital expenses, and thus disregards yearly operations expenses. The resulting information can indicate the distribution of expenditures to be made during the transition period.

2.3. Data sources

For this research, data was collected from many different sources. A leading role was reserved for the roadmap report by the Groningen municipality and E&E Advies (Gemeente Groningen, 2018). In this report all actions and developments the Groningen municipality foresees are discussed. An overview of the specific actions listed in that report can be found in appendix A. All other literature and data sources that are addressed here are used to assess the projections made in this roadmap report. Those other sources include: national and municipal data, mainly sourced from CBS Statline and Klimaatmonitor; data on utility buildings, extracted from the Dutch 'Basisregistratie Adresgegevens' (BAG) using open source geographic information software (QGIS); data on environmental aspects of technologies and materials, extracted from life cycle analysis software (SimaPro); technology specific data, as published by relevant institutions; scientific literature; news articles; and multiple sources of grey literature, such as white papers, working papers, government reports and dissertations. The full list of data sources can be found in Appendix C.

2.4. Model components

The Excel model consists of a series of components that each serve a specific purpose. The *Contents* and the *Instructions* components come first. These components serve as a starting point and introduce the spreadsheet with links to each section. Then comes the *Results* component, where all the outcomes of the model are brought together and made visual in a series of charts. These charts will be discussed further in the results section of this report. The *Reduction goals* component contains all the transition goals that serve as input to the model. For this research, those goals are based on the roadmap developed by the city of Groningen. The outcomes as found in the *Results* component are compiled from the *Impacts* component. In this component, impacts are calculated for the three focus areas of the model: avoided emissions, upstream emissions, and investment costs. The components *Library* and *Modules* are used for the calculation of the impacts. The *Library* component lists demographics, energetic and environmental properties, and specifications of all technologies the model considers. The *Modules* exist to allow for a more elaborate computation required by some technologies, such as downscaling. Technologies the Excel model has modules for are insulation, district heating, industry, mobility, and energy supply. A conceptual overview of the model and its data flows is seen in Figure 2.

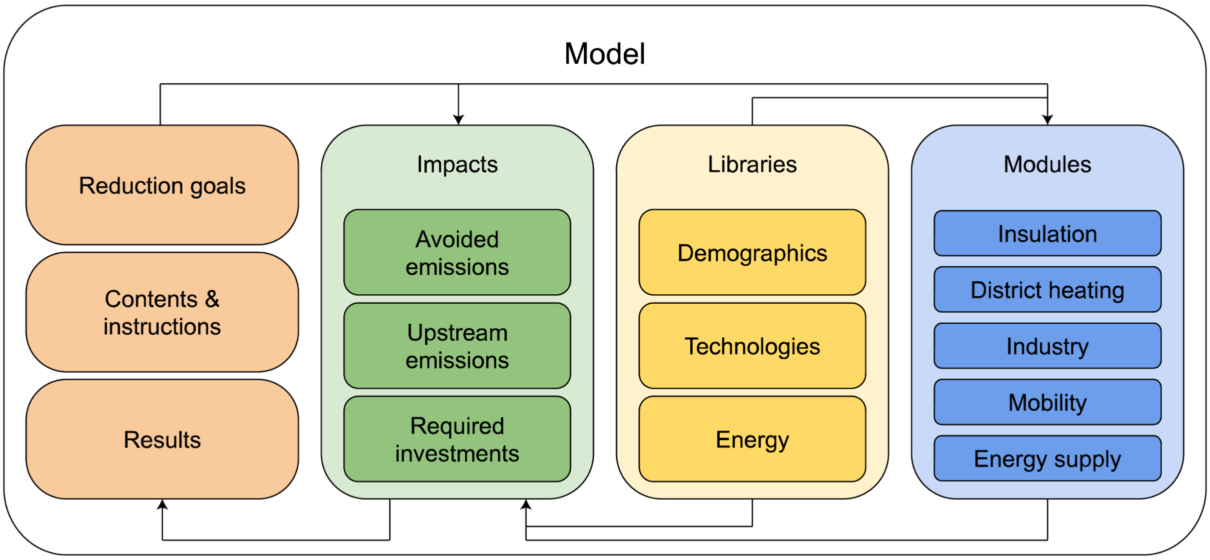

Figure 2: A conceptual overview of the components in the model and their interactions.

2.4.1. Library | demographics

The demographics section of the model is populated with data related to the living situation of Groningen citizens, the built environment, and the land area covered by the municipality. Additionally, habits related to personal transportation are listed. An important remark to be made on the municipal borders is that Groningen merged with the municipalities of Haren and Ten Boer in 2018, vastly increasing the land area the local council oversees. For consistency, the land area of the newly formed municipality of Groningen is used for both the base year 2016 and the goal year of 2035.

2.4.2. Library | energy

In the energy library, properties of energy carriers are listed, such as their energy density and their respective emissions factors. Along with that, energy consumption habits of Groningen residents are detailed, and some basic conversion factors are given. For the emission factors, it is relevant to note that grey electricity production takes place outside of municipal borders. As such, both well-to-tank (WTT) and tank-to-wheels (TTW) emissions fall under scope 2. In contrast, biomass pellets and their raw materials are produced by local companies and, therefore, both WTT and TTW emissions fall under scope 1.

2.4.3. Library | technologies

The final library contains specifications and performance indicators of the technologies the model considers. These specifications are listed for single units of each technology and serve as input for the computations in the relevant module components. In the modules, the technologies are then scaled to the situation of Groningen.

2.4.4. Modules | insulation

Household insulation

The first module to be discussed more thoroughly is the *insulation module*. This module is used to compute the total cost of insulation for the whole of the municipality, and the average cost of insulation per dwelling and per utility building. To this end, the share of residential natural gas consumption that is used for space heating is first defined. Then, the natural gas use per dwelling in cubic metres per square metre is specified per dwelling type and per energy label of the dwelling. Using the average Dutch dwelling size, the higher heating value (HHV) of Groningen gas ("Gronings Gas," 2020), the efficiency factor of an average condensing boiler, and the aforementioned share destined for space heating, the annual heat demand is calculated per dwelling type. The municipality of Groningen predicts a heat demand reduction of 20% per household (Gemeente Groningen, 2018; page 29). Combined with the annual heat demand data, this translates to an average reduced heat demand per energy label. Utilising the average cost of insulation per square metre per energy label from the *library* component, the average cost per label step can be calculated, and, in turn, the total cost of the required heat demand reduction per label. As the division of dwelling types per label was unavailable for the city of Groningen at the time of the research, the numbers were taken for the whole of the Netherlands, and then downscaled for Groningen based on the local dwelling type division. Now, we find the total cost of insulation for the whole municipality, as well as the average cost per dwelling. From the results, both upstream emissions and avoided emissions are calculated. The upstream emissions use an emission factor that represents a popular combination of insulation materials, namely glass wool, stone wool and polystyrene foam slabs. The respective emissions factors are derived from the SimaPro software for lifecycle analysis. The avoided emissions result from lower condensing boiler production by virtue of the projected heat demand reduction and returns a value for both WTT and TTW emissions.

Utility building insulation

Groningen projects a heat demand reduction for utility buildings of 30%. The city houses 3200 of these buildings (Gemeente Groningen, 2018; p. 40). Utility buildings cover a wide variety of commercial and public sectors and range from small single-room constructions to multi floor office towers. To assess the heat demand reduction potential of the utility buildings, the total in use floor space was extracted from 'Basisregistratie Adresgegevens' (BAG), a database where all nationwide addresses and living spaces are registered (PDOK, 2021). This floor space was then classified based on the construction year of the building and its purpose of use. National average heat demand per square metre of these segregation categories was scaled to Groningen using the total gas demand of utility buildings in the municipality and the percentage of gas demand that is generally used for space heating per purpose of use category. Data on heat demand reduction per label and the accompanying investment based on insulation practises (Schilling, 2018) was then applied to the resulting local heat demand per utility building class, giving the total investment required for a 30% heat demand reduction. Subsequently, upstream emissions were computed by taking the emissions per euro invested from the residential heat demand reduction, and then administering that number to the total investment for utility buildings. For this, I assume that the investment cost of the material used is similar for both sectors. Avoided emissions are found in the same manner as for residential buildings.

2.4.5. Modules | district heating

The *district heating module* is used to estimate the average investment cost per dwelling or per utility building of a district heating network to be newly constructed, including consumer installations. The costs in this module are derived from a paper by Gudmundsson *et al.* (2013). In that paper, the investment cost of a new network is determined for both pre-built and new-built dwellings in either inner city, outer city, or park areas. Their findings are translated to the city of Groningen, with the assumption that residential district heating is only applied to pre-built dwellings in inner city areas and new-built dwellings in outer city areas, and commercial district heating is only applied to pre-built offices in inner city areas and new condense-built offices or industrial halls in green-field areas. Using the current and the projected number of dwellings and utility buildings, combined with the planned percentage of network connections (Gemeente Groningen, 2018; p. 25), we arrive at the average investment cost per dwelling and per utility building. Upstream emissions are derived from an article by Oliver-Solà *et al.* (2009), with the adjustment that, for Groningen, no powerplant is built for the district heating network. Avoided emissions are those that would otherwise have been allotted to the condensing boilers that are replaced. The emissions generated during the heat production for the network are accounted for elsewhere, depending on the source of the heat. In the model, they can be found under *Modules | supply* as emissions from waste heat.

2.4.6. Modules | industry

The third module in the model is the *industry module*. This module serves to estimate the cost of replacing current technologies used for low temperature heat with more sustainable ones. In the case of Groningen, the more sustainable heat will come from electric boilers and from biomass boilers. Groningen plans a shift to electric boilers for 50% of the food and paper sectors, which are its main industry sectors. Other sectors will use 50% electric boilers and 25% biomass boilers, according to the municipality. Electrification through electric boilers is particularly interesting if a sufficiently robust electricity network is already present. It is therefore assumed that for the industry that adopts electric boilers, no intensification of the net is required. This might be the case if, for instance, the facility in question was previously connected to a cogeneration network (Hers *et al.*, 2015). The gas consumed by the Groningen industry was taken from Klimaatmonitor (n.d.). Using the growth projections from the municipalities and the average efficiency of an industrial combustion boiler, the total energy demand of the industry was estimated for 2035. Groningen mentions that its largest 11 percent of companies consume 84 percent of the energy used by businesses. As Groningen main companies (Suiker Unie/Cosun Beet Company, Niemeyer, Hooghoudt, Smurfit Kappa, Solidus Solutions) are almost exclusively in the food and the paper sectors, it is therefore assumed that 84% of the energy use can be allotted to these sectors. Based on electric and biomass boiler efficiency and capacity factors, the required capacity of both boiler types is estimated. From this, the needed investment is found. Upstream emissions from the construction of an electric boiler are adapted from a life-cycle assessment (LCA) performed by Abbas (2015). For the biomass boiler, it was assumed the upstream emissions would be comparable to those of an industrial combustion boiler. Replacing the boiler as part of planned maintenance would thus not result in any additional upstream emissions. Avoided emissions were determined by comparing well-to-wheel (WTW) emissions of natural gas to those of grey electricity and biomass in a Dutch context.

2.4.7. Modules | mobility

Private transport

The mobility module is the next module to be discussed. In this module, the shift towards a sustainable personal car fleet is first assessed. Groningen estimates that by 2035 90% of personal cars will be fuelled in a sustainable manner. Based on current trends, the sustainable vehicle type of choice is assumed to be a battery electric vehicle (BEV). From data on the composition of the Dutch car fleet of the past five years, yearly inflow and outflow percentages are extracted. Separately, to the example of Riesz *et al.* (2016), an adoption curve is designed for electric vehicles in Groningen, rising from 0% adoption in 2016 to 90% in 2035, and with its steepest point in 2027. While the average purchase price of a BEV was significantly higher than that of a car with an internal combustion engine (ICE) in 2016, that price is expected to decrease steadily to achieve price parity in 2024. The fleet of personal BEVs in Groningen is modelled to increase in accordance with the adoption curve. Now, the cost of the sustainable personal car fleet transition is to be calculated. If the BEV inflow remains below the total inflow of personal vehicles for a given year, only the additional cost of a BEV is counted. Whenever the inflow as predicted by the adoption curve exceeds the regular inflow of vehicles, the total cost of those extra vehicles is counted. Upstream emissions accounted for by the transition to BEVs are computed based on the battery pack in the vehicles. Avoided emissions are found by comparing WTW emissions of an ICE car to those of a BEV fuelled by grey electricity. For the BEV, emissions are based on the current median range EV: the Chevrolet Bolt EV 2021. While the current average range will be less, this is expected to change in the years leading up to 2035. Therefore, we expect the current median range model to be a good reflection of the future average range model. The fuel economy of this model is combined with the average mileage projected for 2035 to find the average yearly electricity consumption.

Charging stations

An important part of the transition to more BEVs is the installation of a charging station infrastructure. A significant number of new charging points is necessary, as electric vehicles will not be able to rely on the existing pump station network. Charging points come in three main flavours: public chargers, semi-public chargers, and fast chargers. Public and semi-public chargers have a capacity up to 22 kW. Public chargers are available to the public on a 24/7 basis, while semi-public chargers tend to depend on the opening hours of the company whose grounds they are installed on. Fast chargers tend to be located near arterial roads and generally openly accessible. They come in capacities below 50 kW, in between 50 and 150 kW, or over 150 kW. The share of each flavour of charger was derived from national numbers. The division of charging capacities of fast chargers in urban areas differ from national averages as outside of cities, along main roads and highways, higher capacities are more common. Following this, the division for this research is based on what is currently at hand in Groningen. The shares per charger type are assumed to remain constant, as each type serves its own use case. Funke *et al.* (2019) found that a new charge point is required for every 8th new electric vehicle. This number can be used to find how many chargers Groningen will need. Mathieu *et al.* (2020) developed a metric to assess the sufficiency of charging infrastructure. This indicator was applied to verify the estimated charge point requirement. In the same publication, the cost development of charging infrastructure is discussed. This development is here adapted to Groningen to find the cost of said infrastructure.

Public transport

Next within the mobility module is public transport. To make its bus fleet more sustainable, Groningen made greenification part of the public transportation tender. Its partner Qbuzz is to replace the diesel fleet with electric busses for inner city transport and a mix of hydrogen busses and electric busses for connections with surrounding villages. As this report focuses on the city of Groningen, only electric busses are considered. Qbuzz has 318 busses in operation in its concession for the provinces of Groningen and Drenthe (Brouwer & Van der Mei, 2020). It is assumed that about a quarter of this, 80 busses, serve the city of Groningen and its main arterial roads. Currently, the added cost of battery packs is the main component that increases the price of electric busses over that of diesel busses. From the price per kWh of a battery and the battery capacity of the most common bus in the inner-city bus fleet of Groningen, along with the difference in body price per bus type, the additional cost of an all-electric bus fleet can be derived. Upstream emissions are the emissions accounted for by the production of the batteries. Avoided emissions are found by multiplying the mileage of busses in Groningen with their fuel economy and the respective emission factors for both battery electric busses and diesel busses. The difference gives the avoided emissions.

Freight transport

Freight transport forms the last section of the mobility module. As part of the transition outlook, 50% of the local commercial vehicle fleet will be powered by hydrogen, 40% will be powered by bio-LNG, and 10% will be battery electric. Fleet size and growth rate are scaled down from provincial numbers. Presently, BEVs and especially fuel cell electric vehicles (FCEVs) are pricier than their ICE counterparts. The purchase price, however, is expected to drop significantly once the technologies further mature. Bio-LNG vehicles depend on an already more mature technology, making their purchase price comparable to that of traditional ICE vehicles. For the commercial vehicle fleet, the same adoption curve as for personal vehicles is used, only this time reaching up to 100% of sustainable vehicles instead of the previous 90%. Following the same metrics as before, the number of vehicles of each propulsion type in the commercial fleet of Groningen is derived. The commercial vehicle fleet mainly consists of light commercial vehicles (LCVs), supplemented with trucks, tractor units, special vehicles, and busses. Busses have already been accounted for in the previous section. Special vehicles vary too much in their nature, forcing me to leave them out of the scope. This leaves LCVs, trucks, and tractors. Commercial vehicle prices in this report are taken for LCVs. In general, purchase prices are found to be twice and three times as high for medium duty trucks and heavy-duty tractors, respectively. As such, a price multiplier is incorporated in the model. Now, the model can calculate the total additional cost of the commercial vehicle transition. Upstream emissions are again taken as the impact of battery pack production. Avoided emissions are the difference between emissions from a commercial fleet consisting purely of diesel LCVs and emissions from the proposed mix of sustainable LCVs. According to Van Gijlswijk *et al.* (2018), LCVs produce 50% of urban logistics emissions, while making up over 80% of the commercial fleet. The total avoided emissions are adjusted accordingly.

2.4.8. Modules | supply

Solar PV fields

The supply module considers the generation of sustainable energy at commercial scale. The techniques discussed are PV fields, onshore and offshore wind, geothermal and waste heat, and imported energy. First up are PV fields, where Groningen has defined a goal state of 500MWp. Using the capacity of a single PV panel derived from a real PV field installation, the required number of panels is computed. The investment per unit then leads to the total required investment. For the upstream emissions, emissions per kWh are scaled up to the total of required panels. For the avoided emissions, grey electricity WTW emissions are replaced for the total production of the to be installed PV field. The green electricity that comes in its place has zero WTW emissions.

Onshore wind

For onshore wind, Groningen projects an installed capacity of 36MWp. This capacity is limited mainly because of area constraints in urban spaces. The capacity of an average large wind turbine determines the number of turbines required to meet the projected installed capacity. The cost of a single wind turbine was adapted from Bennaceur *et al.* (2019) and the Commission Éolienne du Syndicat des énergies renouvelables (2014), and helps find the total investment. Upstream emissions for the wind turbines are derived from an article by Gomaa Behiri *et al.* (2019). A report by EAZ Wind, a local manufacturer of small wind turbines, is used to find the local capacity factor for wind turbines (EAZ, n.d.). This is then applied to the average large onshore wind turbine mentioned before to find the estimated production per turbine, and the total estimated production. As with PV fields, the green electricity produced by the wind turbines replaces grey electricity, which results in the avoided emissions.

Geothermal and waste heat

Then geothermal heat production and waste heat. As was already hinted at in the roadmap, Groningen now has decided to replace geothermal with residual heat from data centres. However, deviating from the report, the residual heat from data centres located at Zernike is used instead of residual heat from those in Eemshaven. This means that the energy is still coming from municipal grounds and is generated close to the end user, eliminating the cost of additional pipeline infrastructure. The remaining pipeline infrastructure necessary to bring the heat to the end user is already accounted for in the district heating module, as are the avoided emissions from gas boilers. Only the newly generated emissions from waste heat are therefore assessed in this section. The emissions from waste heat on municipal grounds are WTW and do not consider co-firing. The required production is the heat demand for space heating and domestic hot water (DHW).

Offshore wind

Offshore wind is of course difficult to realise in an urban environment. Still, Groningen claims a share of the planned Dutch offshore wind capacity. The nameplate capacity of a modern offshore wind turbine presents us with the number of turbines required for this claimed capacity. The cost of installation per wind turbine as part of a Dutch offshore wind farm is adapted from Bulder *et al.* (2021). With the capacity factor at sea, we find the total production. As before, the produced green electricity replaces grey electricity and its emissions.

Imported energy

The final section in the supply module is important energy. While Groningen aims to increase energy production within municipal borders, space is too limited to achieve full self-sufficiency. The city projects to still import 35% of its original energy demand by 2035. This imported energy is composed of electricity, green gas, bio-LNG, and other biofuels. Emissions factors specific to each energy carrier and the carrier they replace are used to calculate avoided emissions for both scope 1 and scope 2.

2.5. Limitations

During this research project, efforts were made to ensure all data considered was as accurate as possible; however, due to time constraints, limited available data or other reasons, the research is not without its limitations. In some ways, the results of the model are subject to shortcomings in the modules. These are often caused by a lack of specific, accessible data. In these cases, assumptions were made, or proxies were developed. Depending on the technology, the impact on the model outcomes may vary.

A dominant simplification is made for the upstream impact of materials used for insulation. In the model, this is represented by a static number per square metre of living space, based on a typical mix of materials. Nevertheless, the static number does not account for all prevalent insulation materials, such as windowpanes. Furthermore, the specific mix of materials varies strongly per building, depending on specifications such as its age, size, and composition. It is not clear how a more inclusive representation of insulation materials would affect the realised upstream emissions, as it is not known whether the omitted materials would drive the currently assumed number up or down. Furthermore, materials that are currently popular in the market are not always the most sustainable materials. A shift in applied materials seems therefore plausible in the not-too-distant future, possibly as a result of new regulation.

Another significant assumption regards how the total natural gas consumption is assigned to the different industry sectors in Groningen. This division is important as it determines the degree to which the respective section of industry must invest in electric or biomass boilers. My assumption is that 84% percent of industry operates in either the food or the paper sector. These two sectors are asked to shift half of their heat production from industrial combustion boilers to electric boilers plus 25% to biomass boilers. Other industry sectors are only expected to only adopt the 25% biomass boilers. Therefore, the chosen percentage significantly affects the investment the industry sector has to make, and the emissions it can avoid. Regardless, the total investments made in the industry sector of Groningen represent only a small percentage of the total required investments in the city.

For the composition of sustainable drivetrains of cars for personal transport, I also had to make an assumption that has its reflections on the results of the model. Here, these drivetrains are considered to be purely electric (BEV), in line with current developments in the market. Simultaneously, Groningen does not elaborate on the mix of these drivetrains. A different mix would probably alter the involved costs and emissions considerably. At present, other candidates such as FCEVs overshoot BEVs in purchase price; however, the price is expected to come down more rapidly as the technology matures. The resulting cost variation would therefore depend largely on the momentum behind the transition.

Remaining on the topic of transportation, charging infrastructure for public and freight transport is not considered. Nor are emissions related to charging points as a whole. Unfortunately, research into this field is sparse, making it difficult to acquire the necessary data. Yet, it is clear that a further inclusion of the charging infrastructure in the model will increase the outcomes for all impact categories.

A strongpoint of the mobility module is how it considers an adoption curve for personal electric vehicles that includes planned replacements of vehicles currently in operation. Such planned replacements have a positive effect on the extra investments required by the transition. It often serves as a natural moment for households and businesses to weigh all the options and to consider investing in more future-proof technologies. Other technologies could also benefit from including planned replacements in their calculations.

As are some other points of data modelled, the grey electricity fuel mix is kept static, while naturally, it would develop over time. The year 2016 is maintained as the reference year for this, to allow for tracking developments. Still, since most actions will be implemented in a year other than the reference year, the grey electricity and the emissions that are replaced will have a different composition than what is considered in the model. As the grey electricity mix as of 2016 is still heavily reliant on coal and natural gas, it actually results in the most well-to-wheel emissions per kWh used of all fuel types considered. This means that without a substantial presence of green electricity, the advent of electrification will as a matter of fact increase fuel related emissions. To analyse sensitivity with respect to this gap in the model, 2026 is considered as a second reference year. In this year, emissions per kWh of grey electricity used are assumed to have halved.

The above shortcomings are mainly a result of lacking availability of data. Other limitations to the model are forthcoming due to time constraints. For one, a more elaborate series of sensitivity analyses would help to assess the dependency of the model on the assumptions discussed above. Additionally, no form of discounting is applied currently. Discounting the cost of future investments will give a more accurate, risk-free estimation of the current value of those investments. Considering the range of investments studied, the uncertain timing of most investments, and the even more opaque return on those investments, finding a reasonable discount rate would have been decidedly complicated and time consuming.

3. Results

3.1. Outcomes of the model

For all the mitigation actions Groningen proposes in its CO_2 transition, impacts are computed in the categories: avoided emissions, upstream emissions, and investment costs. Below, tables with the outcomes for each impact category are found. Every table describes the impact both per technology and per sector. The technologies are those for which Groningen has defined explicit mitigation actions in its roadmap report (Gemeente Groningen, 2018). A list of these actions can be found in Appendix A. The sectors are those Groningen assigns the actions to. The first impact category, avoided emissions, is split up into two tables: Table 1 focuses on emissions avoided within municipal borders, *i.e.* scope 1, while Table 2 also includes emissions from scope 2. The upstream emissions of the desired technologies are found in Table 3. Table 4 displays the required investment costs. Graphical representations of these tables are found in Appendix B.

Avoided emissions

Table 1: avoided scope 1 emissions (in ktCO_2 per year)

Technology / Sector	**Households**	**Businesses**	**Industry**	**Mobility**	**Supply**	**Total**
Insulation	43.60	42.86				**86.46**
Solar PV roof	0.00	0.00				**0.00**
Solar thermal	23.83	3.41				**27.24**
District heating	98.91	36.26				**135.16**
Heat pump	141.30					**141.30**
Heat pump w/ thermal storage		60.42				**60.42**
Electric boiler			60.40			**60.40**
Biomass boiler			2.56			**2.56**
Private transport				163.05		**163.05**
Public transport				4.33		**4.33**
Freight transport				42.12		**42.12**
Solar PV fields					0.00	**0.00**
Onshore wind					0.00	**0.00**
Geothermal / waste heat					-19.87	**-19.87**
Offshore wind					0.00	**0.00**
Imported energy					142.68	**142.68**
Total	**307.64**	**142.94**	**62.96**	**209.50**	**122.82**	**845.85**

Emissions avoided as a result of the mitigation actions are found in Table 1 (above) and 2 (on the next page). The first of the two only lists avoided emissions in scope 1: emissions released on municipal grounds. The other, Table 2, also includes emissions from scope 2: emissions that stem from energy consumption. In scope 1, most emissions can be avoided in the households sector. The numbers show that especially local emissions related to space heating can be reduced through cleaner technologies. Switching more vehicles to electric drivetrains, thus eliminating tailpipe emissions, also has a significant impact on local emissions. Electricity producing technologies, such as solar PV and wind turbines, do not avoid any local emissions as the polluting power stations they replace are located outside municipal boundaries.

Table 2: avoided scope 1 and 2 emissions (in ktCO_2 per year)

Technology / Sector	Households	Businesses	Industry	Mobility	Supply	Total
Insulation	46.02	45.24				91.26
Solar PV roof	86.61	49.89				136.51
Solar thermal	25.15	3.60				28.75
District heating	104.39	38.27				142.66
Heat pump	33.42					33.42
Heat pump w/ thermal storage		-46.77				-46.77
Electric boiler			-61.56			-61.56
Biomass boiler			2.84			2.84
Private transport				106.98		106.98
Public transport				-1.00		-1.00
Freight transport				53.15		53.15
Solar PV fields					260.06	260.06
Onshore wind					44.04	44.04
Geothermal / waste heat					-19.87	-19.87
Offshore wind					161.09	161.09
Imported energy					457.68	457.68
Total	295.60	90.23	-58.72	159.13	903.00	1,389.24

If we include scope 2 emissions, the supply sector prevents the most carbon emissions annually, thanks to the production of green electricity that replaces grey electricity. Some of the numbers in Table 1 and 2 are negative, indicating that the replacement technology actually increases carbon emissions over the old situation. In most instances, this is a result of oil or gas being replaced by electricity, where, in the case of grey electricity, coal is responsible for the significant emission factor. This signals the importance of a timely transition from grey to green electricity. The total of 1.39 MtCO_2 falls short of the 1.5 MtCO_2 of yearly emissions Groningen reported in 2016. Yet, this is an impressive reduction in scope 1 and 2 emissions of 92.6%.

Upstream emissions

Table 3: Upstream CO_2 investment (in ktCO_2)

Technology / Sector	Households	Businesses	Industry	Mobility	Supply	Total
Insulation	260.58	104.26				364.84
Solar PV roof	140.20	80.76				220.96
Solar thermal	63.02	9.01				72.04
District heating	87.72	2.15				89.87
Heat pump	343.34					343.34
Heat pump w/ thermal storage		31.21				31.21
Electric boiler			1.07			1.07
Biomass boiler			0.00			0.00
Private transport				694.31		694.31
Public transport				3.02		3.02
Freight transport				16.61		16.61
Solar PV fields					26.66	26.66
Onshore wind					17.46	17.46
Geothermal / waste heat					0.00	0.00
Total	894.87	227.40	1.07	713.94	44.12	1,881.40

Table 3 reports the CO_2 investment that is paired with the transition to new technologies. The production of these new technologies comes with upstream emissions, which are computed here. Again, almost fifty percent of the impact is found in the households sector, with heat pumps and insulation material bringing significant contributions. The technology with the single highest upstream emissions is private transport, as a result of battery pack production. In total, upstream emissions of the proposed actions amount to 1.88 $MtCO_2$.

Required investment costs

Table 4: Required investment costs (in million euros)

Technology / Sector	**Households**	**Businesses**	**Industry**	**Mobility**	**Supply**	**Savings**	**Total**
Insulation	807.26	322.98					**1,130.24**
Solar PV roof	289.57	166.80					**456.37**
Solar thermal	236.55	33.83					**270.38**
District heating	207.55	5.05					**212.61**
Heat pump	540.68						**540.68**
Heat pump w/ thermal storage		54.80					**54.80**
Electric boiler			3.11				**3.11**
Biomass boiler			2.09				**2.09**
Private transport				1,413.09			**1,413.09**
Public transport				4.98			**4.98**
Freight transport				266.54			**266.54**
Solar PV fields					442.89		**442.89**
Onshore wind turbines					46.15		**46.15**
Geothermal / waste heat					0.00		**0.00**
Offshore wind turbines					191.22		**191.22**
Air conditioning						-333.00	**-333.00**
Fossil decentralised						-284.00	**-284.00**
Total	**2,081.62**	**583.46**	**5.20**	**1,684.60**	**680.26**	**-617.00**	**4,418.15**

Above, in Table 4, results in the investment cost category are presented. About half of the total cost is found in the households sector. The two technologies requiring the highest upfront investment are insulation, divided over households and businesses, and private transport. The ‘negative’ investments reported under ‘air conditioning’ and ‘fossil decentralised’ do not stem from the model, but are mirrored from the Groningen roadmap report. They are not discussed in the roadmap, but they are reported as savings in the cost overview. As part of the transition towards different fuels and technologies, less of an investment in the current technologies is necessary, and thus, money can be saved in those instances. Since the roadmap report did not include any explanation of the formation of these savings, the numbers were duplicated directly into the results of the model.

3.2. Model outcomes in perspective

From the direct outcomes of the model listed in chapter 3.1, further insights that go beyond the three impact categories can be generated. These insights are essential to assess the potential of each individual mitigation action and to place them into perspective. First, in Figure 3, the investment costs are displayed in terms of the emissions the respective technologies can avoid yearly. After that, the time needed for the avoided emissions to account for the upstream emissions of a technology is portrayed in Figure 4. Then, Figure 5 and 6 show avoided emissions for two different compositions of the electricity mix. These two compositions help determine the model's sensitivity to changes in the electricity mix. Finally, Figure 7 and 8 respectively detail the investment costs of actions that are to be borne by a single average household or that are attributed to a single utility building.

Emissions reduction cost

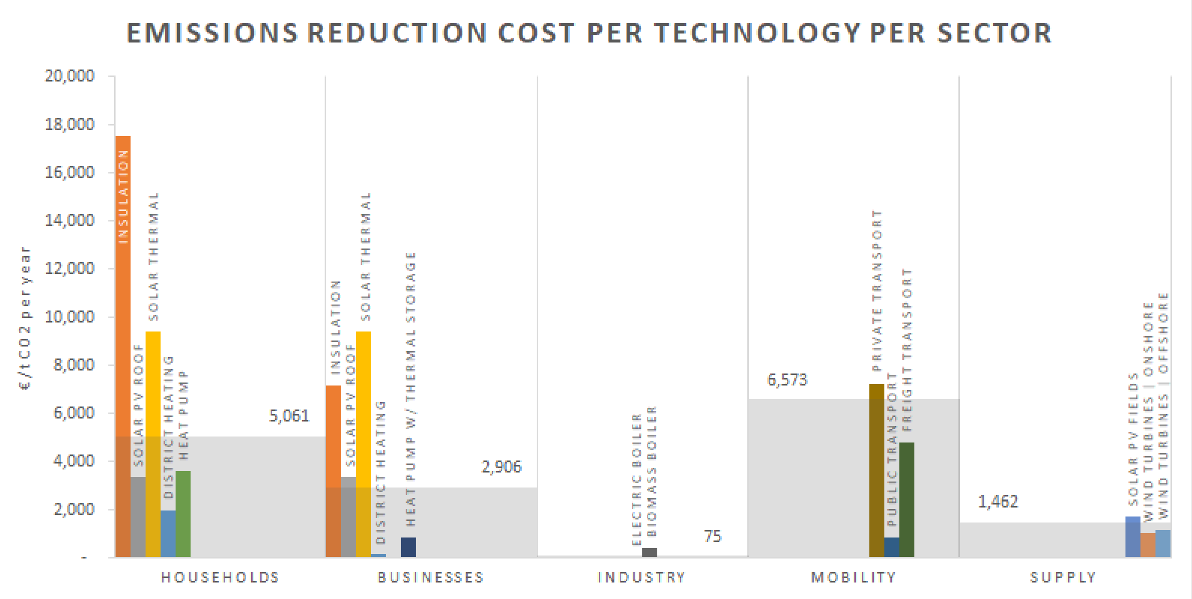

Figure 3: Emissions reduction cost per technology per sector. Averages are shown as shaded areas and in numbers for each sector.

Figure 3 shows the cost of emission reduction. This cost is given in euros per kilogram of annually prevented CO_2 emissions. The numbers used in Figure 3 are calculated without considering CO_2 newly emitted by the technologies, as to limit the influence of the electricity mix's emissions factor. The costs are divided per technology and per sector. For each sector, the average emissions reduction cost is displayed too. From the figure, it follows that the highest average cost is found in the mobility sector, being €6,573 per tCO_2 per year. The highest costs per technology are found in the households and business sectors, for insulation and to a lesser degree solar thermal. The industry sector scores notably well, with a emissions reduction cost of €75 per tCO_2 per year. The number of industrial boilers in Groningen is limited, but the amount of fuel a single unit handles is significant. This means that many emissions from fuel combustion can be avoided with just a limited investment.

The figure only considers emissions from fossil fuels that are prevented through the mitigation actions. In some cases, fossil fuel consumption is replaced with electricity, making the affected technologies dependent on the electricity mix. Groningen plans to rely on a wholly green electricity supply by 2035. If, unhoped-for, this cannot be realised fully, the emissions reduction cost will increase for technologies that are electricity driven. Technologies that are particularly susceptible are heat pumps (with and without thermal storage), electric (industrial) boilers and battery electric vehicles.

The average for all considered technologies amounts to €3,590 per tCO_2 per year.

Upstream emissions payback time

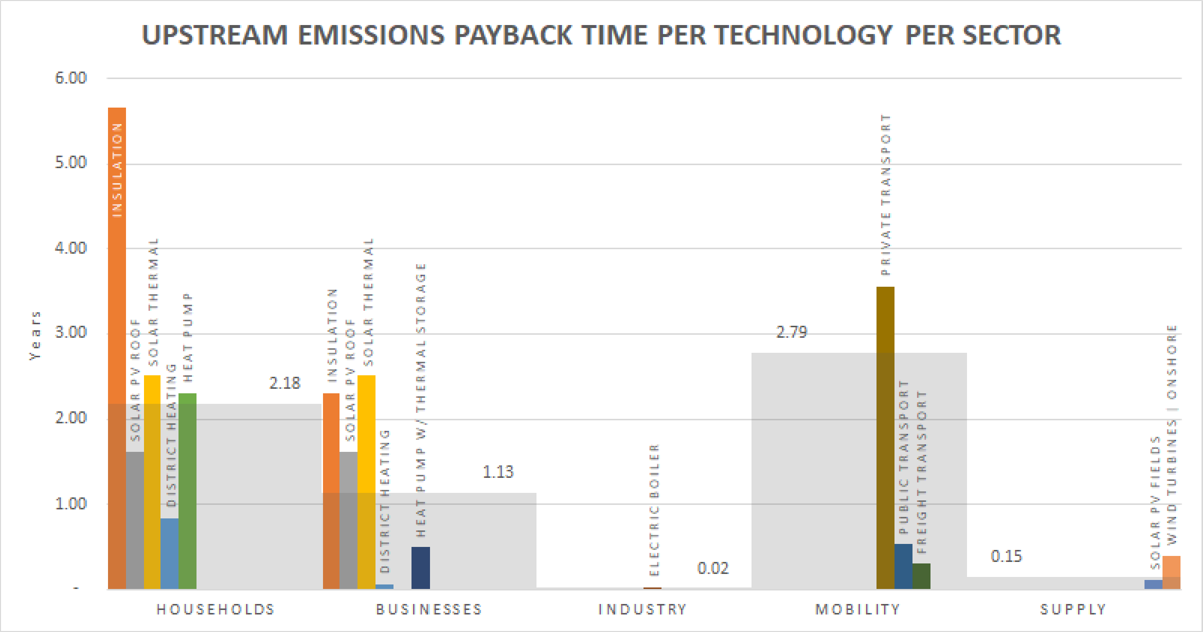

Figure 4: Upstream emissions payback time per technology per sector. Averages are shown as shaded areas and in numbers for each sector.

Installation of new equipment requires upstream emissions. As such, it will take time before avoided emissions surpass the initial CO_2 investment. This time is calculated as the time it takes for the combined emissions prevented in scope 1 and 2, compared to the 2016 emissions baseline, to surpass the recorded upstream emissions. The upstream emissions payback time is shown in Figure 4. Again, the numbers are divided per technology and per sector, in combination with the averages per sector. The sector with the longest average payback time is the mobility sector, driven by the upstream emissions of electric vehicle battery production. Insulation material stands out as the technology that takes the longest time to account for the production, transportation and installation emissions.

As with the emissions reduction cost, the industry sector scores well in terms of the upstream emissions payback time, displaying a payback time of just 0.02 years, or just over a week. Like before, this can be linked to the considerable reduction in scope 1 and 2 emissions from fossil fuels, as long as the electricity mix used is mostly green. In line with Figure 3, Figure 4 only considers emissions from fossil fuels that are prevented through the mitigation actions for its avoided emissions and considers the electricity mix to consist wholly of green electricity. Another sector that performs exceptionally well in this section is the energy supply sector. The score of 0.15 years is earned by replacing grey electricity, with a high emissions factor, with green electricity at scale.

The total sum of upstream emission can be accounted for in 0.96 years, or just over 350 days. Yet, if reflected against the final avoided emissions instead of the prevented emissions, the payback time increases to 1.35 year, or just over 494 days.

Electricity mix sensitivity

As was already mentioned under the avoided emissions results, a timely transition to a green electricity mix will help reduce emissions of technologies that rely on electricity for power. The model uses the 2016 mix as the reference electricity mix. This mix has a high emissions factor, causing some technologies to have higher emissions that the conventional fuel-based technologies they replace. To determine the effect the composition of the electricity mix has on the performance of the proposed technologies, the model considers a potential electricity mix for the year 2026 with an increased share of green electricity. Consequently, the emissions factor is assumed to have halved. Avoided emissions of affected technologies are visualised for both 2016 and 2026 in Figures 5 and 6, respectively.

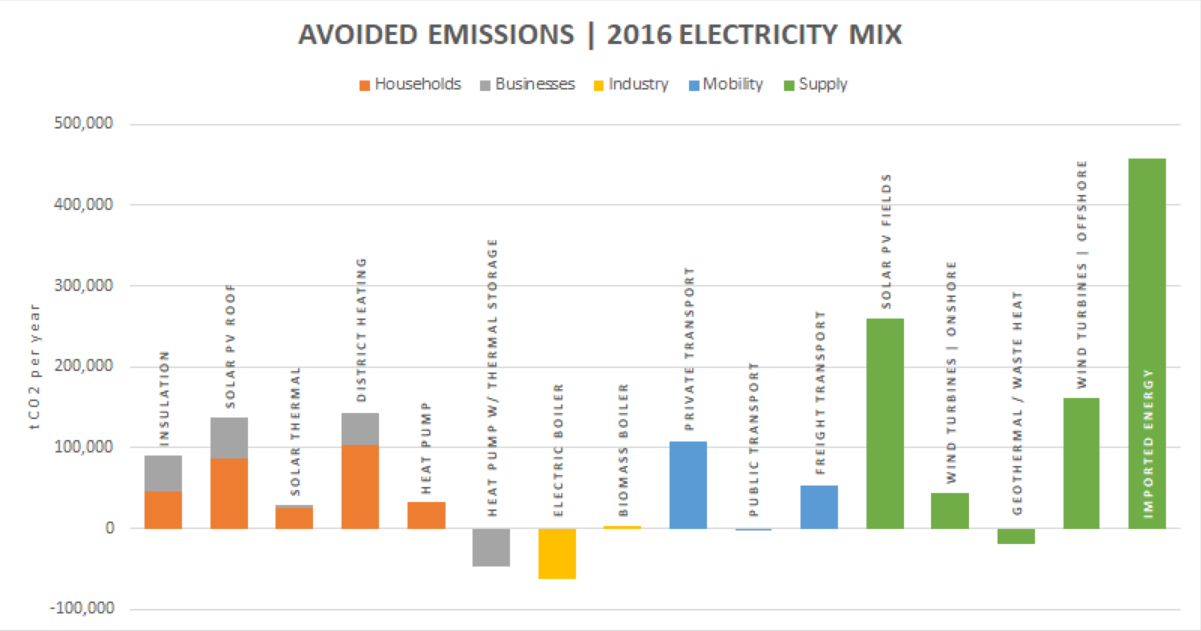

Figure 5: Avoided emissions from technologies based on the electricity mix of 2016.

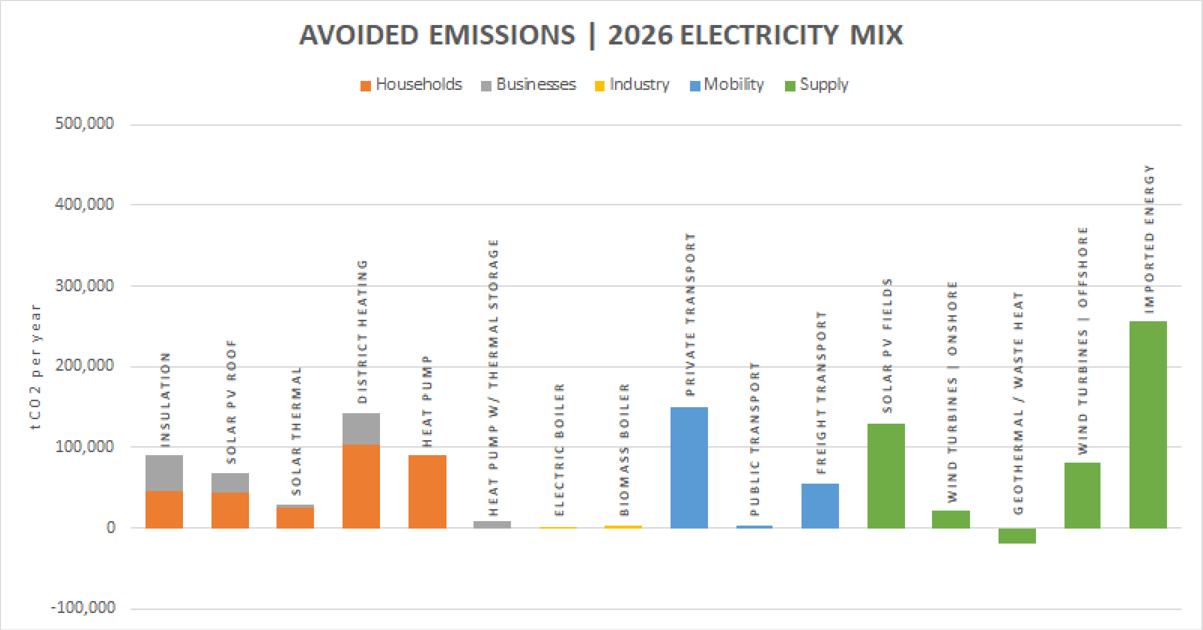

Figure 6: Avoided emissions from technologies based on the electricity mix of 2026.

When comparing Figure 5 with Figure 6, we find that a greener electricity mix has a clear effect on avoided emissions. Technologies that produce green electricity will replace less polluting grey electricity, resulting in decreased avoided emissions. On the other hand, electricity consuming technologies have increased avoided emissions when they can rely on a less carbon intensive electricity mix. Transitioning to heat pumps with thermal storage, industrial electric boilers or electrified public transport would mean increasing emissions in 2016; however, all electricity powered technologies contribute to lowering emissions by 2026.

Investment cost per building

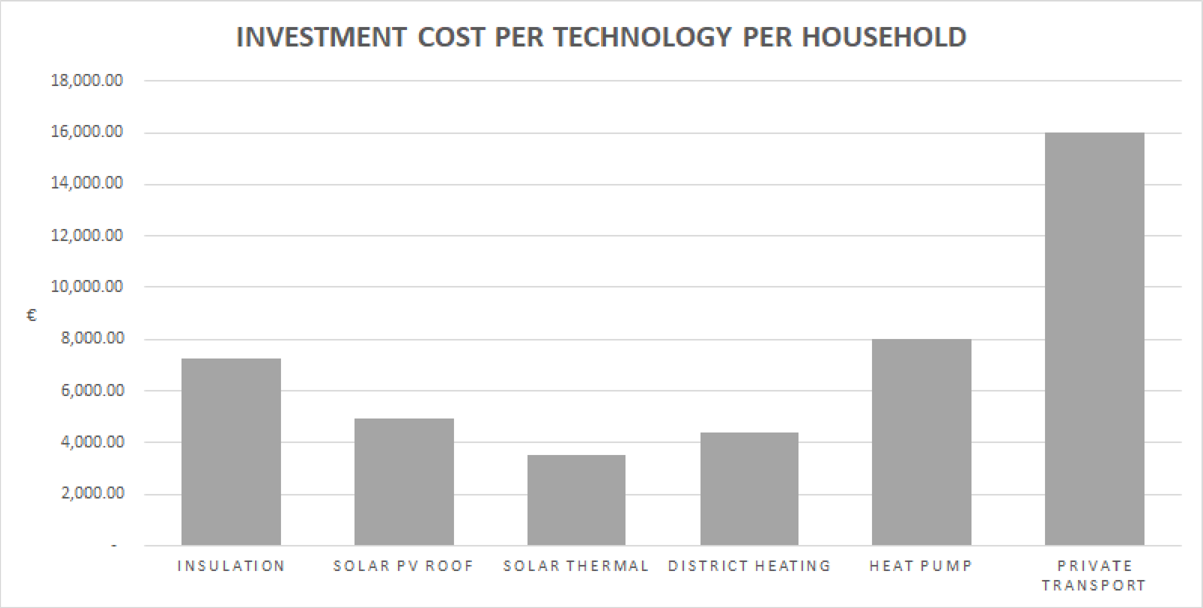

Figure 7: Investment cost per technology per household.

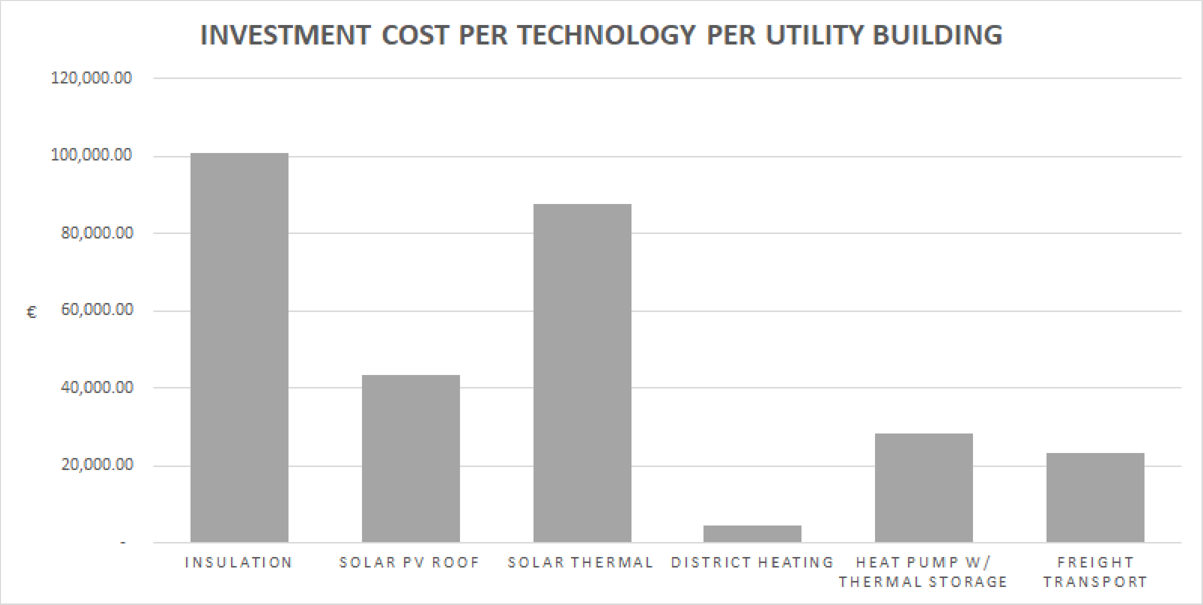

Figure 8: Investment cost per technology per utility building.

Figure 7 and 8 present the average investment costs per technology that can be attributed to a single household or utility building, respectively. For the technologies insulation, roof-based solar PV and solar thermal panels, and heat pumps the costs for businesses come in at a factor 10 to 20 above the costs for households. A district heating network connection and investments in transport are comparable for both households and businesses. Buildings usually need to be connected to a district heating grid only once, and while some businesses operate an extensive vehicle fleet, a considerable share of businesses do not own any vehicles.

A relevant notion is that not all investments listed here necessarily come at the expense of the home or business owner. District heating network infrastructure and EV charging points for personal transport are also covered in the investment costs. Additionally, a building owner does not necessarily have to invest in each of the technologies. For instance, if a building is connected to a district heating network, investing in a heat pump is often not needed.

4. Discussion

In the previous section of this report, we find that with their current roadmap, Groningen can effectuate a reduction of annual scope 1 and 2 emissions of 1.39 $MtCO_2$, 92.6% of current emissions. Combined, the proposed actions demand a total investment of €4.4 billion to be spent over a 20-year timespan. In the following chapter, the investment costs found using the model developed in this research are compared to the numbers published by the municipality of Groningen. Furthermore, I will discuss the implications of the model results for all three impact categories.

4.1. Roadmap comparison

In this section, I will discuss the differences between the outcomes of the investment costs category of the model and the related numbers disclosed by the Groningen municipality (Gemeente Groningen, 2018). Considering the opaque calculations behind the investments reported by Groningen, the adequacy of these calculations and the underlying data quality are difficult to determine. It is therefore interesting to see how the model approximates the reported investments. The comparison is made visual in two graphs. The first graph can be found in Figure 9 and displays the comparison per sector. The other graph compares the model and the roadmap report per technology. That graph is found in Figure 10.

The first distinction that is immediately obvious is the total sum of investments that are deemed necessary. Groningen expects this to amount to €2.3 billion. At the same time, the model developed in this research finds a vastly higher sum of investments, namely €4.4 billion. The disparity between these numbers is stark: the model overshoots Groningen's estimations by 93.6%. That will make it all the more interesting to analyse the causes of this gap. To this end, we start by zooming in to the sector level.

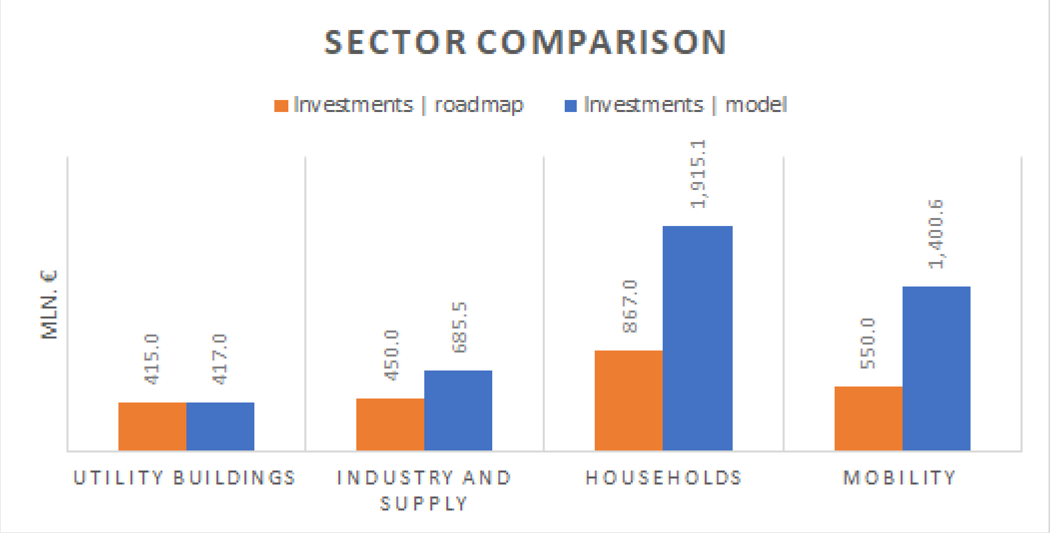

Figure 9: Comparison of investment costs per sector.

When looking at Figure 9 above, one of the first things that stands out is that there are four sectors displayed instead of five. The graph mirrors how Groningen's roadmap report communicates the investments per sector, combining the investments in the industry sector and the energy supply sector. For consistency, and because the combined reporting on Groningen's part makes it difficult to assess the numbers separately, the outcomes of the model are combined too. Groningen also announced two technologies with significant negative investments, likely because planned investments for these technologies will not be needed anymore after a successful energy transition. It is, however, unclear within what sector these 'savings' are. In Figure 9, 'fossil decentralised' is accounted for in the mobility sector for the model and the 'air conditioners and radiant heaters' is split equally between the utility buildings and households sectors. Further constituents of each sector can be found in Table 4 in chapter 3.1.

The investments required in the utility buildings sector are practically equal between the model and Groningen roadmap report. The combined industry and supply sector has investments that are about fifty percent higher in the model, perhaps chiefly as an effect of higher estimated costs for solar PV fields. For the households and mobility sectors, however, the model projects required investment costs that are more than twice as high. Especially in the households sector, it seems the model estimates all individual technologies to be more expensive than what Groningen has considered. The largest contributor to this sector is the cost of insulating dwellings, bringing in €807.3 million. Yet, even without this technology, the investments greatly exceed the total projection from the report. The difference in the mobility sector is likely explained by how the private transportation investments are appraised. Additionally, it seems reasonable to assume that the cost of charging infrastructure was not considered by the municipality. This will be discussed more in depth on the basis of Figure 10, where a comparison is made on technology level.

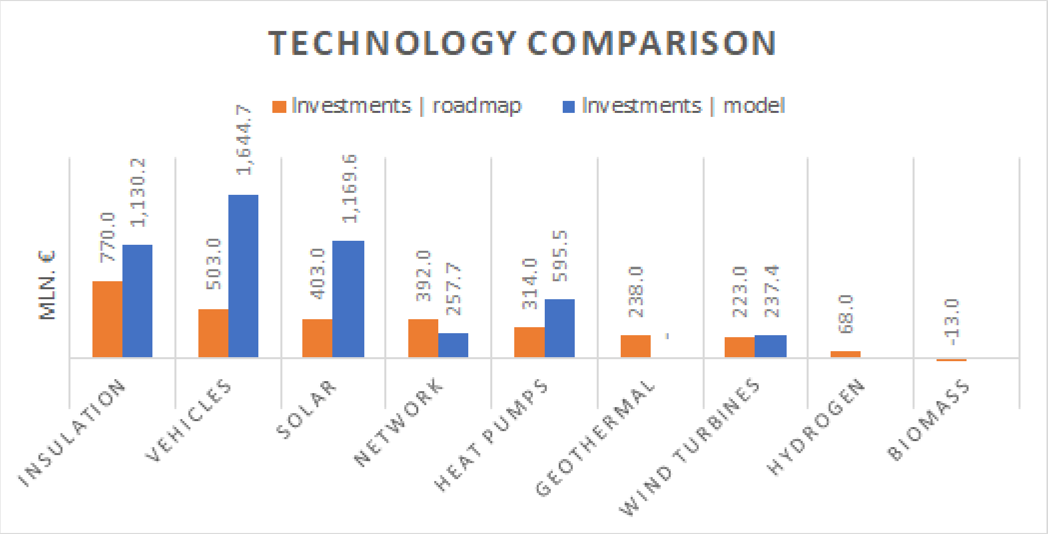

Figure 10: Comparison of investment costs per technology

The graph in Figure 10 lists the technologies as per how Groningen makes the subdivision. Insulation includes the investments for both dwellings and utility buildings; vehicles encompasses private, public and freight transport, but not charging infrastructure; solar accounts for rooftop solar PV and solar thermal panels, along with solar PV fields; vehicle charging infrastructure and the district heating infrastructure is counted under network; heat pumps has investments for both dwellings and utility buildings, and includes the associated thermal storage; geothermal includes investments in geothermal energy generation and waste heat; wind turbines combines investments in local onshore wind turbines and the share of offshore wind capacity that Groningen claims. Finally, hydrogen and biomass represent investments in those respective technologies. Groningen's subdivision also includes the negative investments in 'fossil decentralised' and 'air conditioners and radiant heaters', but since these numbers are duplicated directly in the model and thus equal, they are left out of the graph.

Again, we see that most technologies are estimated to be far more expensive by the model as compared to the roadmap. I shall go over the technologies one by one to discuss the differences. The cost of insulation is found to be some €360 million higher, 46.8%. If we compare this to the difference found in the utility buildings and households sectors in Figure 9, the disparity seems to lie entirely in the costs that come at the expense of households as the results in the utility buildings sector were practically equal. This cost difference for insulation only accounts for a small part of the gap for households between the model and the roadmap report in the sector comparison, indicating the considerable role the other technologies have too. Vehicles is the technology where the biggest discrepancy is encountered. The main contribution to this technology is made by privately owned vehicles. These vehicles add €1.41 billion to the total. This is far more than what Groningen expects for the entire mobility sector. It appears as if Groningen did not consider a price disparity between internal combustion engine vehicles and battery electric vehicles, nor did it take into account an adoption curve. Even with these two exclusions taken into consideration, the difference seems stark. As was hinted at by the large disparity for households, the cost of solar is higher in the model as well. Both solar PV on rooftops and in fields alone are projected to cost about as much the whole of solar in the roadmap report. It is possible that Groningen did not consider the cost of installation of the solar panels, but that is unlikely to explain the entire difference. If the output of the model is to be trusted, it appears that Groningen might have underestimated the cost of the panels themselves too.

The accumulated network investment cost is one of the few cases where the Groningen report indicates a higher cost than the model does. It is, however, not quite clear what Groningen has gathered under this category. From the model, expenses for vehicle charging infrastructure and for district heating networks are considered. It is probable that Groningen recognised the cost of improving resilience of the electricity grid here. With the model, I did not account for this, as it was not discussed explicitly in the roadmap report. Accordingly, the model does not put a value to this. With the increased reliance on electricity, however, investments in the electricity grid are certainly a necessity. Incorporation of these investments in the model would further increase the expected cost of the transition, only widening the gap with the cost estimate of the roadmap report. Heat pumps are approximated to carry about twice the investment cost by the model. This difference is likely caused by a distinction in the appraisal of the cost of installation of a single unit. Wind turbines are projected to require slightly higher investments according to the model outcomes when compared with the municipality. Encompassing wind turbine cost,

cost of installation, and where applicable cost of a support structure, the total required investment cost for this category is relatively straightforward. Considering the limited difference in projected costs, it is likely that a similar appraisal method was applied. Groningen also mentions investments in hydrogen and in biomass. Yet, these have not been discussed explicitly in the report, and were therefore not included in the model. Though, the investments in these two technologies are limited and will not have any serious implication on the final numbers.

In the above discussion, it becomes clear that the model estimates required investment costs to be more substantial for almost every single technology. In the few cases with lesser investment costs from the model, it appears as if Groningen actually considered investments the model did not. As a result of the opaqueness of what is included in each category, this might also be the case in the categories where the model already came out more expensive. Therefore, it is entirely possible that the real investment the transition to carbon neutrality will require is even above the figure predicted by the model. This is in addition to the fact that the model does not fully reach carbon neutrality with the included technologies and without accounting for upstream or historic emissions. Public projects have a tendency of being more expensive than what government bodies outline in advance. The results displayed in this report may serve as a warning for the municipality of Groningen that financial means might be more of a hurdle in this transition than what they might have expected. Unsatisfactory cost estimates seem a recurring problem. Municipalities often do not have direct access to required expertise on specific subjects. This causes them to outsource much of the research on which they base their decisions. By outsourcing, they also let go of control over what is included in the final numbers. Another important risk related to outsourcing is the limited understanding of these final numbers and their implications. This instigates a deficiency in transparent reporting.

With the model built in this project the aim is to tackle this problem, detailing costs and impacts per technology, per sector and per cost bearer. The model is designed to require a limited number of inputs, while returning understandable and complete results. In its current state, the model is tailored towards the municipality of Groningen. Even with its limitations, the model already appears to present a concise overview of the repercussions the actions in Groningen's proposed roadmap will have. Furthermore, with limited adjustments it can be applied to other cities too. This would allow the local councils to incorporate environmental criteria in their policy making without having to rely on third parties.

4.2. Feasibility and implications

It is undisputed that the goal of Groningen to reach carbon neutrality by the year 2035 is ambitious. If the results of this research are any indication, the roadmap outlined by the city has the potential of bringing the city in close vicinity of achieving its goal. The proposed energy transitioning actions were calculated to account for an emissions reduction of 1.39 $MtCO_2$. This is a significant reduction and will drastically limit Groningen's contribution to the emission of greenhouse gasses to the atmosphere. Still, from the base year 2016, this is only a reduction of 92.6%, meaning that Groningen is likely to fall just short of its goal if no further action is taken. An important reason for this is that after the transition Groningen is still not fully self-sufficient in its energy supply. While the transition each sector must undergo is significant, most sectors need not be fully compliant in order to meet the roadmap reduction goals. This indicates that, for the right price, the reduction in emissions projected by the model seems feasible. While unlikely, it could be imagined that local green energy production increases beyond the goals set in the roadmap. This can, for instance, be achieved through an increase in the installed solar PV capacity. If Groningen can further decrease their reliance on imported energy, full carbon neutrality might actually be within reach. Still, with the current plan, Groningen will not be energy neutral, and it will not electrify all sectors fully. In its roadmap report, Groningen states that the fossil fuels that remain in use, after having implemented all specified actions, will be substituted with carbon neutral alternatives. Unfortunately, it is unclear how this should be achieved and what the related costs will be.

Even without the introduction of alternatives for the remaining fossil fuels, the city and its communities face a serious challenge. And that challenge can be expected to come paired with a considerable upfront investment. In this research, I found that the proposed roadmap demands an aggregated investment of €4.42 billion, close to double the number Groningen disclosed in its roadmap report (Gemeente Groningen, 2018). When annualised over the period from 2016 to 2035, this number equates to 2.4% of the yearly gross municipal product (Economic Board Groningen, 2018; Provincie Groningen, 2017). A significant figure that indicates the magnitude of the transition that is ahead.

Predictably, the municipality is not planning to pay for the costs all by itself. While the model only calculates the investment cost per technology and assigns that cost to a specific sector, for most technologies a cost owner can be clearly identified. In that spirit, the cost of installing insulation in a dwelling comes at the expense of the homeowner, for example. Of the total required investment, 47.1% can be linked directly to the improvement of the carbon footprint of dwellings. This means that per dwelling on average €15.4 thousand needs to be invested to meet the roadmap goals. 62.9% of dwellings in Groningen are either owner-occupied or privately owned rental properties (StatLine, 2020). As such, much of the cost will be borne by households. In addition to this will come the investment required for zero-emissions vehicles. Of the 97,963 private vehicles that the model predicts for 2035, 90% should be emission free according to the roadmap. On top of regular expenses for vehicle replacements, this transition requests an investment of €1.37 billion. Per household, this equates to an extra €10.2 thousand on average. Combining the investments for dwellings and personal vehicles, an average homeowner can expect to spend €25.6 thousand before 2035. Per year, an expense of €1.3 thousand would be required. Note, however, that most investments need to be paid in one go.

Such investments are significant, and the majority of households cannot be expected to bear the complete investment. The same can be said for businesses, where the average required investment per utility building is €219.9 thousand before 2035, or €11.0 thousand per year. Of course, sizable companies will have to cover a larger share, but still these amounts are substantial. This highlights the need for government grants and subsidies. The private sector cannot be expected to make the investment decision on its own and needs to be nudged in the right direction. On top of that, for most actors, the upfront investments the energy transition asks for are simply too hefty to be borne by just them. This is also where the limited power of a municipality comes into view. Municipalities do not have many options in forcing its communities to follow a certain path. In some cases, it can demand conformity through permits and tenders, but in most situations a city is restricted to giving out subsidies and setting the right example. In its current state, the report does not manifest how Groningen plans to ensure compliance with its energy transition, save for a few agreements with 39 of the city's companies through the *Groningen Energieneutraal* platform (Gemeente Groningen, 2018). In the report, Groningen states that for policy instruments it can stimulate, (de)regulate, finance, facilitate, enthuse, and in some cases initiate. It remains to be seen if this will be enough to convince households and businesses; to drive on behavioural changes and to stimulate investments.

It is also interesting to consider carbon pricing schemes and their influence on energy transitions. The European Emissions Trading System (EU ETS) allows for trading in carbon permits. The price of such an EU Allowance (EUA) has recently surpassed €44 per tCO_2 for the first time (Quandl, 2021). Analysts forecast that this price will rise further in coming years (Twidale, 2021). This bodes well for investments in the industry sector, where the model indicates that the emissions reductions cost might be as low as €75 per ton of CO_2. Investing in new technology might have the added benefit of lowering operating costs. This benefit might already be enough to make the decision to invest favourable over having to pay for carbon permits.

Still, the model suggests that for most other technologies, the emissions reduction cost will run into multiple thousands of euros per ton of CO_2 prevented from being released into the atmosphere. Especially the cost of insulating dwellings is significant in this respect. In itself, insulation does not necessarily reduce emissions beyond a certain percentage by lowering demand for space heating. However, a well-insulated house paves the way for other technologies that might eliminate emissions from space heating entirely. Additionally, a lower heat demand will slowly but certainly pay back the considerable upfront investment. These are important factors that should be included in the consideration of costs.

As calculated by the model, the commissioning of new technologies will also result in 1.88 $MtCO_2$ additional upstream emissions. Groningen did not make mention of these additional emissions in their report. Still, this amount is the equivalent of one year and three months of

Groningen current emissions: a significant addition to the emissions they aim to curtail. As such, the city should find a way to account for these extra emissions. It is likely that these emissions are released into the atmosphere outside of municipal boundaries. A good start would be for the city to start tracking the upstream emissions they are responsible for. Based on the information this data provides, Groningen should consider carbon offsetting or sequestration options.

Furthermore, leading up to the goal year of 2035, Groningen can still be expected to be carbon positive through its continued reliance on fossil fuels, further increasing its historic emissions. As more transitions take place, emissions will slowly progress to zero already before 2035. Consequently, cumulative emissions will gradually level out. The swiftness of adoption will determine the final level of cumulative emissions. At this point, it is unclear whether Groningen will ever have the ambition to account for these cumulative emissions too.

An important variable for the extent of these cumulative emissions is the electricity mix. Based on the year 2016, emissions resulting from a kilowatt hour of electricity are a factor 2.6 higher than those resulting from a kilowatt hour of natural gas. With green electricity growing its presence in the electricity mix as part of the energy transition, that factor will eventually change in favour of electricity. With this in mind, it is important to initiate electrification as early as possible, but to make sure that the installed capacity of green energy sources will grow at an equal, if not greater, pace. If this can be achieved in a satisfactory manner, it will help decelerate the inflation of cumulative emissions.

5. Future research

5.1. Opportunities for model improvement

Part of the aim of this research was to develop a model to aid city representatives in formulating policy with integrated environmental criteria. In order to present a coherent overview and to increase applicability, there are some aspects of the model that require further elaboration. A few of the aspects that stand out will be discussed here.

Lowering the reliance on carbon intensive fuels will inevitably promote further electrification in all of the considered sections. Such an increased dependence on electricity will increase the load on the electricity net. To support this growth, investments will have to be made in the high, medium, and low voltage networks. As the extent of these investments are unknown, it is not currently incorporated in the model. It is certain, however, that this development will lead to additional costs during the period of transitioning.

Additionally, the model currently only considers carbon mitigation actions included in Groningen's roadmap report. Obviously, the range of potential carbon saving technologies is much wider and ever increasing. Supplementing the library of technologies the model can draw from will benefit its comprehensiveness.

As it stands, the model does not fully evaluate who will bear the cost presented by each transitioning action. While the focus is currently on assessing the costs of each action in relation to its impact, the feasibility of the transition relies upon the willingness of the cost bearers. Different levels of government offer a multitude of subsidies to promote the advent of sustainable energy. An inclusion of these subsidies would certainly help to offer a more conclusive overview of at whose expense the cost of each mitigation action will be. The same is true for the cost of ownership. Operational and maintenance costs are likely to change between the proposed technologies and the technologies they replace. In some cases, the cost of ownership will increase in the new situation; however, BEVs, for example, include much fewer moving parts than ICE vehicles, and they rely upon a cheaper form of energy as fuel, driving the cost of ownership down. This means that some technologies have the ability to 'pay for themselves' when put in operation for multiple years, potentially making the investment desirable for cost bearers.

An advantageous insight for local councils would be to know not just which mitigation actions will have the largest impacts in their city, but also what order to implement them in for the actions to reach their full potential. Many of the technologies climate-conscious cities are putting their faith in are interdependent. Consequently, the presence of one technology will determine the effectiveness of another. A leading example of this is the installed capacity of renewable electricity. Its presence is important to mitigate the negative impact of coal-powered power plants, but if many technologies still rely on fossil fuels its potential will not be fully utilised. The model could be expanded with a mechanism to rank and order the available technologies. A city could then easily adapt the results into a timed roadmap with clear checkpoints.

Finally, a subject region will still be net carbon emitting leading up to the moment it reaches carbon neutrality. For every year that passes, cumulative emissions will increase, each transitioning action will come paired with some upstream emissions, and on top of that CO_2 is far from the only greenhouse gas responsible for the current warming of the climate. For a municipality to make a real difference, and to account for all the emissions it is responsible for, these emissions must be considered as well. Tracking all these emissions and allowing municipalities to weigh carbon sequestration options will support them in handling this extra step in becoming a true climate friendly city.

5.2. Next steps for Groningen

As a first case, the Excel model developed in this research was applied to assess the roadmap report Groningen produced to detail its pathway towards becoming a carbon neutral city. The results the model has posted made clear that Groningen's own assessment on the costs and impacts of mitigation actions it proposed is presumably overly optimistic. The inbound energy transition will require more generous investments while their effect appears to fall just short of accounting for all of the city's carbon emissions.

Consequently, the city council needs to re-evaluate their own assessment and reconsider the contribution it requires from its communities. In their original report, Groningen already noted that almost half of the estimated investments were not yet accounted for. With the insights from this report, that share will most certainly rise steeply. In order to safeguard willingness among its communities, Groningen should take a leading role in supporting initiatives to bring down the cost of mitigation actions. Another opportunity is for the municipality to educate its residents and its businesses on the potential return on their investments, as many of the replacement technologies come with a decreased cost of operation.

In comparison with their earlier ambitions detailed in the report *Masterplan Groningen energieneutraal* (Gemeente Groningen, 2011), the city takes a step back in terms of self-sufficiency. In their new roadmap, the city no longer strives to become energy neutral, still planning to import a considerable amount. With the increased reliance on electricity driven equipment, the successful conclusion of the carbon transition depends largely on an electricity mix with a negligible carbon content. As such, the municipality takes a risk betting on the abundant availability of green electricity for import. A further evaluation of the options to produce sufficient green energy on municipal grounds could help mitigate this risk.

Both this research and Groningen's *Routekaart Groningen CO_2-neutraal 2035* report refer to 2016 as the base year for the emissions. All the emissions the mitigation actions are supposed to help avoid are compared to this year. To have an understanding of the progress made so far, and to be in a position to adjust course in a timely manner, it is important for Groningen to reappraise its annual carbon impact regularly.

Lastly, the carbon neutrality Groningen currently strives for should not be the end station. As a prosperous urban area, Groningen has accumulated significant carbon emissions over the decades. Not just in scope 1 and 2, the scopes the city considers at present, but also in scope 3, through consumption-based emissions. If Groningen wishes to cement its position as a green city, Groningen needs to look further. The full scope of emissions must be mapped, and the city council should start drawing up their next roadmap towards eliminating its entire impact on the environment well before the current one is brought to a satisfactory conclusion.

6. Conclusion

The municipality of Groningen has made it clear that it wishes to be a frontrunner in the energy transition. It has set itself the ambitious goal of becoming carbon neutral by 2035. Groningen has developed a roadmap with specific actions in five main sectors to guide them towards this goal. This research assesses those transitioning actions to find out how feasible the goal of Groningen is. I find that, in line with what Groningen states in their report, the proposed measures are technologically well within reach. It seems, however, that the number of emissions that can be avoided with the current roadmap is insufficient for Groningen to bring their net carbon emissions down to zero. Yet, it is certainly not impossible for Groningen to reach their goal before 2035, as there are still options to further increase electrification and their self-sufficiency in terms of energy production.

Another important hurdle is the cost that is involved with the transition. With this research, I find that the investments required by the Groningen roadmap are likely to be significantly higher than what the municipality disclosed themselves. As the current roadmap will fall short of achieving net zero carbon emissions, the total sum of investments needed will possibly be even greater. Groningen is not in the position to carry out all actions by itself and relies on its communities to make the transition a success. Convincing all sectors to partake will prove difficult considering the significant investments that are necessary. This is specifically true for the households sector, where the largest share of the total investment cost is found.

The substantial gap between the cost estimates highlights a recurring problem in governmental decision-making: limited control over and understanding of outsourced research. The model developed in this research is meant to aid in alleviating that problem. Designed to give a clear overview of the potential impacts of the spectrum of available solutions, it grants city councils the freedom to adjust demographic or policy related variables so they can finetune energy transition policy to their local circumstances.

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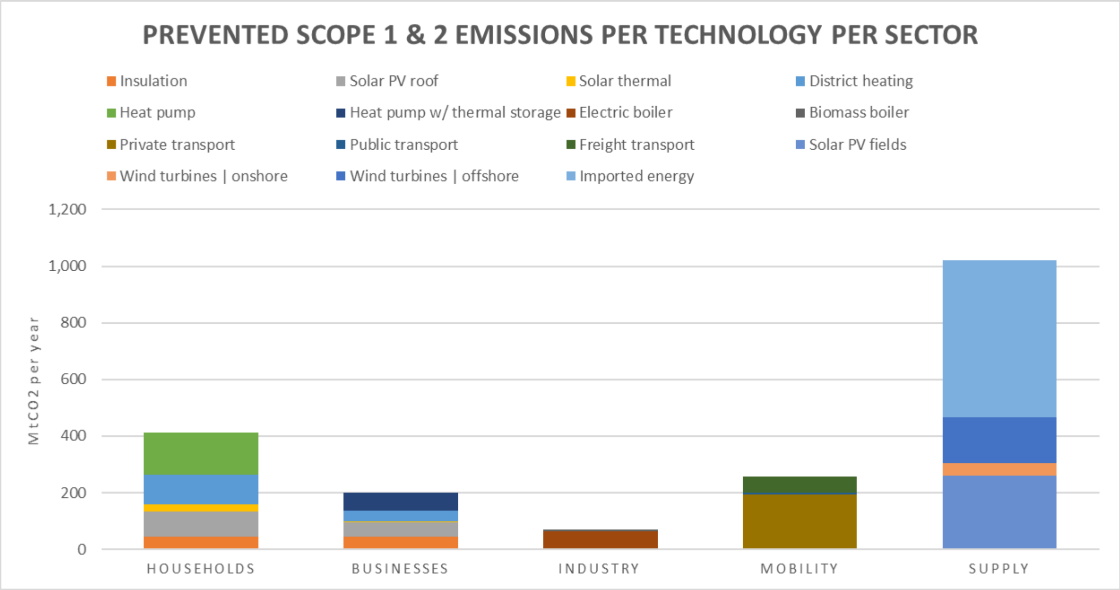
10. Appendices

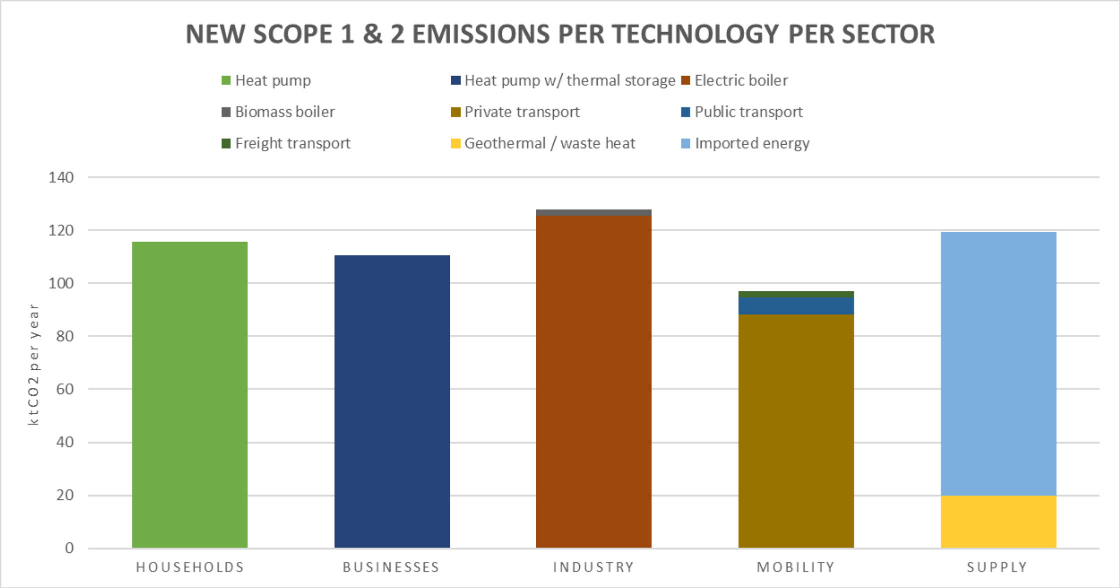
A. Overview of changes in 2035 and 2023, as defined by Groningen

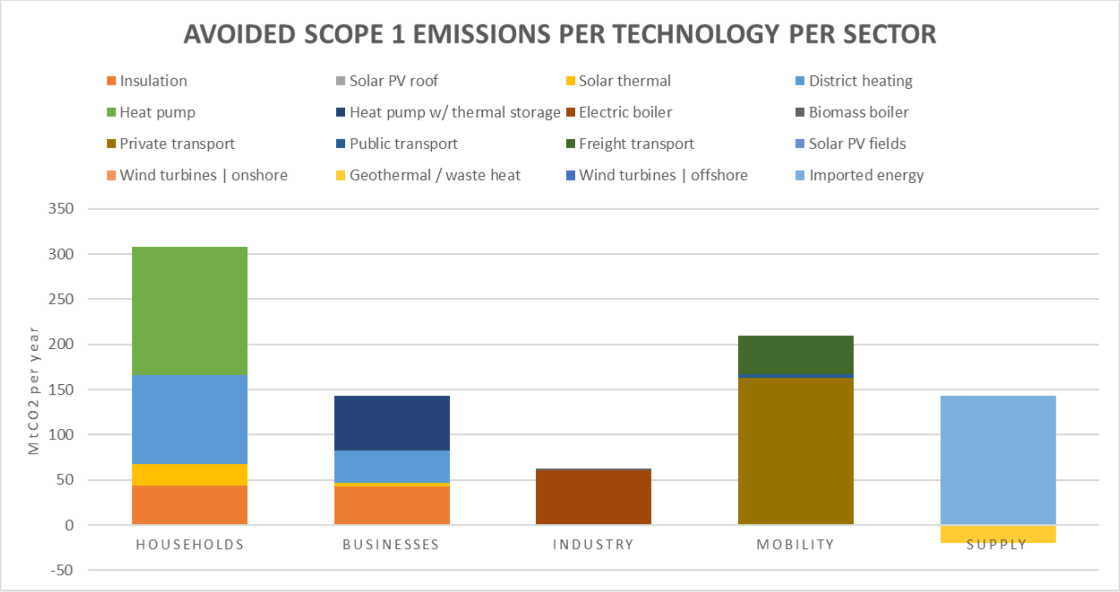
	End goal (2035)	Intermediate goal (2023)
Households	20% reduction in heat demand through insulation	7.5% reduction in heat demand through insulation
	200 MWp solar PV on rooftops	50 MWp solar PV on rooftops
	Solar thermal on 50% of dwellings	10 MWp solar thermal on rooftops
	District heating for 35% of dwellings	District heating for 5% of dwellings
	Heat pumps for 50% of dwellings	● 5000 hybrid heat pumps ● 3000 air source and 2000 ground source heat pumps
Businesses	30% reduction in heat demand through insulation	7% reduction in heat demand through insulation
	110 MWp solar PV on business rooftops	30 MWp solar PV on business rooftops
	District heating connection for 30% of SMEs and thermal storage for 50%	● District heating connection for 5% of SMEs ● Thermal storage for 5% ● Biomass boilers for 5%
Industry	Offices label A++	At least label C, with 20% label A
	Food, paper sectors to 50% electric boilers for heat generation	Preparation of transition
	Other industry to 50% electric heat production and 25% biomass	Preparation of transition
	1% efficiency improvements per year	1% efficiency improvements per year
Mobility	90% of vehicles use renewable fuels (mainly electric or green hydrogen)	CO_2-emissions reduction in private transport of 15%
	100% of public transport drives emission-free	20% electric, 5% hydrogen, diesel engine busses use fossil-free diesel
	100% of freight transport is CO_2-neutral. An estimated 50% is hydrogen, 40% bio-LNG, 10% electric	CO_2-emissions reduction in freight transport of 20%
Sustainable energy generation	500 MWp solar PV in solar parks	150 MWp solar PV in solar parks licensed
	36 MWp installed capacity of onshore wind	10.6 MWp installed capacity of onshore wind (3 large turbines are in procedure)
	100% biofuels	● Road transport: 5% biodiesel, bioethanol and bio-LNG ● Network gas: 5% green gas
	Geothermal for district heating	Preparation of future production

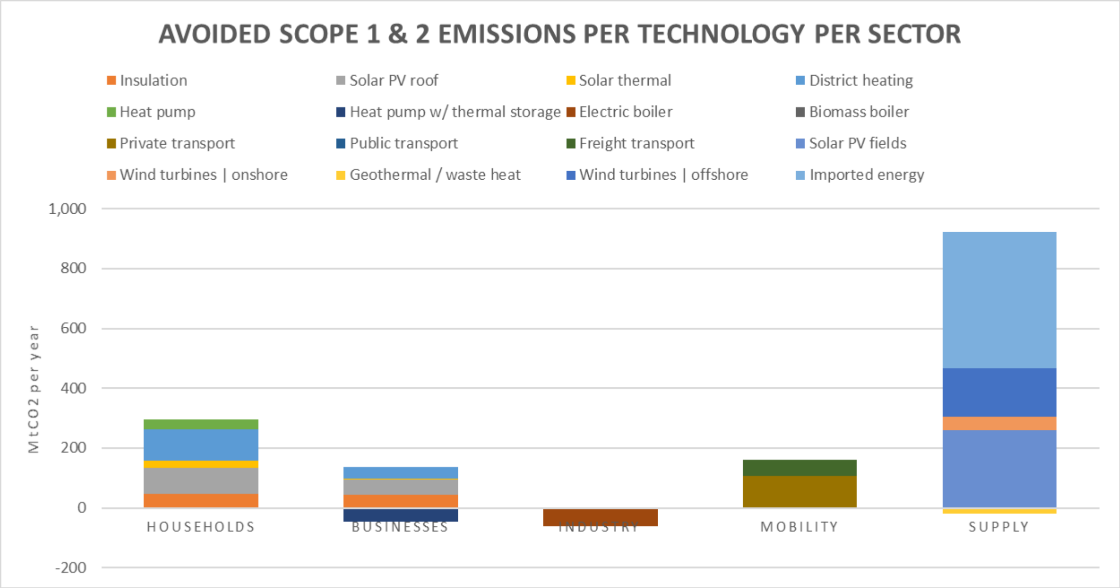
(Gemeente Groningen, 2018)

B. Additional graphs detailing model results

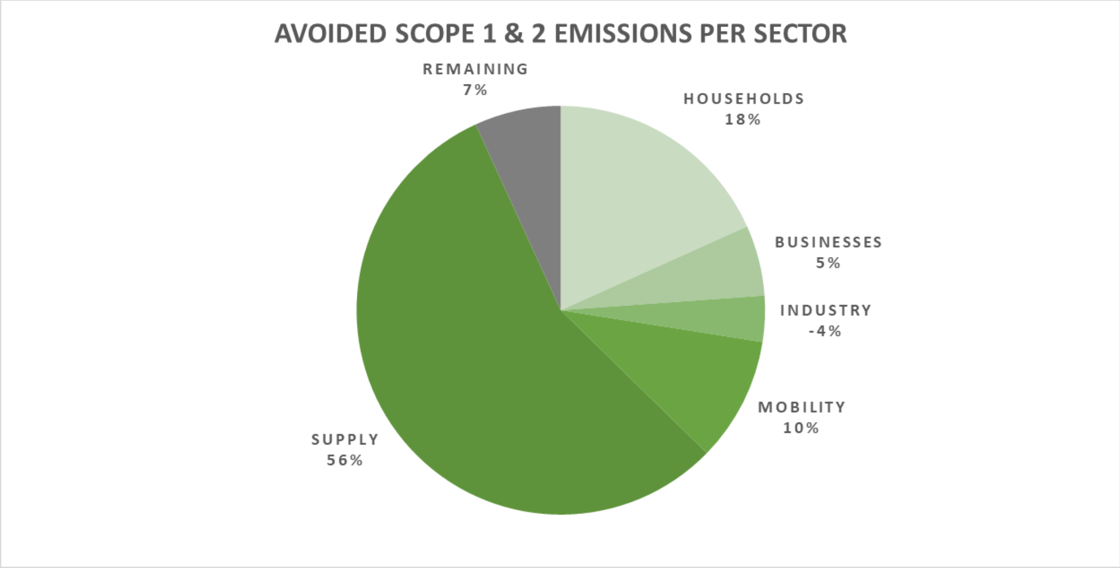




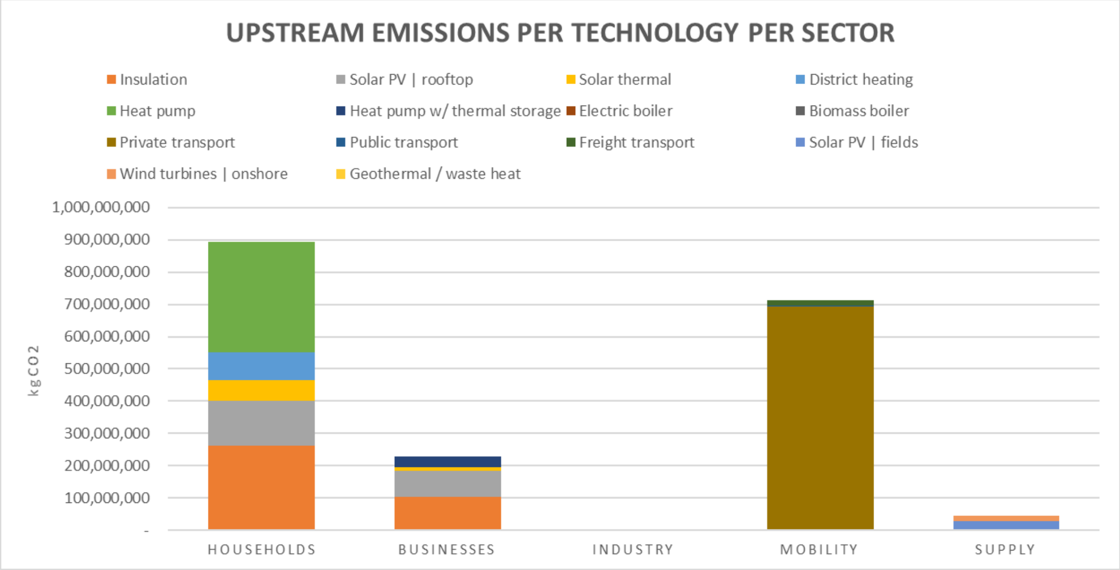




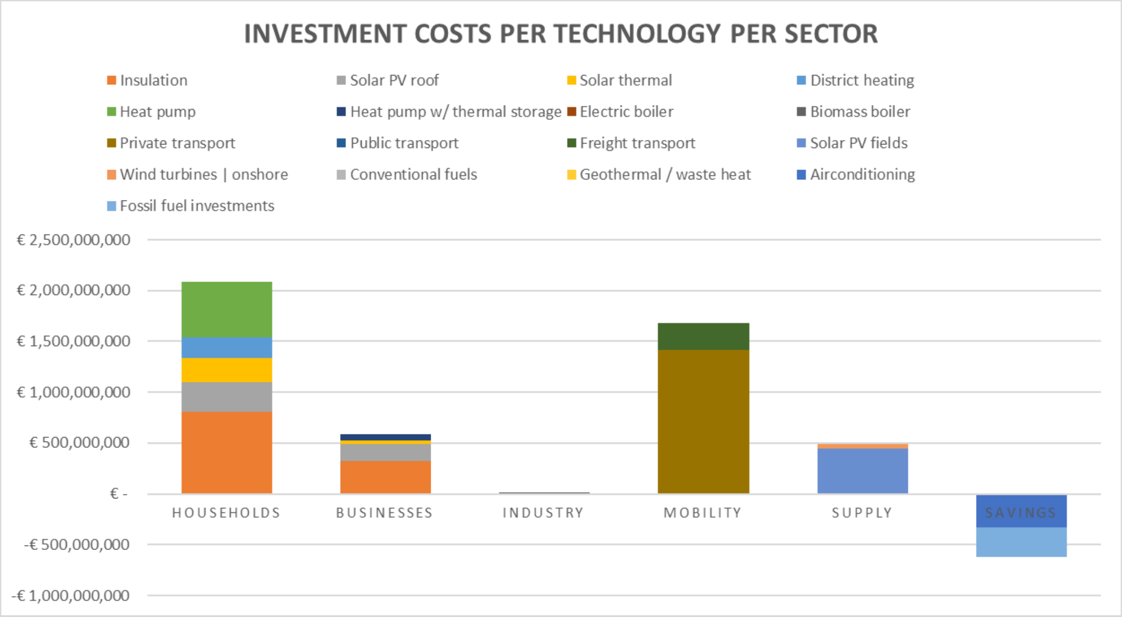
AVOIDED SCOPE 1 & 2 EMISSIONS PER TECHNOLOGY PER SECTOR

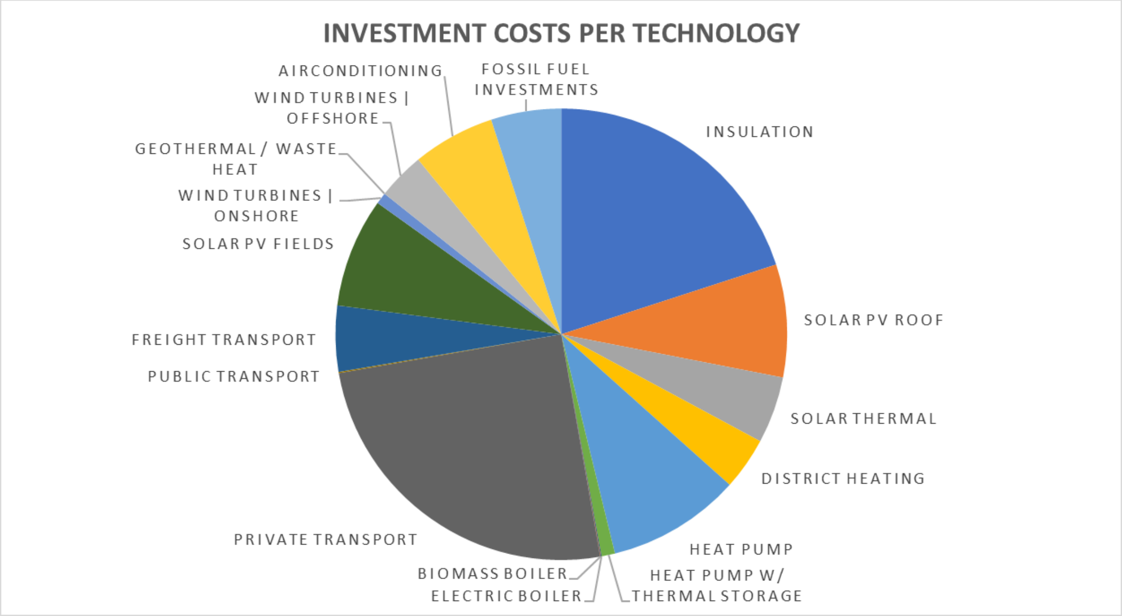


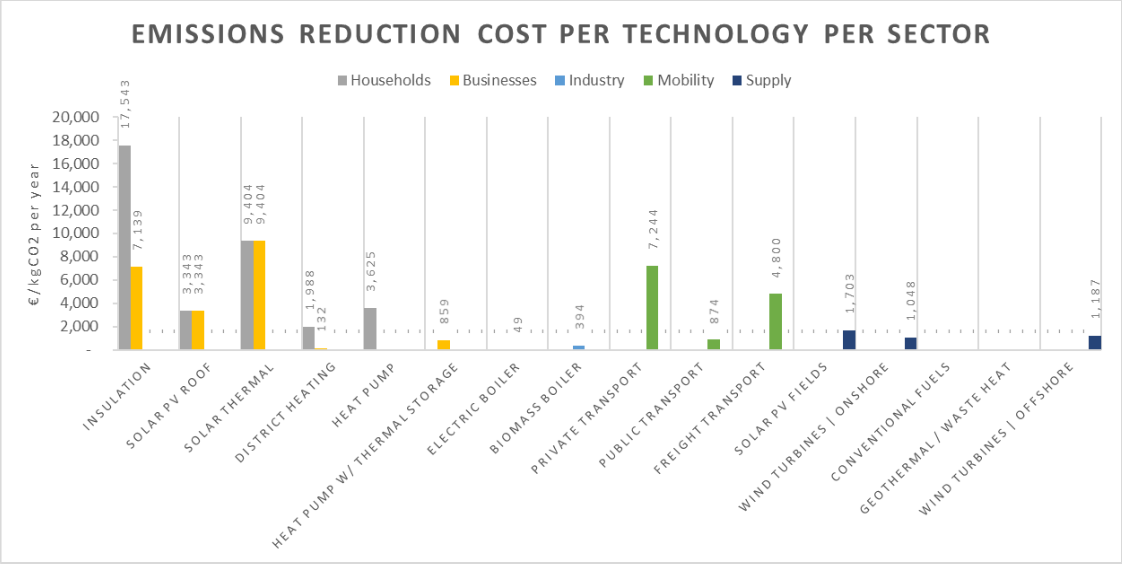
AVOIDED SCOPE 1 & 2 EMISSIONS PER SECTOR



UPSTREAM EMISSIONS PER TECHNOLOGY PER SECTOR


INVESTMENT COSTS PER TECHNOLOGY PER SECTOR
Insulation
Solar PV roof
Solar thermal
District heating
Heat pump
Heat pump w/ thermal storage
Electric boiler
Biomass boiler
Private transport
Public transport
Freight transport
Solar PV fields
Wind turbines | onshore
Conventional fuels
Geothermal / waste heat
Airconditioning
Fossil fuel investments
€ 2,500,000,000
€ 2,000,000,000
€ 1,500,000,000
€ 1,000,000,000
€ 500,000,000
€ -
-€ 500,000,000
-€ 1,000,000,000
HOUSEHOLDS
BUSINESSES
INDUSTRY
MOBILITY
SUPPLY
SAVINGS


INVESTMENT COSTS PER TECHNOLOGY
AIRCONDITIONING
FOSSIL FUEL INVESTMENTS
WIND TURBINES | OFFSHORE
GEOTHERMAL / WASTE HEAT
WIND TURBINES | ONSHORE
SOLAR PV FIELDS
INSULATION
FREIGHT TRANSPORT
PUBLIC TRANSPORT
SOLAR PV ROOF
SOLAR THERMAL
DISTRICT HEATING
PRIVATE TRANSPORT
HEAT PUMP
BIOMASS BOILER
HEAT PUMP W/ THERMAL STORAGE
ELECTRIC BOILER


EMISSIONS REDUCTION COST PER TECHNOLOGY PER SECTOR
Households
Businesses
Industry
Mobility
Supply
€/kgCO2 per year
20,000
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
-
17,543
7,139
3,343
3,343
9,404
9,404
1,988
132
3,625
859
49
394
7,244
874
4,800
1,703
1,048
1,187
INSULATION
SOLAR PV ROOF
SOLAR THERMAL
DISTRICT HEATING
HEAT PUMP
HEAT PUMP W/ THERMAL STORAGE
ELECTRIC BOILER
BIOMASS BOILER
PRIVATE TRANSPORT
PUBLIC TRANSPORT
FREIGHT TRANSPORT
SOLAR PV FIELDS
WIND TURBINES | ONSHORE
CONVENTIONAL FUELS
GEOTHERMAL / WASTE HEAT
WIND TURBINES | OFFSHORE

C. Data sources used in the model

Data point	**Source**
HVO biodiesel energy density	Aatola,H., Larmi, M., Sarjovaara, T. & Mikkonen, S. (2009). Hydrotreated Vegetable Oil (HVO) as a Renewable Diesel Fuel: Trade-off between NOx, Particulate Emission, and Fuel Consumption of a Heavy Duty Engine. SAE International Journal of Engines, 1(1), 1251–1262. https://doi.org/10.4271/2008-01-2500
Industrial electric boiler upstream emissions	Abbas, A.M. (2015). Life cycle assessment of water heating systems used in health clubs [Master’s thesis, An-Najah National University]. An-Najah Repository. https://scholar.najah.edu/sites/default/files/Ali%20M.%20Abbas_0.pdf
Petrol and diesel energy density	ACEA. (2016, 24 September). Differences Between Diesel and Petrol. European Automibile Manufacturers Association. Retrieved from: https://www.acea.be/news/article/differences-between-diesel-and-petrol/
Average BEV purchase price	ANWB. (2020, 3 December). Elektrisch rijden monitor 2020 [Fact sheet]. Retrieved from: https://www.anwb.nl/binaries/content/assets/anwb/pdf/belangenbehartiging/mobiliteit/anwb_elektrisch-rijden-monitor-2020_infographic.pdf
Onshore wind turbine capex	Bennaceur, F., Merzouk, N.K., Merzouk, M. & Hadji, A. (2019). Technical and economic viability of a wind farm installed in a windy area of Algerian western south region. Euro-Mediterranean Journal for Environmental Integration, 4, Article 7. https://doi.org/10.1007/s41207-018-0088-3
Geothermal pipeline capex	Blom, M.J., Aarnink, S.J., Roos, J. & Braber, K. (2014, July). MKBA Warmte Zuid-Holland [Report no. 14.7D18.46]. CE Delft. Retrieved from: https://ce.nl/wp-content/uploads/2021/03/CE_Delft_7D18_MKBA_Warmte_Zuid-Holland_DEF.pdf
Bus fleet size Groningen	Brouwer, M. & Van der Mei, A. (2020). Kansen voor zero-emissiebussen in Nederland – Onderzoek dagkilometrages per voertuig, 2019 (Report no. K-D096). CROW-KpVV. Retrieved from: https://www.crow.nl/downloads/pdf/collectief-vervoer/duinn_businzet-en-kansrijke-omlopen-elektrisch-en.aspx
Offshore wind turbine capacity	Bulder, B.H., Krishna Swamy, S., Warnaar, P.M.J., Maassen van den Brink, I.D. & De la Vieter, M.L. (2021). Pathways to potential cost reductions for offshore wind energy. TKI Wind Op Zee, Topsector Energie. Retrieved from: https://www.topsectorenergie.nl/sites/default/files/uploads/Wind%20op%20Zee/Documenten/20210125_RAP_Pathways_to_potential_cost_reduction_offshore_wind_energy_F03.pdf
Average vehicle age	CBS. (2016, 21 May). Personenauto’s steeds ouder. Centraal Bureau voor de Statistiek. Retrieved from: https://www.cbs.nl/nl-nl/nieuws/2016/20/personenauto-s-steeds-ouder
Average vehicle mileage	CBS. (n.d.) Hoeveel rijden personenauto’s? Centraal Bureau voor de Statistiek. Retrieved 8 March, 2021, from: https://www.cbs.nl/nl-nl/visualisaties/verkeer-en-vervoer/verkeer/verkeersprestaties-personenautos

Heat pump capex	CE Delft. (2019). Factsheets warmtetechnieken [Fact sheet]. Retrieved from: https://www.wassenaar.nl/_flysystem/media/informatiebladen-warmteoplossingen.pdf
Dwelling types per label	CLO. (2020, 13 August). Energielabels van woningen, 2010 - 2019 [Data set]. Compendium voor de Leefomgeving, Rijksoverheid. Retrieved from: https://www.clo.nl/indicatoren/nl0556-energielabels-woningen
Emission factors	CO2 Emissiefactoren. (2021, 22 February). Lijst emissiefactoren. Retrieved from: https://www.co2emissiefactoren.nl/lijst-emissiefactoren/
Onshore wind turbine capex	Commission Éolienne du SER. (2014). État des coûts de production de l'éolien terrestre en France. Syndicat des Énergies Renouvelables. Retrieved from: https://pdf4pro.com/amp/cdn/etat-des-co-219-ts-de-production-de-l-201-olien-1afab5.pdf
Solar thermal production	Duurzaammbo. (n.d.). Zonneboilers. Retrieved 16 April, 2021, from: https://www.duurzaammbo.nl/zonneboilers-en-warmte
Small wind turbine capacity	EAZ wind. (n.d.) Our windmill. Retrieved 16 February, 2021, from: https://www.eazwind.com/ourwindmill
Charge point division	Eco-movement. (n.d.) Chargepoints. Retrieved 1 March, 2021, from: https://chargepoints.eco-movement.com/widget/500/600/key/53.20369/6.60249/12
Diesel fuel well-to-wheels emissions	Edwards R., Larivé, J.F., Rickeard, D. & Weindorf, W. (2014). Well-to-wheels Report Version 4.a [Report no. EUR 26237 EN]. Institute for Energy and Transport, Joint Research Centre, European Commission. https://doi.org/10.2790/95629
Ethanol energy density	Energy content of biofuel. (2021, 29 January). In Wikipedia. https://en.wikipedia.org/wiki/Energy_content_of_biofuel
Condensing boiler efficiency	Energy Matter. (2014). Rendement HR-ketel: nader onderzoek tbv warmteregeling [Report no. 14.604]. Retrieved from: https://www.internetconsultatie.nl/wijzigingwarmteregeling/document/1316
Industrial boiler capacity factor	EPA. (2015). Biomass Conversion Technologies. U.S. Environmental Protection Agency (EPA) Combined Heat and Power (CHP) Partnership. Retrieved from: https://www.epa.gov/sites/production/files/2015-07/documents/biomass_combined_heat_and_power_catalog_of_technologies_5._biomass_conversion_technologies.pdf
Average onshore wind turbine capacity	EWEA. (n.d.). Wind energy's frequently asked questions (FAQ). The European Wind Energy Association. Retrieved 16 February, 2021, from: https://www.ewea.org/wind-energy-basics/faq/

Electric vehicles per charge point	Funke, S.A., Sprei, F., Gnann, T. & Plötz, P. (2019). How much charging infrastructure do electric vehicles need? A review of the evidence and international comparison. Transportation Research Part D: Transport and Environment, 77, 224–242. https://doi.org/10.1016/j.trd.2019.10.024
Reduction goals	Gemeente Groningen. (2018). Routekaart Groningen CO2-neutraal 2035. Retrieved from: https://gemeente.groningen.nl/sites/default/files/Routekaart-Groningen-Energie-%28CO2---neutraal%29.pdf
LCV urban logistics emissions share	Van Gijlswijk, R., Van Kempen, E., Spreen, J., Hoen, A., Van Bokhorst, M. & Wagter, H. (2018). Elektrische bestelauto's in Nederland – Marktontwikkelingen 2017-2025 (Report no. TNO 2018 P10518v2). TNO. Retrieved from: https://topsectorlogistiek.nl/wptop/wp-content/uploads/2018/09/TNO-2018-P10518v2_-EINDrapportage-E-van-Elektrische-bestelautos.pdf
Onshore wind turbine upstream emissions	Gomaa Behiri, M.R., Rezk, H., Mustafa, R.J. & Dhaifullah, M. (2019). Evaluating the Environmental Impacts and Energy Performance of a Wind Farm System Utilizing the Life-Cycle Assessment Method: A Practical Case Study. Energies, 12(17), Article 3263. https://doi.org/10.3390/en12173263
Geothermal capex	In 't Groen, B., De Vries, C., Mijnlieff, H. & Smekens, K. (2019, 6 May). Conceptadvies SDE++ 2020 - Geothermie [Report no. 3692]. Planbureau voor de Leefomgeving. Retrieved from: https://www.pbl.nl/sites/default/files/downloads/pbl-2019-conceptadvies-sde-plus-plus-2020-geothermie_3692.pdf
Groningen gas energy density	Gronings gas. (2020, 30 March). In Wikipedia. https://nl.wikipedia.org/wiki/Gronings_gas
District heating capex	Gudmundsson, O., Thorsen, J.E. & Zhang, L. (2013). Cost Analysis Of District Heating Compared To Its Competing Technologies. WIT Transactions on Ecology and the Environment, 176(12), 3–13. https://doi.org/10.2495/ESUS130091
Solar thermal storage capacity	Hartmann, N., Glueck, C. & Schmidt, F.P. (2011). Solar cooling for small office buildings: Comparison of solar thermal and photovoltaic options for two different European climates. Renewable Energy, 36(5), 1329–1338. https://doi.org/10.1016/j.renene.2010.11.006
Average BE LCV battery capacity and fuel consumption	Hoen A. & Leestemaker, L. (2020, November). TCO-analyses bestelauto's in het kader van de WLO [Report no. 20.200372.152]. CE Delft. Retrieved from: https://ce.nl/publicaties/tco-analyses-bestelautos-in-het-kader-van-de-wlo/
Heat pump usage multiplier	HPAC. (2018, 12 January). How to choose the right size heat pump. Retrieved from: https://www.hpac.co.nz/blog/how-to-choose-the-right-size-heat-pump/
Offshore wind turbine capacity factor	IEA Wind Technology Collaboration Programme. (2018). 2017 Annual Report. IEA Wind. Retrieved from: https://community.ieawind.org/HigherLogic/System/DownloadDocumentFile.ashx?DocumentFileKey=dd7c47c2-b19d-00bf-6c38-970494257e43&forceDialog=0

Biomass boiler avoided emissions	Jeswani, H.K., Whiting, A. & Azapagic, A. (2019). Environmental and Economic Sustainability of Biomass Heat in the UK. Energy Technology, 8. Article 1901044. https://doi.org/10.1002/ente.201901044
Average duration of vehicle possession	Kampert, A., Nijenhuis, J., Van der Spoel, M. & Molnár-in ‘t Veld, H. (2017, February). Nederlanders en hun auto - Een overzicht van de afgelopen tien jaar. Centraal Bureau voor de Statistiek. Retrieved from: https://www.cbs.nl/nl-nl/achtergrond/2017/08/nederlanders-en-hun-auto
Electric vehicle median battery capacity	Kane, M. (2019, 23 August). Official: 2020 Chevy Bolt EV Goes 259 Miles Per Charge. InsideEVs. Retrieved from: https://insideevs.com/news/366750/2020-chevrolet-bolt-ev-259-miles-range/
Energy demand	Klimaatmonitor. (n.d.) Database Klimaatmonitor [Data set]. Rijkswaterstaat, Ministerie van Infrastructuur en Waterstaat. Retrieved 18 February, 2021, from: https://klimaatmonitor.databank.nl/Jive/
Thermal storage seasonal performance factor	Le, K.X., Huang, M.J., Shah, N.N., Wilson, C., Mac Artain, P., Byrne, R. & Hewitt, N.J. (2019a). High Temperature Air Source Heat Pump Coupled with Thermal Energy Storage: Comparative Performances and Retrofit Analysis. Energy Procedia, 158, 3878–3885. https://doi.org/10.1016/j.egypro.2019.01.857
Thermal storage seasonal performance factor	Le, K.X., Huang, M.J., Shah, N.N., Wilson, C., Mac Artain, P., Byrne, R. & Hewitt, N.J. (2019b). Techno-economic assessment of cascade air-to-water heat pump retrofitted into residential buildings using experimentally validated simulations. Applied Energy, 250, 633–652. https://doi.org/10.1016/j.apenergy.2019.05.041
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Industrial biomass boiler opex	Lensink, S.M. & Van Zuijlen, C.L. (2014, October). Eindadvies basisbedragen SDE+ 2015 [Report no. ECN-E--14-035]. ECN. Retrieved from: https://publicaties.ecn.nl/PdfFetch.aspx?nr=ECN-E--14-035
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