# Utilization of Labor Towards Carbon Neutral Heat in Dutch Terraced Houses

An exploration of the utilization of labor in implementing green gas, heat districts, and electrification measures in the transition of Dutch terraced houses towards carbon neutral heating in 2050


Alwin van der Ven – 4021703

Student Address: Oudegracht 235, 3511NK Utrecht

E-mail: a.c.a.vanderven@students.uu.nl


Master: Sustainable Development, Energy & Materials Track

Supervisor: Dr. Robert Harmsen

Number of ECTS: 30

Start Date: 20 February

Internship: Yes

Host Institution: Liandon Energy Consultancy, Dijkgraaf 4, 6921 RL Duiven

Contact Person: Maarten van Blijderveen, maarten.van.blijderveen@alliander.com

# Summary

In the context of global warming the Dutch government aims to have carbon neutral heating in houses by 2050. In this heat transition natural gas, as the main source of heat for households, must be replaced with carbon free sources of heat such as green gas and heat pumps with PV-panels. Carbon free heat could also be supplied by a heat district. Furthermore, heat demand must be reduced through high levels of insulation in all houses. Analyses of previous efforts to reduce emissions from households have shown the barriers and the economic and societal effects of the heat transition. A recurring barrier is the shortage of skilled labor and that more in depth knowledge of the required labor is needed. However, the research that has been done on the labor requirements of this heat transition is generally based on a top down approach using e.g. expected investments as a proxy for labor. This research aims to provide more direct quantitative and qualitative insights in the required labor and the utilization of it by using a bottom up approach. This knowledge can be used by policy makers to better guide the heat transition and educational programs. To ensure sufficient depth of the research, the scope is limited to terraced houses. The main research question is: ''*How can the current Dutch labor supply be utilized most efficiently towards achieving carbon neutral heating before 2050 in all Dutch terraced houses?'*. As the aim of this research is to illustrate how labor can be utilized, the labor supply has been held static and is defined as the current available labor that is deployable for the heat transition of terraced houses. Labor is expressed in terms of full-time jobs. The required labor for retrofitting houses and adapting the infrastructures was determined by collecting data from construction and installation companies, as well as from grid operator 'Alliander'. Five main building periods of terraced houses and their average characteristics were identified. These characteristics were used to calculate the required labor per house for green gas, electrification, and district heating as well as the expected $CO_2$-emissions of retrofitted houses from different building periods. The 'Energiebesparingsverkenner' of the RVO was used to model the annual $CO_2$ emissions of retrofitted houses. Labor efficiency is expressed in terms of the required full-time jobs per ktonne $CO_2$ reduction of annual emissions. With this efficiency and the deployable labor, five scenarios were constructed to explore how labor could be utilized most efficiently. The least amount of emissions with the least amount of labor can be made when heat pumps, PV-panels, and insulation measures are installed concurrently in the oldest terraced houses first. If no priority is given to the age of buildings, green gas, electrification, and a mix of sources have identical emissions as the bottleneck of their retrofitting pace is determined by insulation measures. Green gas requires no labor within the system boundaries of this research and as such is the least labor-intensive measure, but the availability of green gas might be limited. Labor for heat districts is relatively scarce and so more time is required to construct them resulting in more cumulative $CO_2$ emissions than the other options. Insulation is the least efficient use of labor and it requires the most labor in all scenarios. But as a requisite measure for low-temperature heat districts and electrification, and as a measure to reduce the demand for green gas, it is a vital measure to be taken in the heat transition. The most efficient use of the current labor supply would be to implement a mix of carbon neutral heat sources combined with insulation measures as this would distribute the required labor over more professions thus reducing the overall scarcity of labor.

# Preface

The past two years I have been dedicated to master the field of sustainable development of energy and materials at Utrecht University. This thesis is last project of my study and looking back I must conclude that I am happy I chose this master and (hopefully) future field of work. Although, in the coming months I'm looking forward to focus on the music of my bands, to visit friends in other countries, and having a more hands-on type of job. Maybe I can even find a job to insulate houses or install PV-panels, who knows.

First and foremost, I want to thank Maarten for providing the opportunity to work on this project and the support when I needed it. But mostly I want to thank him for his positivity throughout this whole process. During my research I was helped by colleagues from various departments in Liandon and Liander which I want to thank for their time and often interesting and informative talks.

Secondly, I want to thank Robert as my supervisor for providing guidance and feedback not only during this thesis, but also during his courses. Which were among the most interesting and valuable courses I have followed during my master due to his dedication to teaching and enthusiasm.

This thesis marks the end of my academic career here at Utrecht University of the past six years. Throughout my studies I have had the support of my friends and bandmates which I will not all thank individually, but who will hopefully know that I am grateful for them. Although, there is one person who has been there since the beginning of my studies and for whom I do want to use this opportunity to thank. Many thanks to Aafke for all the coffee, beers, food, and moments of laughter and friendship we have shared these past years and will share in the future.

Furthermore, I want to thank my niece and nephew, Isis and Rorik, for being completely crazy and always making me smile. I would like to thank my sisters Miriam and Viviannne for always supporting me in all that I do. Most importantly I want to thank my parents as without them I would not even be here. I want to thank my father, Cees, for his great support allowing me to pursue my goals. To my mother, Anne, who always was a source of motivation, thank you for your everlasting support and love.

# Table of Contents

# Chapter 1: Introduction

## 1.1. Context

A fundamental change in the provision of energy is required to keep $CO_2$-emissions within the limit of $2^oC$ global warming (IPCC, 2014). As part of international agreements (UNFCCC, 2018a, 2018b) the Dutch government has set out to reduce $CO_2$-emissions to near zero levels by 2050 in the Netherlands (Klimaatakkoord, 2018). Sub-targets and pathways are defined in the 'Klimaatakkoord', which is currently still under development. One target is to make the transition towards a carbon-neutral housing sector, which requires a significant reduction of the heat demand and replacement of natural gas as the main source of heat by a carbon neutral source (Klimaatakkoord, 2018). In other words, all houses need higher levels of insulation and a carbon-neutral source of heat. Subsequently, the energy infrastructure needs to be adapted to meet the changes in energy demand. The Dutch housing sector consists of more than 7 million houses and thus the retrofitting pace will need to exceed 200.000 houses per year. The magnitude of the required effort and the urgency to reduce emissions underline the need for an efficient use of the available resources within the limited time available for the heat-transition.

Preceding the 'Klimaatakkoord', multiple other actions[1] have been undertaken by the Dutch government to start the transition of the existing housing stock. Analyses of these actions have shown that the resources, labor, planning, and guidance are currently not sufficient to reach the required retrofitting pace[2] (MEZ, 2016; SER, 2016, 2017; Schoots et al., 2017). Studies of the heat transition of the housing stock have been done on topics such as the macro-economic effects (Grootenboer et al., 2013), effects on the deployment and quality of labor (Koning et al., 2016), potential savings (e.g. Slingerland et al., 2016; Wijngaart et al., 2014), trends and developments of the transition (RVO, 2017), and the available techniques towards energy neutral housing (RVO, 2014a). Most of the found studies focused on the (potential) results and the barriers and few detailed studies have been done on the requirements of the heat transition. For example, Straatmeijer & Koning (2015) assessed some of the qualitative and quantitative aspects that were needed of the construction sector's labor force.

## 1.2. Problem Definition

One important and recurring barrier in the heat transition is the shortage of skilled workers in the installation and construction sectors (BuildUpSkills, 2012; SER, 2016, 2017). This is confirmed in the past few years by an overall shortage of labor in the installation and construction sector. The shortage is a result of a greater demand, aging of the workforce, a small inflow of new workers, and an education system that falls short (Aalst & Beukel, 2017; EIB, 2018). The growing demand for labor is a result of the greater need for new housing as well as for renovations (EIB, 2018). It is expected that the shortage will continue to grow in the next five years and competition for skilled workers will increase between sectors. Simultaneously, a greater effort is required to attract and keep workers working within the

[1] Examples are the 'Energieakkoord' (SER, 2013), 'Stroomversnelling' (Stroomversnelling, 2013), the 'Energieagenda' (MEZ, 2016), and 'Green Deal Aardgasvrije Wijken' (Green Deal, 2017).

[2] The realized NOM-houses between 2012 and 2016 were estimated at 3,150 (RVO, 2017).

installation and construction sectors. A small part of the labor shortage can be filled by imports, but the greatest source of new labor is education (EIB, 2018).

The mismatch between the demand and supply of labor is an important barrier to overcome in the heat transition. Due to the expected scarcity of labor for the heat transition, limited available time, and the urgency to prevent greenhouse gas emissions it is of key importance to utilize the available labor as efficiently as possible in terms of time and emissions. To construct new policy measures towards a more efficient use of labor, more detailed research on qualitative and quantitative aspects of labor is needed (SER, 2016, 2017, 2018; Straatmeijer & Koning, 2015).

## 1.3. Research Aim and Questions

So far, most studies have assessed the future labor demand by proxy through a top-down approach, generally based on expected investments (e.g. Grootenboer et al, 2013; Koning et al., 2016). By taking a bottom-up approach this study will provide more direct insights in the qualitative and quantitative aspects of the required labor, and how labor can be utilized most efficiently in terms of $CO_2$ reductions and cumulative $CO_2$ emissions. This is done by collecting the average figures of the required labor per measure, which differs per housing type. To ensure sufficient depth of this research, the data collection was limited to terraced houses, which constitute 41% of the total Dutch housing stock (see Appendix A).

The main research question is as follows:

'*How can the current Dutch labor supply be utilized most efficiently towards achieving carbon neutral heating before 2050 in all Dutch terraced houses?'*

To answer the main research question, five sub-questions have been formulated:

1. What is the required labor for retrofitting terraced houses towards carbon neutral heating?
2. What are the potential reductions of annual $CO_2$ emissions of various retrofitting measures in terraced houses?
3. What is the efficiency of each retrofitting measure in terms of FTE per ktonne $CO_2$ emission reduction of annual $CO_2$ emissions due to heat in terraced houses?
4. What are the total $CO_2$ emissions of all terraced houses when current labor is fully utilized in the heat transition?
5. What are the total $CO_2$ emissions of all terraced houses when labor is utilized dispersedly over measures and terraced houses in the heat transition?

## 1.4. Thesis Outline

Chapter 2 provides descriptions and definitions of the concepts used in this research. Firstly, it will show the current energy use and performance of average Dutch houses. Followed by a description of the Dutch housing stock in terms of housing types and their energy performance. Thirdly, the potential retrofitting measures for terraced houses are described. After which, a description of the infrastructures and the potential adaptations are given. The chapter concludes with the concepts related to labor: the type of labor considered in this research, the definitions of labor availability and deployability, and what constitutes as a full-time job.

Chapter 3, discusses all the methods used in this research. First, the data collection and preparation methods needed for the input data of the scenarios are described. The input data consists of the housing stock, available and deployable labor of the construction and installation sectors, and the required labor per retrofitting measure. Furthermore, potential retrofitting measures are identified and the modelling tool for determining the $CO_2$ emissions of retrofitted houses will be described. This input data will be used to create the scenarios of which the methods will be explained in the second part of chapter 3.

Chapter 4 presents the results. The structure of this chapter follows the sub-research questions. First the required labor per measure per housing type for individual houses and the total terraced housing stock is given. Secondly, the potential reductions of annual $CO_2$ emissions are presented, again per measure per housing type for individual houses and the total terraced housing stock. The third sub-chapter presents the efficiency of measures in terms of FTE's per ktonne $CO_2$-reduction of annual emissions. The fourth sub-chapter provides the development of annual and cumulative $CO_2$ emissions when all deployable labor is fully utilized in the transition as well as the years it would take to completely install each set of retrofitting measures. Finally, the fifth sub-chapter, shows the development of annual and cumulative $CO_2$ emissions when labor is utilized dispersedly over time by different focusses on measures and the age of buildings.

Chapter 5 is a discussion on the results where remarks are made on the assumptions made in this research and their potential influence on the direction of the results; i.e. overestimations or underestimations of the labor and potential $CO_2$ reductions and emissions. The contribution of this research to the existing literature will be discussed and this chapter is concluded with recommendations for further research.

Logically, chapter 6 will provide the answers to each sub-question respectively and the research question will be answered thus concluding the research.

## 1.5. Liandon Energy Consultancy

Alliander is a company concerned with the distribution of electricity, gas, and heat. To secure the provision of reliable, affordable, and accessible energy during the heat transition, it is important to continuously create new knowledge and skills to anticipate changes. Liandon Energy Consultancy, the consultancy branch within Alliander, was interested in the required expenditures of materials, time, area, and energy for the transition towards a sustainable energy system. This knowledge is valuable in their advice to customers that often work with complex systems, as it shows the relationships and interdependencies between different material and social systems. This thesis was written for the Energy transition, Gas, & Circularity (ECG) branch of Liandon as an exploration of the required time for the heat transition.

Figure 1 shows the organizational structure surrounding Liandon. Within Alliander, Liandon is the knowledge center and its activities are the design, construction, management, and maintenance of complex energy grids and large (industrial) installations. Liandon consists of three parts: Energy Consultancy, Marketing & Sales, Asset Management. Liandon Energy Consultancy, in turn consists of five teams: 'Ruimte & Recht', 'Energietransitie, Gas & Circulariteit', 'Telecom & IT', 'Warmte Koude Procestechniek', and 'Elektrotechniek'.

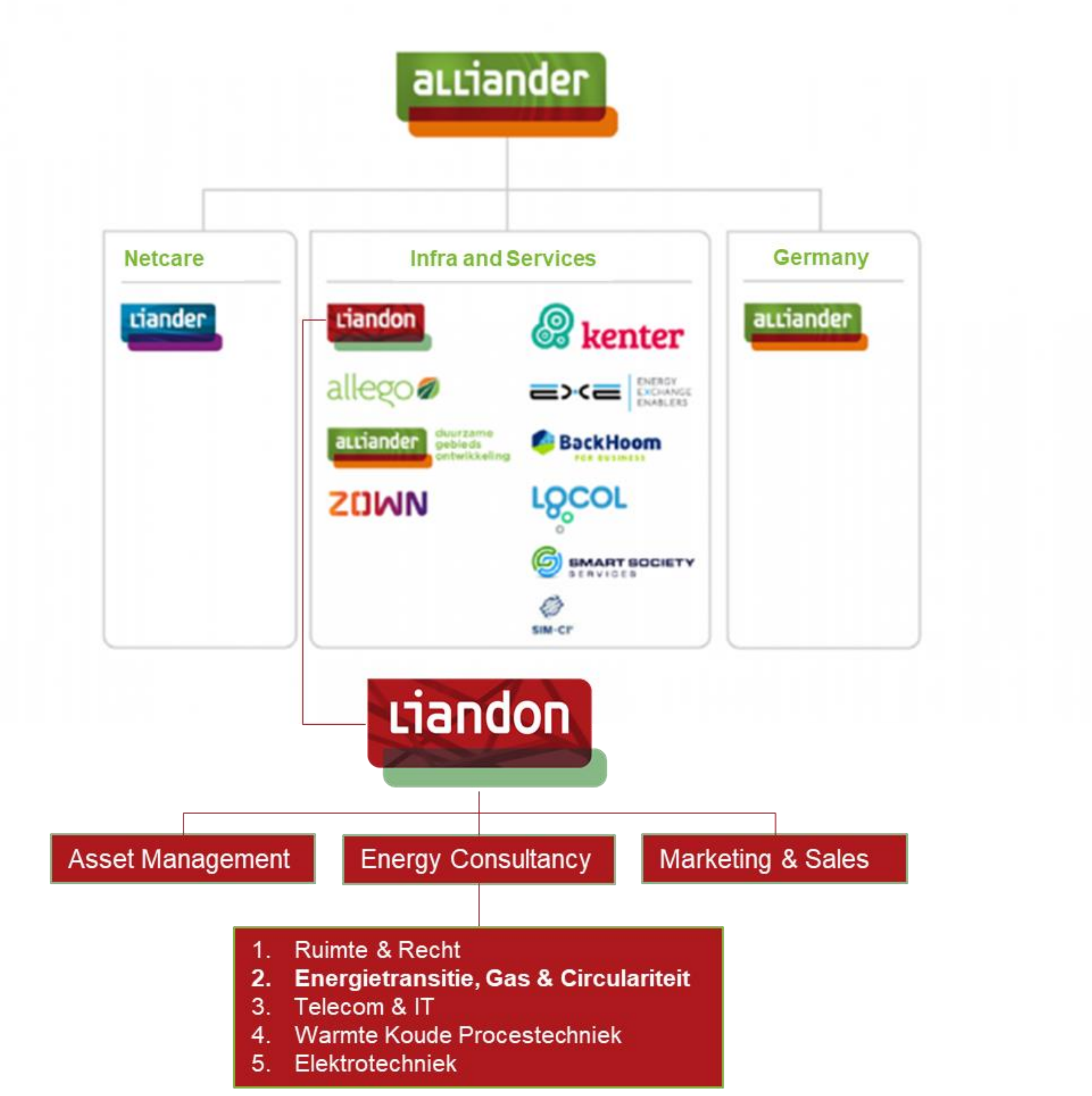


FIGURE 1 ORGANOGRAM OF ALLIANDER AND LIANDON

# Chapter 2: Definitions and concepts

## 2.1. Energy Use

The energy consumption of Dutch households is shown in figure 2, 68% of the end use is heat (space heating, tap water, cooking) and 32% is electricity (lighting and other use). The development in the average energy use of all households from 1997 till 2014 is shown in figure 3. The natural gas use has been steadily declining since 1997 due to improved insulation of houses and the implementation of high efficiency condensing boilers. Electricity use has been increasing since 1997 and has been decreasing after the financial crisis of 2008 to the level of 1997 (BZK, 2016). Overall it can be stated that the energy intensity of Dutch households has been decreasing in the past decade.

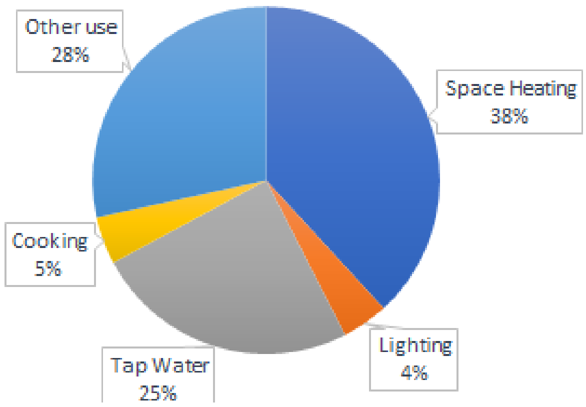


**FIGURE 2 ENERGY USE PER FUNCTION OF HOUSEHOLDS (RVO, 2018A)**

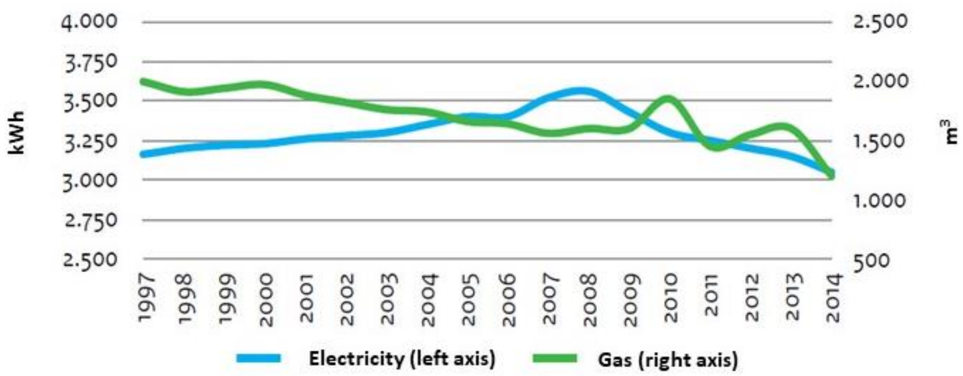


**FIGURE 3 AVERAGE ELECTRICITY AND GAS-USE BETWEEN 1997 AND 2014 IN THE NETHERLANDS (BZK, 2016)**

Heat demand which consists of space heating, hot tap water, and cooking, is mostly fulfilled by using natural gas (RVO, 2017). The most common equipment used for heating in Dutch households is a condensing boiler (85%), heat districts have a share of 9%, and other individual heating systems (e.g. wood stoves) account for 6% (Menkveld, 2009). Space heat demand is mostly determined by the ratio of the floor and surface area, level of insulation, and by the habits of the residents. While the demand for electricity and hot tap water is mostly determined by the number of residents and their habits (Majcen et al., 2013; Menkveld, 2009).

The Dutch government expresses the energy performance of existing buildings by the Energy-Index (EI)[3] which is calculated through the NEN7120 norm (Regeling Bouwbesluit, 2012)[4], which takes the insulation levels, heating systems, and other energy related aspects bound to a building into account (RVO, 2014b). The boundaries of the system considered in this method are: the energy use is to be determined under standard use and climate conditions, only the energy use bound to the building is to be considered (final energy), the energy production can take place outside of the building, the net energy use will be determined over a year, and local measures can be included through the EMG norm (RVO, 2014b).

## 2.2. Housing Types

A representation of housing stock and the energy use of houses, used by policy makers and researchers in the Netherlands, consists of seven housing types and five building periods (BZK, 2011a)[5]. The shares of each housing type in the Dutch housing sector are shown in table 1. There is a strong correlation between year of construction and energy performance (BZK, 2016; Majcen et al., 2013). Housing types also show a relationship with the energy performance (BZK, 2011c; Menkveld, 2009). This relationship is illustrated in table 2.

TABLE 1 SHARES OF EACH HOUSING TYPE PER PERIOD OF CONSTRUCTION AS IN JANUARY 2006 (BZK, 2011C)

| Year of Construction / Housing Type | < 1946 | 1946-1964 | 1965-1974 | 1975-1991 | 1992-2005 | Total |
|---|---|---|---|---|---|---|
| **Detached** | 6.5% | | 1.8% | 3.3% | 2.6% | 14.1% |
| **Semi-Detached** | 4.2% | | 2.1% | 3.3% | 2.6% | 12.1% |
| **Terraced** | 7.7% | 7.0% | 8.9% | 12.9% | 5.2% | 41.7% |
| **Maisonette** | 3.3% | | 0.3% | 1.4% | 0.6% | 5.6% |
| **Gallery Flat** | 1.0% | | 2.6% | 1.6% | 1.7% | 6.8% |
| **Porch Flat** | 3.8% | 3.9% | 1.7% | 2.1% | 1.0% | 12.5% |
| **Other Flat** | 1.5% | | 1.8% | 1.8% | 2.0% | 7.1% |
| **Total** | 38.8% | | 19.1% | 26.4% | 15.6% | 100.0% |

The average energy indices of each housing type per period have declined over the years, as is shown in table 2. The houses built before 1964 have an average EI of 2.71 and those built between 1992 and 2005 have an EI of 1.2. A strong improvement in terms of energy-efficiency occurred in the period 1975-1991, which can be explained by the stricter energy performance requirements implemented in

---

[3] The EI can be translated to the Energy-Label, but the methods to determine their values are not identical anymore as of 2014 (RVO, 2016).

[4] The NEN7120 calculation method is also used to determine the Energy Performance Coefficient (EPC) which is the indicator for energy efficiency of newly built houses (RVO, 2018c).

[5] Currently another, less detailed categorization is in use, which is used to determine the EPC value of new buildings (RVO, 2018b). This categorization has grouped maisonettes, porch and other flats under apartment complexes. Furthermore, it explicitly differentiated between regular and corner terraced house, instead of it being a sub-category in the 'voorbeeldwoningen' categorization (BZK, 2011c).

the 80’s (Tigchelaar & Leidelmeijer, 2013). Roughly four periods in the EI can be identified: before 1964, 1965-1974, 1975-1991, and 1992 to 2005. A distinction between terraced houses and porch flats from the building periods before 1946 and between 1946 till has been made on request from the users of this typology. The physical characteristics of these houses differ to such an extent that there are considerable differences in the potential measures that can be taken (BZK, 2011b).

**TABLE 2 AVERAGE ENERGY-INDEX PER HOUSING TYPE (BZK, 2011B)**

| Housing Type \ Year of Construction | < 1946 | 1946-1964 | 1965-1974 | 1975-1991 | 1992-2005 | Total Weighted Average |
|---|---|---|---|---|---|---|
| **Detached** | 2.7 | | 2.29 | 1.52 | 1.15 | 2.09 |
| **Semi-Detached** | 2.51 | | 2.21 | 1.54 | 1.21 | 1.92 |
| **Terraced** | 2.69 | 2.46 | 2.11 | 1.57 | 1.19 | 1.99 |
| **Maisonette** | 2.91 | | 2.5 | 1.56 | 1.27 | 2.38 |
| **Gallery Flat** | 2.91 | | 2.6 | 1.66 | 1.21 | 2.09 |
| **Porch Flat** | 3.01 | 2.95 | 2.4 | 1.54 | 1.21 | 2.52 |
| **Other Flat** | 2.77 | | 2.65 | 1.75 | 1.24 | 2.05 |
| **Total** | 2.71 | | 2.28 | 1.57 | 1.2 | 2.09 |

## 2.3. Retrofitting Measures

The energy performance of buildings can be improved by implementing retrofitting technologies, of which some are shown in figure 4. Retrofit technology types can be categorized into three groups: demand side management, supply side management, and energy consumption patterns. The energy demand can be reduced by using more efficient equipment or by reducing the heat and cooling demand. Retrofitting technologies also include renewable energy technologies and the electrification of heat sources within a building. Technologies allowing the management of human behavior are a part of building retrofit technologies as well, as changes in energy consumption patterns are often required (Ma et al., 2012).

Retrofitting technologies will henceforth be referred to as retrofitting measures. This research will focus on retrofitting measures related directly to the physical structure of buildings; i.e. insulation, heating systems, and energy producing installations. Three main categories are identified as potential replacements for natural gas as a heat source in households: 1) Full electrification, 2) District Heating, 3) Green Gas. Another category of measures is also considered: 4) Insulation. Insulation is an important determinant of the heat demand of a building and can be complementary measure to the other categories. Insulation provides a higher level of comfort in a house and it reduces the heat demand. Heat districts and electrification commonly deliver low temperature heat through a system with high thermal inertia and thus rely on insulation to heat a house comfortably. Heat districts could also deliver high temperature heat thus mitigating the need for high levels of insulation for comfort.

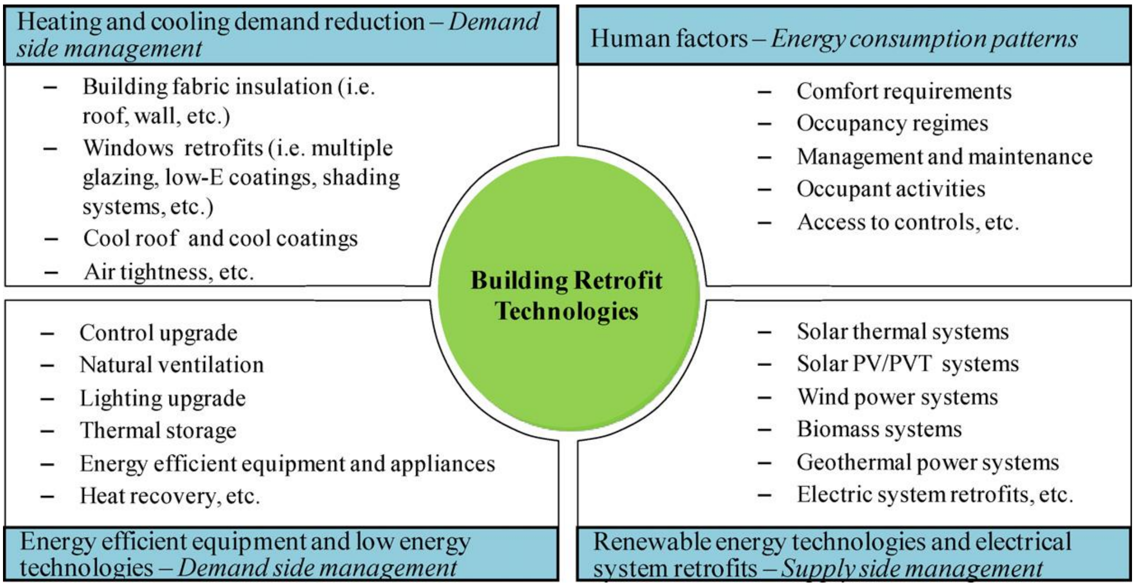


**FIGURE 4 BUILDING RETROFIT TECHNOLOGIES (MA ET AL., 2012)**

## 2.4. Retrofitting Measures in Terraced Houses

The type of insulation is highly dependent on the physical characteristics of houses. Houses have multiple building elements that can be insulated: walls, windows, floors, and roofs. Potential insulation measures per building element of Dutch terraced houses will be described further in this section.

Insulating walls in existing houses is done by injecting the insulant under pressure in the cavity walls. This method is used regardless of the material. The level of insulation through this method is limited to R values of roughly 1,5 to 2 $m^2K/W$ due to the size of cavity walls, commonly ranging from 4 to 8cm. Cavity walls became common in terraced houses since 1930. After 1973 cavity walls have minimal insulation which can generally be complemented by injecting extra insulation. Terraced houses built after the 1990's have solid insulation and thus their insulation values are fixed (personal communication, G. Jansen, May 6, 2018; MilieuCentraal, 2018). Higher levels of insulation can be attained by installing an extra building shell around the house. Furthermore, building shells can make the house air-tight and can have integrated installations such ventilation or PV-panels (RVO, 2014a). Façade elements typically include windows and doors.

Replacing windows in all housing types is dependent on the material of the frame and the glazing type (dry or wet). The time required is mostly determined by the glazing types and the types of glass used. For example, plastic and aluminum frames with double glass can easily be replaced with other double glass but cannot be fitted with triple glass which would require complete replacement of the frame. Most wooden frames with single glass can be fitted with double glass, but this would require more time (B. van Kruistum, Personal Communication, June 5, 2018; E. Namink, Personal Communication, June 5, 2018).

Floors can be insulated by filling the crawl space with loose insulant material, spraying PUR foam onto the bottom of the floor, covering the crawl space with foil, placing thermos cushions, or by insulating the top of the floor. The first two measures are the most common and feasible solutions in Dutch houses. However, terraced houses built before the 1940's have a low crawl space (<30cm) and thus insulation is limited to loose insulant material, like polystyrene pearls. Terraced houses from other building periods have various types of crawl spaces and are usually high enough for PUR foam or other insulant measures (50cm>) (personal communication, G. Jansen, May 6, 2018; MilieuCentraal, 2018).

Roof insulation in all housing types can be done by installing various insulant materials (e.g. PUR-foam, insulating plates) on the inside or the outside of the roof. There are little to no limitations for specific insulation materials. PUR-foam on the inside would be the least labor-intensive measure, but as this is measure is often seen as unaesthetic this measure is often combined with some type of finishing work which increases the required labor (personal communication, G. Jansen, May 6, 2018; MilieuCentraal, 2018). Plate insulation measures require no extra work and can be installed on the inside or the outside (personal communication, G. Jansen, May 6, 2018; MilieuCentraal, 2018; personal communication, R. van der Wal, 12 June, 2018).

Besides insulation measures there are installations to be installed in the retrofitting of houses: PV-panels, heat pumps, heat district connections, and ventilation systems. Heat district connections are heat exchangers that replace boilers and can directly be connected to the central heating and hot water system in case of high temperature heat districts. In case of low temperature heat districts, a low-temperature heating system, high levels of insulation, and an extra installation to reach high temperatures for hot tap water (e.g. heat pump, electric boiler) might be required. Installation of PV-panels can be limited by construction constraints or due to aesthetics. There are various types of heat pumps that transfer heat between different mediums: air-air, air-water, water-water, or ground-water. Air-air and air-water are the widest applicable types of heat pumps as these can be placed anywhere where air is available. Whereas, water-water requires a body of water to exchange heat with and ground-water requires either boreholes in the ground or a considerable area of land (Milieucentraal, 2018; RVO, 2014a).

Well-insulated houses require mechanical ventilation to keep air fresh and humidity low in houses. Terraced houses built before 1992 typically rely on natural ventilation and require airshafts to be constructed for mechanical ventilation. Whereas, terraced houses built after 1992 typically have a mechanical ventilation system in place and do not need new airshafts (BZK, 2011b). There are multiple ventilation installations to be implemented: mechanical ventilation continuously refreshes the air in a house with a constant flow, a demand driven ventilation system measures the air quality and adjust the air flow accordingly, and a balanced ventilation system is a mechanical ventilation system which recovers heat from the outgoing air to heat the incoming air (RVO, 2018d).

## 2.5. Infrastructures

Houses do not standalone and interact with the infrastructures surrounding it to fulfill its needs. Dutch houses are connected to water pipelines, sewage, electricity and gas grids, and some are connected to a heat district. Heat districts, electricity grids, and gas grids each supply different types of energy to houses and have their own infrastructural elements to provide reliable and sufficient energy. Retrofitting houses can change the demands from these infrastructures and should thus be designed to work in synergy with the grids to reduce the stress put on the network (Sartori et al, 2012) and to prevent extra costs in ancillary services.

Green gas has the same properties as natural gas and thus no significant adaptations to the gas grid on the output side are needed. Implementing green gas on a large scale will lead to a change in ancillary installations to guarantee stability (personal communication, L. Brummelkamp, 19 June, 2018; B. Roelofs., J. Kuiphof., 4 July, 2018). The potential to produce green gas from domestic products is limited[6] and the potential imports in the future are likely to be limited by competing demands between countries and sectors (Groen Gas Forum, 2014).

Households with heat from heat pumps in either with or without PV-panels for electricity will increase the load on the grid and thus its load capacity needs to be increased. Low and medium voltage grids are considered in this research. Load capacity of these grids is increased by laying extra cables and increasing the capacity of the substations. Laying cables requires that streets are opened, trenches are dug, and that the streets are closed and paved again. The capacity of substations can be increased by installing extra components.

Heating districts are not widely available in the Netherlands, as only 9% of the houses has a heat district connection (Menkveld, 2017). In most cases a new connection to heat a district will require the construction of a new heat district or an extension of an existing one. A distinction is made between heat districts that supply high temperature heat or low temperature heat to houses. High temperature heat (>70$^{o}$C) can be used in existing heating systems (e.g. radiators) in houses. Whereas, low temperature heat (<70$^{o}$C) might require retrofitting measures to be taken in the house (see section 2.4.). For the construction of heat districts three main activities were identified: laying and welding pipelines, digging, paving streets.

## 2.5. Labor – Professions and Definitions

### 2.5.1. Professions and skills

The transition will introduce new technologies in the existing houses and infrastructures. During the life-cycle of a technology different kinds of labor are needed and can be categorized in five stages: 1) Research and Design, 2) Development and Manufacture, 3) Construction and Installation, 4) Operation and Maintenance or Service, 5) Updating and/or Dismantling (Sastresa et al., 2009). This research will focus on stage 3 which require physical labor for construction and installation. Examples of activities from these sectors are: insulating building shells, glazing, assembly of pre-fab building elements,

[6] As for now, the potential for green gas is estimated at 1 million Nm$^3$ in 2030 (Groen Gas Forum, 2014).

installing heat pumps, constructing a heat district, and installation of PV-panels. A list illustrating the multitude of professions related to retrofitting buildings is included in appendix B.

It was found that a lot of professionals are highly specialized in one specific task (e.g. insulating cavity walls, heat pump installation). Specific skills are therefore allocated to broader categories with a similar knowledge base or that could be expected to fulfill or learn certain tasks easily. This allocation was based on information from profession profiles (Geurlings & Hofman, 2015a, 2015b, 2015c, 2015d, 2015e, 2015f, 2015g), job descriptions (found on Volandis, 2018), interviews with companies and experts, and the assessment of the author. The categorization of professions and measures is shown in table 3. It should be noted that this categorization is an indication and not an absolute description of skills from professionals.

The installation sector consists of mechanical and electrotechnical installers, and HVAC technicians. Mechanical installers have the skills to install indoor climate installations such as ventilation or heat pumps as well as connecting houses to a heat district. Their activities overlap with the HVAC technicians, who perform more specialized tasks regarding the installations for indoor climate control. Electrotechnical installers work with various electrical installations and connections in households or the electricity grid. Many professionals could potentially install PV-panels, although only electrotechnical installers are able to install PV-panels fully operational.

TABLE 3 OVERVIEW OF MEASURES AND THEIR RELATED PROFESSIONS

| (x1000) | Mechanical Installer | Electrotechnical Installer | HVAC technicians | Carpenter | Mason | Line installer | Pipe Layer | Road Constructors | Paviour | Roofer | Other Construction Workers |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Insulation Wall | | | | | | | | | | | |
| Insulation Roof | | | | | | | | | | | |
| Insulation Floor | | | | | | | | | | | |
| Ventilation | | | | | | | | | | | |
| PV-Panels | | | | | | | | | | | |
| Heat Pumps | | | | | | | | | | | |
| Electricity Grid Net | | | | | | | | | | | |
| Electricity Grid Cables | | | | | | | | | | | |
| Electricity Grid Street | | | | | | | | | | | |
| Heat District Connection | | | | | | | | | | | |
| Heat District Ground | | | | | | | | | | | |
| Heat District Street | | | | | | | | | | | |
| Heat District Pipes | | | | | | | | | | | |

Professions from the construction sector considered in this research are carpenters, masons, line installers, pipe layers, road constructors, paviours, roofers, and other construction workers. Carpenters are considered to have the skills to insulate floors, walls, roofs, and windows, as well as installing prefab building elements on site. Masons are capable of insulating walls when brickwork or stones are involved. Although, for this research, it is assumed they're able to insulate walls and install prefab building elements as well. Roofers are specialized workers that can insulate roofs and install prefab roof elements. The category 'other construction workers' consists of various professions, although it doesn't include professions dealing with structural or finishing activities such as bar benders and tilers (EIB, 2017). Other construction workers are assumed to be capable of insulating walls, roofs, and floors. Road constructors perform various activities associated with road works which include asphalting and digging and moving ground. Paviours pave roads with bricks, tiles, or other types of paving and can perform some digging and moving ground work. Line installers are specialized workers that lay cables in the ground. Pipe layers are workers specialized in sewage systems, drainage, and laying various sorts of pipes and tubes in the ground. It should be noted that the welding of pipes requires experienced specialists for each type of pipe or tube (Simmelink, 1996).

### 2.5.2. Definition Available and Deployable Labor

The description of activities and the professions are part of the labor, although labor can also be expressed in terms of time. A common time unit to measure work is the full time equivalent (FTE), which is defined as 1880 hours per year; when assuming work weeks of 40 hours, 5 days off-work due to national holidays, and 4 weeks of vacation (Eurostat, 2013; FNV, 2018).

For this research a differentiation is made between available and deployable labor. Available labor is equal to the total amount of FTE's of a certain profession; i.e. the number of professionals. Deployable labor is the number of professionals performing a specific activity within their sector (e.g. carpenters constructing new buildings or mechanical installers performing maintenance and repairs). All professionals are assumed to work full-time.

# Chapter 3: Methods

This chapter will explain the methods used for data collection, preparation, and the calculations. Figure 5 provides an overview of the data used in this research and how these relate to each other. The grey squares show the input data and their sources, the blue squares are the intermediary data points, and the green squares show the results of each sub-question.

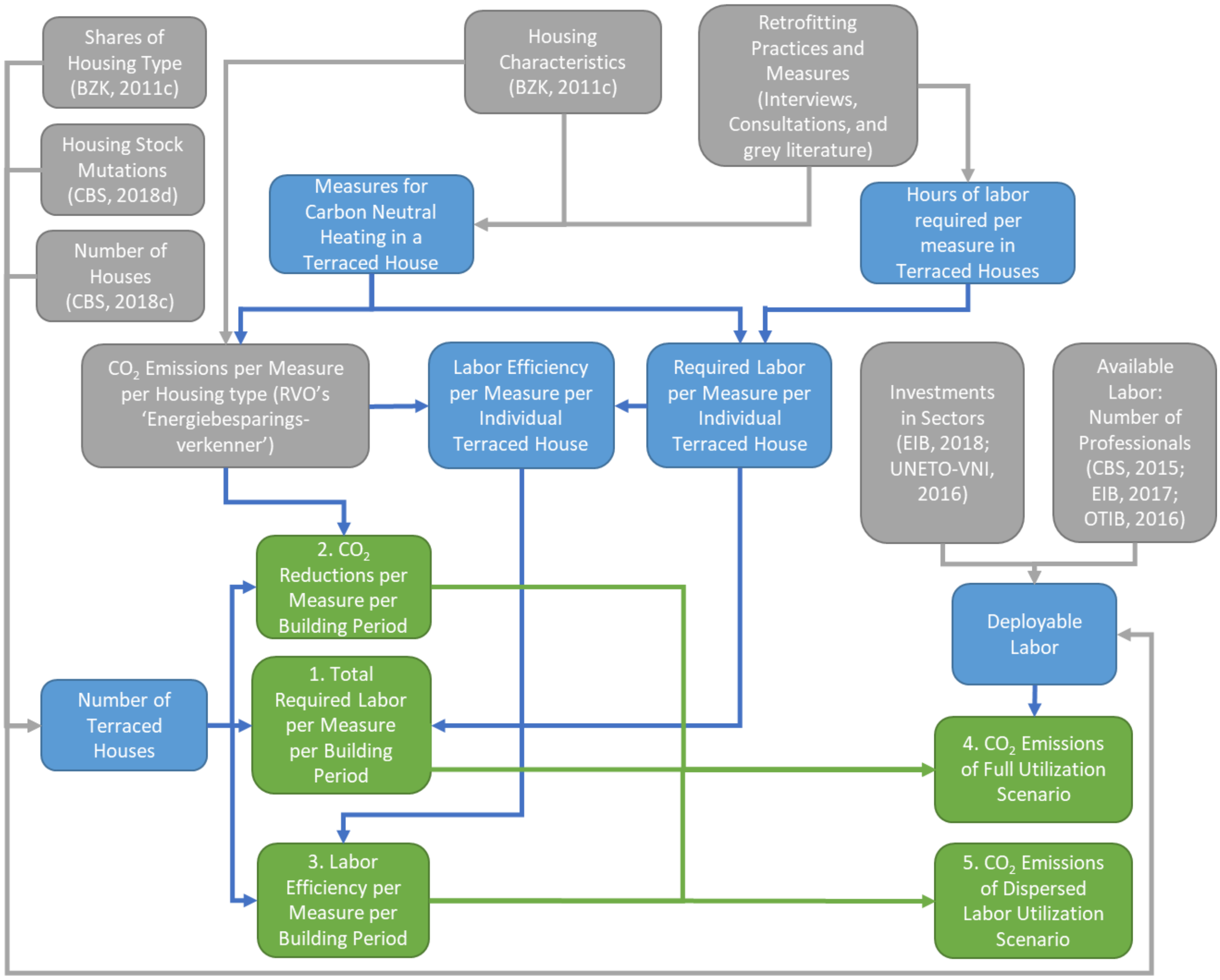


FIGURE 5 METHODOLOGY (GREY SQUARES ARE DATA INPUT, BLUE SQUARES ARE INTERMEDIARY DATA POINTS, AND THE GREEN SQUARES ARE THE RESULTS PER SUB-QUESTION)

## 3.1. Data Collection and Preparation

### 3.1.1. Housing Stock

The number of terraced houses has been determined by collecting data from the Dutch Central Bureau of Statistics (CBS) and the ministry of the Interior and Kingdom Relations (BZK). CBS does not provide data on terraced houses, it classifies the housing stock on single or multifamily dwellings and size of the living space (CBS, 2018a). The BZK classifies houses' energy index on dwelling types and the year of construction (BZK, 2011c). However, this data only includes the shares of dwelling types and not the absolute numbers. Therefore, the two datasets are combined to create a categorization of the Dutch housing sector based on the housing type and the year of construction, including the number of terraced houses from different building periods.

The BZK data was based on a study done in 2006 and currently the housing stock is almost 10% larger (CBS, 2018b). The amount of withdrawals and additions of specific housing types or year of construction is unknown, it is only known for the total housing stock (Cijfers over Wonen en Bouwen 2016; CBS 2018d). The distribution of various sizes of living space has barely changed since 2012[7] (CBS, 2018a), which is an indication that housing types have not changed considerably as there is a strong connection between the living space size and housing types (BZK, 2011a). To deal with the potential changes in the housing stock, the choice has been made to distribute the additions to housing stock (from the CBS dataset) evenly according to the share of each housing type built after 1992 (the BZK dataset). The same distribution method has been applied for the withdrawals, which were allocated to houses built before 1992.

Table 3 shows the distribution of terraced houses. Of the existing terraced houses 16% has been built before 1946, 15% has been built between 1946 and 1964, 19% of the terraced houses is from the period 1965-1974, 27% has been built between 1975, and the houses built after 1992 account for 23% of the terraced housing stock. The distribution of all housing types has been in included in Appendix A.

TABLE 4 NUMBER AND SHARES OF TERRACED HOUSES IN 2017 (ADAPTED FROM BZK, 2011B; CBS, 2018A, 2018D)

| Terraced Housing | < 1946 | 1946-1964 | 1965-1974 | 1975-1991 | 1992> | Total |
|---|---|---|---|---|---|---|
| Houses | 510,262 | 463,875 | 589,784 | 854,855 | 711,514 | 3,130,290 |
| Share | 16% | 15% | 19% | 27% | 23% | 100% |

### 3.1.2. Labor – Quantity

Data on available labor has been collected from the Central Bureau of Statistics (CBS) and two main associations that monitor and support the installation and construction sectors: the Opleidings- en ontwikkelingsfonds Technisch InstallatieBedrijf (OTIB) and the Economisch Instituur voor de Bouw (EIB) respectively. A selection was made of relevant professions for this research and is shown in table 5. The installation sector consists of HVAC technicians, and mechanical, electrotechnical, and other installers. The construction sector has been split into construction of buildings and construction of infrastructures as these require fundamentally different activities. The construction sector of buildings

[7] 2012 is the first year data regarding the living space of dwellings became available

consists of carpenters, masons, roofers, and other construction workers. The construction sector of infrastructures includes road constructors, paviours, line installers, and pipe layers.

Some considerable differences can be found in the datasets between the number of professionals as can be seen in table 5. This could partly be explained by the years in which the data was collected: the installation sector data from OTIB is from 2015, the construction data from EIB is from 2016, the CBS data is from 2015. Although, in the CBS and EIB data the sums of labor from businesses are almost identical (±300), and the variations in data might be better explained by differences in methods and categorizations. The data from the EIB also includes labor from self-employed workers and is thus considered a more complete description of available labor. Another explanation for the differences could be that the dataset from the CBS has a more detailed categorization, which is based on activities from businesses. Data of pipe layers was unavailable in the EIB and OTIB datasets and the number of line installers from the EIB dataset was considered unrealistically low (personal communication, M. Blijderveen, 15 August 2018). Therefore, data from EIB and OTIB was used for all labor except for line installers and pipe layers, for which the CBS data was used.

TABLE 5 AVAILABLE LABOR IN THE INSTALLATION, CONSTRUCTION BUILDING, AND CONSTRUCTION INFRASTRUCTURE SECTORS (CBS, 2017; EIB, 2017; OTIB, 2016) (THE USED DATA IS SHOWN IN BOLD)

| Sector | Profession | Available Labor (FTE's/year) (EIB and OTIB) | Available Labor (FTE's/Year) (CBS, 2017) |
|---|---|---|---|
| **Installation** | Mechanical Installer | **48,900** | 22,000 |
| | Electrotechnical Installer | **66,000** | 43,600 |
| | HVAC Technician | **3,900** | 20,500 |
| | Other Installers | **-** | 18,900 |
| **Construction Buildings** | Carpenter | **51,670** | 5,800 (+6,800)[8] |
| | Mason | **13,180** | 1,600 |
| | Roofer | **7,160** | 5,500 |
| | Other Construction | **35,370** | 23,300 |
| **Construction Infrastructure** | Road Constructor | **4,410** | 18,400 |
| | Paviour | **5,470** | 2,900 |
| | Line Installer | 1,800 | **12,600** |
| | Pipelayer | - | **3,000** |

[8] 5,800 are carpenters working on construction sites, 6,800 carpenters produce carpentry for the construction sector.

Not all available labor can be deployed towards the heat transition as there is competition with new construction projects and other sectors than housing. No primary source of data was found on the number of deployable employees for the heat transition. Therefore, the deployable labor was determined using the share of expected investments in the construction and installation sector for renovating houses and adapting the infrastructures. These are shown in table 6 and 7.

The investments within the construction sector is shown in table 6. The reconstruction and renovation of houses (17%) mainly competes for labor with new construction of houses and utility buildings (76%). There is less competition with external subcontracting (7%), which consists of activities done by construction companies hired by parties outside of the construction sector. Most of the investments (63%) made in the infrastructure construction sector are for constructing new infrastructures (e.g. roads, railways, tunnels). The other 37% of the investments are made for the reconstruction and renovation of infrastructures.

TABLE 6 INVESTMENTS IN THE CONSTRUCTION SECTOR IN 2017 (ADAPTED FROM EIB, 2018) (THE USED FIGURES ARE SHOWN IN BOLD)

| | | Million € | Share |
|---|---|---|---|
| **Construction Buildings** | **Housing** | | |
| | New Construction | 11,400 | 23% |
| | Reconstruction and renovation | 8,450 | **17%** |
| | **Utility** | | |
| | New Construction | 8,950 | 18% |
| | Reconstruction and renovation | 6,175 | 13% |
| | Maintenance Buildings | 10,625 | 22% |
| | External Subcontracting | 3,250 | 7% |
| | **Total** | 48,850 | 100% |
| **Construction Infrastructure** | **Infrastructure (ground, water, road)** | | |
| | New Construction | 10,625 | **63%** |
| | Reconstruction and renovation | 6,175 | **37%** |
| | **Total** | 16,800 | 100% |

The found data of investments in the installation sector were categorized in two manners: per activity and one per professional field (see Appendix C for the source data). Table 7, shows the aggregate of these categorizations. This aggregate has been made by multiplying the investment shares of each activity (e.g. new construction of housing) with the share of the investments made per profession in a specific sector (e.g. electro in housing). Most investments, for each profession, are in constructing new houses and utility buildings. Followed by the investments made in reconstructing and renovating existing houses. Only a small percentage of the total investments made for electro and climate installers is for the new construction and reconstruction of infrastructures. In the dataset used, the climate sector consists of workers who can install heating and air treatment installations the share of climate is thus linked to the profession of HVAC technician. The plumbing sector consists of professionals able to install gas and water pipes as well as heating and mechanical installations (UNETO-VNI, 2016) and is therefore linked to the profession of mechanical installer.

TABLE 7 SHARES OF INVESTMENTS IN THE INSTALLATION SECTOR PER PROFESSION AND ACTIVITY IN 2017 (ADAPTED FROM UNETO-VNI, 2016, SOURCE DATA ON INVESTMENTS IS FOUND IN APPENDIX C) (THE USED FIGURES ARE SHOWN IN BOLD)

| | Electro | Climate | Plumbing |
|---|---|---|---|
| **Housing** | | | |
| New Construction | 22% | 21% | 26% |
| Reconstruction and renovation | **19%** | **17%** | **22%** |
| Maintenance | 9% | 8% | 11% |
| **Utility** | | | |
| New Construction | 23% | 25% | 21% |
| Reconstruction and renovation | 12% | 13% | 11% |
| Maintenance | 10% | 11% | 9% |
| **Infrastructure** | | | |
| New Construction and Reconstruction | **3%** | **3%** | |
| Maintenance | 2% | 2% | |
| **Total** | 100% | 100% | 100% |

The deployable labor is the multiplication of the investment shares (table 6 and 7) and the available labor per profession (table 5), of which the results are shown in table 8. It is assumed that the share of the investments in the reconstruction and renovation of housing (17%) reflects the deployable share of each profession in the building construction sector for the heat transition. As heat districts still need to be constructed, it is assumed that the share of the expected investments in the new construction of infrastructure (63%) reflects the share of the available labor that is deployable for constructing heat districts. The electricity grid requires adaptations and therefore the expected share of investments for the reconstruction and renovation (37%) is assumed to reflect the deployability of the available labor for infrastructures towards adapting the electricity grid. The shares used to calculate the deployable labor of mechanical (22%), electrotechnical (19%) and HVAC technicians (17%) are taken from the shares of investments made in reconstructing and renovating houses. The expected shares of investments in the new construction and reconstruction of infrastructures (3%) reflect the deployable labor from electrotechnical installers for grid adaptations.

TABLE 8 TOTAL DEPLOYABLE LABOR FROM THE CONSTRUCTION AND INSTALLATION SECTOR FOR HOUSE RETROFITTING AND INFRASTRUCTURAL CONSTRUCTION AND ADAPTATION IN 2017

| Sector | Profession | Deployable Labor (FTE's/year) |
|---|---|---|
| **Installation** | Mechanical Installer | 10,758 |
| | Electrotechnical Installer (housing) | 12,540 |
| | Electrotechnical Installer (Electricity Grid) | 1,980 |
| | HVAC technician | 663 |
| **Construction Buildings** | Carpenter | 8,938 |
| | Mason | 2,280 |
| | Roofer | 1,239 |
| | Other Construction | 6,118 |
| **Construction Electricity Grid** | Road Constructor | 1,632 |
| | Paviour | 2,024 |
| | Line installer | 4,662 |
| **Construction Heat District** | Road Constructor | 2,778 |
| | Paviour | 3,446 |
| | Pipelayer | 1,890 |

Besides labor competition between sectors there is competition between housing types. The deployable labor shown in table 8 would be the total labor deployable towards the transition of the entire housing stock. To address the competition between housing it is assumed that the total deployable labor will be evenly distributed among the shares of each housing type. Terraced houses constitute 41% of the total housing stock (see Appendix A) and thus it is assumed that 41% of the total deployable labor is deployable towards retrofitting terraced houses, which is shown in table 9.

TABLE 9 DEPLOYABLE LABOR FOR TERRACED HOUSES FROM THE CONSTRUCTION AND INSTALLATION SECTOR FOR HOUSE RETROFITTING AND INFRASTRUCTURAL CONSTRUCTION AND ADAPTATION IN 2017

| Sector | Profession | Deployable Labor (FTE's/year) |
|---|---|---|
| **Installation** | Mechanical Installer | 4,303 |
| | Electrotechnical Installer (housing) | 5,016 |
| | Electrotechnical Installer (Electricity Grid) | 792 |
| | HVAC technician | 256 |
| **Construction Buildings** | Carpenter | 3,575 |
| | Mason | 912 |
| | Roofer | 495 |
| | Other Construction | 2447 |
| **Construction Electricity Grid** | Road Constructor | 1,865 |
| | Paviour | 810 |
| | Line installer | 653 |
| **Construction Heat District** | Road Constructor | 1,111 |
| | Paviour | 1,378 |
| | Pipelayer | 756 |

### 3.1.3. Required Labor

#### 3.1.3.1. Data Collection

The required labor and the activities for retrofitting measures suitable for terraced houses were determined by consulting companies experienced in renovating existing terraced houses. Of the 68 companies and 6 other organizations that were contacted, 15 responded. The companies contacted ranged from specialized one-man businesses to large companies with more than 2000 employees. Information regarding infrastructures was mostly gathered from databases[9] and consultation of Liander and Liandon employees.

First contact with companies and organizations was made via mail and in some cases by phone. With no response within one or two weeks a reminder message was sent, or a call was made. If case of no response after the reminder, companies were called. Companies were initially asked for average figures on the labor required for specific activities or projects. In some cases, to make the requested information more tangible, companies were provided an example case based on the 'Voorbeeldwoningen' (BZK , 2011). Reasons stated by companies to not give information were: too busy to provide the requested information, the information was considered too sensitive, or no sensible statement of the average hours can be given as each project is unique. The collected figures of various retrofitting measures were averaged and are shown in table 10.

Except for the labor required for floors with a crawl space lower than 30cm and the construction of a heat district, all measures had two or more different sources of data. As no manufacturer of prefab-building shells responded, the labor to produce these is not included in this research. The collected figures of the required labor per measure were expressed in various ways (e.g. hours per project, hours per total surface area, hours per installation) and needed to be converted to a uniform measure. The labor for insulation measures and PV-panels are expressed in hours per $m^2$. Labor for heat pumps, ventilation, grid adaptations, and heat district connections are expressed in hours per house.

Insulation measures that were provided in hours per house were converted to hours per $m^2$ based on the surface area of the facades or the roofs. The surface areas were provided by the respondents except for one case of the prefab facade elements, of which the surface areas were approximated using the measuring tool in Google Earth. As most data of insulation measurs was based on cases of terraced houses, these cannot be assumed to be representative for other housing types.

---

[9] Within the SAP-ERP matrix the subsequent calculations were consulted in which actual hours and costs are reported.

Figures of PV-panels given in hours per panel were converted to hours per $m^2$ based on either information provided by the respondents or an assumed size of $2m^2$ per panel. All figures of heat pumps, ventilation and heat district connections were provided in hours per installation. Data on PV-panels, heat pumps, ventilation excluding new airshafts, and heat district connections are likely to be similar for other housing types as these are not influenced by unique characteristics of terraced houses, but more by the existing installations in houses. The data on ventilation measures which includes air-shafts are less likely to be representative for other housing types as the installation of air-shafts depends on the physical structure of houses to some extent.

TABLE 10 NUMBER OF SOURCES, STANDARD DEVIATION AND THE AVERAGE REQUIRED LABOR PER RETROFITTING MEASURE AND INFRASTRUCTURAL ADAPTATION MEASURES

| $h/m^2$ | N | σ | Average |
|---|---|---|---|
| **Insulation Wall (Wall Cavity)** | 4 | 0.01 | 0.13[10] |
| **Insulation Floor (>50cm)** | 8 | 0.08 | 0.18 |
| **Insulation Floor (<30cm)** | 1 | - | 0.06 |
| **Insulation Roof (Finished)** | 2 | 0.18 | 0.67 |
| **Insulation Roof (Unfinished)** | 2 | 0.09 | 0.20 |
| **Insulation Roof (Roofplates)** | 4 | 0.11 | 0.71 |
| **Insulation Glass** | 6 | 0.23 | 1.15 |
| **Insulation Wall (Prefab Facade Element)** | 2 | 0.31 | 0.45 |
| **PV-Panels** | 7 | 0.12 | 0.41 |
| h/house | | | |
| **Ventilation (including airshafts)** | 2 | 0.00 | 16.00 |
| **Ventilation (excluding airshafts)** | 3 | 2.31 | 6.00 |
| **Heat Pump (water-air)** | 2 | 11.31 | 22.00 |
| **Heat Pump (water-ground)** | 2 | 22.63 | 40.00 |
| **Heat District Connection[11]** | 1 | - | 5.00 |
| **Heat District Streetwork[11]** | 1 | - | 10.80 |
| **Heat District Groundwork[11]** | 1 | - | 14.80 |
| **Heat District Pipeline[11]** | 1 | - | 18.70 |
| **Electricity Grid Streetwork** | 7 | 2.02 | 3.11 |
| **Electricity Grid Cable** | 7 | 2.23 | 4.29 |
| **Electricity Grid Net** | 7 | 1.63 | 2.1 |

The labor required for the grid adaptations was collected from 7 NOM-neighborhood[12] projects, ranging from 14 to 131 terraced houses (personal communication, L. Schenkel, June 19, 2018). These NOM-houses were equipped with air-water heat pumps and 6kW of PV-panels. This data consisted of hours and costs made per activity for the total project. Three main activities of relevant labor for this research were identified, laying cables, ground and street work, and adaptations to the voltage spaces and connections. Alliander employees reported their hours directly and could be used without any

[10] $0.13h/m^2$ is expressed as a fraction of 1 whole hour, 0.13 would thus be equal to 0.13 x 60 minutes ≈ 8 minutes.

[11] This data was provided as average values, therefore no deviation from the average value could be provided.

[12] NOM is the common term used in the Netherlands and can be translated to Net Zero Energy Buildings.

further data preparation. Hours from contractors were calculated by dividing the total costs of specific activities divided by the average tariffs per hour for those activities (personal communication, E. ten Hoeve, July 31, 2018). The total amount of hours per activity in a project was divided by the number of houses that were part of the project to identify the hours per house.

Figures on the average labor hours needed per heat district connection were provided from an in-house expert on heat districts (personal communication, R. Bremer, 25 June, 2018). This labor is the labor for high temperature heat districts. Low temperature heat districts (40 to 50$^{o}$C), might require 10 to 20% more labor due to the greater circumference of the pipes. Although, the labor is more significantly determined by the specific situation and the environment in which it is constructed (personal communication, R. Bremer, 30 August, 2018).

#### 3.1.3.2. Calculations

The collected figures on the labor requirements per measure presented in table 10 will be used to determine the required labor per terraced house. Measures given in hours/m$^2$ will be multiplied by the specific surface areas to be insulated (see table 13) or installed in case of PV-panels to determine the required hours per terraced house from a specific building period. Expressed in formula this is:

*Required Labor per Measure per Individual Terraced House of Building Period*$_X$ *= Specific Surface Area of Terraced House of Building Period*$_X$ x *Required Labor of a Measure per m*$^2$

### 3.1.4 Determining Measures

There is a high variety in insulation measures to be taken, but not all are suitable for the design of a carbon neutral house. Insulating cavity walls are limited in their levels of insulation and an extra outer building shell is necessary to attain high insulation levels for significant energy reductions for all terraced houses (RVO, 2018d). An outer prefab element is placed around a house, which includes the windows. As windows are not limited by existing frames, triple glass windows are assumed to be part of the building element. Thus, the labor considered for wall and window insulation is the labor needed to install a prefab building element.

Floors from houses built before 1946's are assumed to be insulated with loose insulant material, such as polystyrene pearls, as this is the only viable option to insulate crawl spaces below <30cm. The insulation levels of this measure are limited, and higher R-values could be attained by insulating the top of the floors. However, this would require the removal of the floor which is assumed to be an unfavorable option for these older houses. Terraced houses from other building periods can attain high R-levels most easily and for the lowest costs by insulating their crawl spaces with PUR-foam.

There are little to no restrictions in types and materials of roof insulation. Plate insulation can have high R-values, is relatively easy to be installed, and is considered aesthetically the most pleasing material. Therefore, it is assumed that for all houses roof plate insulation was used in retrofitting.

Besides, insulation measures there are installations to be installed in the houses: PV-panels, heat pumps, heat district connections, and ventilation systems. It is assumed that PV-panels can be installed on all houses. The size of the PV-panels was determined by the electricity demand of the heat pump (described in section 3.1.6.). There are different types of heat pumps that can be installed. For this research air-water heat pumps are considered, as this is the most applicable type. Installation of heat pumps or heat district connections do not differ per house and can be connected to the existing heating system.

### 3.1.5. Determining $CO_2$ Emissions

#### 3.1.5.1. Modelling Individual Houses

The emissions of retrofitted houses were modelled with the public tool 'Energiebesparingsverkenner – Reguliere Verkenner' from the Dutch government agency for entrepreneurship (RVO). This model is designed to illustrate the effects on energy use, emissions, and costs of various retrofitting measures in Dutch houses. It is created to be used by professionals to gain insights in multiple scenarios for comparison. Average values regarding the energy use patterns, installations, and levels of insulation in Dutch households are used to determine the energy performance of houses[13] (RVO, 2018d). Therefore, this model is considered as an accurate description of Dutch houses and is used in this research to determine the change of $CO_2$ emissions in the provision of heat to terraced houses of the retrofitting measures considered.

#### 3.1.5.2. Parameters to Calculate $CO_2$ Emissions

The parameters in the model that determine the emission factors are the carbon emission factors, PV-panel characteristics, efficiency of heating installations, and inside temperature. These have been supplied by the RVO at request (RVO, 2018d).

The carbon emission factors used in the RVO model are shown in table 11, which were taken from ISSO 82 (Personal communication, RVO, June 11, 2018). As green gas and carbon free heat from heat districts were not an option in the model, natural gas was modelled, and its emissions were later subtracted to reflect carbon neutrality.

**TABLE 11 CARBON EMISSION FACTORS OF NATURAL GAS, DISTRICT HEATING, ELECTRICITY, AND GREEN GAS (ADAPTED FROM RVO, 2018D)**

| | Conversion Factor | Unit | Conversion Factor (kgCO2/GJ) |
|---|---|---|---|
| **Natural Gas** | 1.78 | $kgCO_2/m^3$ gas | 56.24 |
| **District Heating**[14] | 50.60 | $kgCO_2/GJ$ | 50.60 |
| **Electricity** | 0.48 | $kgCO_2/kWh$ | 157.22 |

---

[13] Average values of energy use patterns, installations, and levels of insulation in Dutch households are similar to the previously mentioned 'Voorbeeldwoningen' (RVO, 2015).

[14] During modelling it was found that heat from heat districts emitted more $CO_2$ than the reference situation. After consulting with a heating district expert at Liandon (Personal communication, R. Bremer, June 22, 2018), it was found that the conversion factor for the Netherlands was more likely to be 27.0 instead of 50.6 kgCO2/GJ. This average value includes waste heat from industry and electricity plants, bio-installations, geothermal, waste incineration, and collective heat pumps with storage. Another source confirms that this value reflects heat districts in the Netherlands more accurately (Schepers & Scholten, 2016).

Within the model the electricity production of PV panels ($E_{pv}$) is calculated as follows: $E_{pv}$ = A x $P_{pv}$ x 0.89. PV-panels are assumed to be oriented towards the south at a slope of 45 degrees, resulting in a load factor of 0,89. The Watt peak power ($P_{pv}$) is 165Wp/m$^2$ and A is the surface area of the panels in m$^2$.

The other parameters determining the heat demand within the RVO model are as follows:

- COP of Air-Water heat pumps, 3,9 for heating and 1,7 for hot tap water
- Efficiency of reference gas boilers, 90-97,5%
- Inside temperature is 17,5 $^oC$
- The non-building related electricity use of average terraced households is shown in table 12.

TABLE 12 NON-BUILDING RELATED ELECTRICITY USE OF AVERAGE DUTCH TERRACED HOUSEHOLDS PER NUMBER OF RESIDENTS (ADAPTED FROM RVO, 2018D)

| Residents | 1 | 2 | 3 | 4 | 5 | 6 and more |
|---|---|---|---|---|---|---|
| kWh/year | 1,000 | 1,850 | 2,350 | 2,800 | 3,000 | 3,100 |

### 3.1.5.3. Model Input: Characteristics of a Carbon Neutral Heated House

The goal is to reduce the carbon emissions of the Dutch household sector in the provision of heat to zero. A carbon neutral house should make highly efficient use of carbon free heat to provide a comfortable living space. In other words, houses should be well insulated and natural gas as the source of heat should be replaced.

The reference houses and the physical characteristics of houses of the previously presented building periods are based on the 'voorbeeldwoningen' defined by the BZK (BZK, 2011c), of which an excerpt is included in Appendix D. The surface areas of the modelled houses are presented in table 13. Houses have four elements that can be insulated, in all scenarios the highest insulation within the model were used, which are shown in table 14.

TABLE 13 SURFACE AREAS OF HOUSES FROM DIFFERENT BUILDING PERIODS (BZK, 2011C)

| (m$^2$) | <46 | 46-46 | 65-74 | 75-92 | 92> |
|---|---|---|---|---|---|
| Closed Facade | 49 | 42.4 | 40.6 | 40.6 | 50 |
| Flat Roof | 17.7 | - | - | - | - |
| Sloped Roof | 56 | 57.2 | 65.4 | 68.6 | 56 |
| Ground Floor | 55 | 47 | 52 | 51 | 56 |
| Windows: Living Area | 11.6 | 11.8 | 14 | 10.6 | 12 |
| Windows: Bedrooms | 9.4 | 9.6 | 11.6 | 8.6 | 9.8 |
| Doors | 2.5 | 1.3 | 1.6 | 1.8 | 2.3 |

TABLE 14 MODELLED INSULATION TYPES AND THE R-VALUES (RVO, 2018D)

| Insulation Type | R-value ($m^2K/W$) |
|---|---|
| **Wall** | 4.00 |
| **Windows** | 0.83 |
| **Roof** | 4.00 |
| **Floor** | 3.50 |

As mentioned before, a mechanical ventilation system is required in well-insulated houses. To keep heat loss to a minimum a balanced ventilation system that recovers heat was used in the model. In each modelled house a 3-person household was assumed. A change of heating systems within a house were left out of consideration for this research. The common heating system in Dutch houses are hot water radiators (BZK, 2011b).

Within each scenario of the three scenarios, measures will be modelled separately and in all possible combinations with each other. The measures in each scenario are as follows:

- Green Gas, requires no change of heating installation of houses; all reference houses have a high efficiency boiler. Only insulation and ventilation measures were modelled.
- Electrification, requires a different heating installation for which air-water heat pump was selected. Insulated houses require a heat pump of roughly 3kW to cover their heat demand. If houses are not insulated, it is assumed that higher capacity heat pumps (6kW) are installed to cover the entire heat demand of households. In all combinations of measures where PV-panels are installed, 20$m^2$ of PV-panels were modelled which covers the increase in the electricity demand (~3kW) due to the heat pump after insulation. Together insulation, ventilation, air-water heat pumps, and PV-panels form the electrification measure that was modelled.
- District Heating, houses have a heat district connection as a heating installation. In this model insulation, ventilation, and a heat district connection were used.

## 3.2. Modelling Scenarios

### 3.2.1. Determining $CO_2$ Emission Reduction

The output of the 'Energiebesparingsverkenner' provides the data of emissions of individual houses retrofitted with a specific set of measures in $kgCO_2$/year. This data was extrapolated to the entire housing sector for each measure taken in a house from a specific building period, expressed in $ktonneCO_2$/year. This is done by multiplying the results of the measures taken in individual houses with the total number of houses of that building period (see table 3 from in chapter 3.1.1.).

### 3.2.2. Determining Required Labor

In each scenario the amount of labor that is required differs as houses from different building periods have different surface areas and houses built before 1946 have smaller crawl spaces. Houses built before 1992 commonly have no mechanical ventilation system in place and thus require airshafts to be constructed increasing the required labor. There are three carbon neutral sources of heat, each with their sets of measures which are shown in table 15.

TABLE 15 MEASURES PER SCENARIO

| Scenario | Measures |
|---|---|
| **Green Gas, Electrification, District Heating, and Mixed Source** | Insulation Wall Prefab |
| | Insulation Roof Prefab |
| | Insulation Floor |
| | Ventilation |
| **Electrification and Mixed Source** | PV-Panels |
| | Heat Pump (air-water) |
| | Electricity Grid Street |
| | Electricity Grid Cables |
| | Electricity Grid Net |
| **District Heating and Mixed Source** | Heat District Connection |
| | Heat District Ground |
| | Heat District Street |
| | Heat District Pipes |

To gain the total required labor per house for that scenario the required labor expressed in hours per house of each measure within a scenario are summed. For the green gas, electrification, and heat district scenarios it is assumed that the entire terraced housing stock will be retrofitted with the required measures of each scenario (see table 15).

A mixed source scenario is also constructed where it is assumed that each carbon neutral source of heat has an equal share in terraced houses; i.e. green gas, electrification, and heat districts each account for one-third of the total retrofitted houses. Insulation measures are taken in all houses. All measures and types of labor presented in table 15 are required in this scenario.

To calculate the total required FTE's per measure, the labor requirements per terraced house from a specific building period are multiplied by the total number of houses of that building period and divided by the total hours of a full-time job (1880hours/year). Expressed in formula:

*Required Labor per Measure for Terraced Houses from Building Period*$_X$ *= Required Labor per Measure per House from Building Period*$_X$ / *Hours per FTE* x *Number of Terraced Houses from Building Period*$_X$

The FTE's of each measure per housing type are then summed to calculate the total required FTE's per measure in a specific scenario for the entire terraced housing stock.

### 3.2.3. Determining Labor Utilization

To address the competition within professions by the different measures, the shortage of labor was allocated to each measure to determine the actual deployable labor per measure per year. The shortage of labor is evenly distributed over the measures according to the share of the total required labor of each measure. This was done by subtracting the total sum of required labor of the activities to be shared in a group of professions from the total sum of deployable labor that was to be shared between professions. For example, roof insulation requires 52% of the deployable labor of carpenters and other construction workers and thus 52% of the shortage is subtracted of the deployable labor for that measure. In formula form the distributed labor per measure is calculated as follows:

*Allocated Deployable Labor =* ((*Shared Deployable Labor - Total Labor Required)* x *Share of the Total Required Labor)* + *The Required Labor* + *Unique Deployable Labor*

### 3.2.4. Full Utilization Scenarios

Scenarios will be made for the complete set of measures (see table 15) for the three carbon neutral heat sources: green gas, electrification, and district heating as well as mixed source scenario in which each source has an equal share (one-third). In each scenario houses the measures towards a carbon neutral heat source will be complemented by insulation measures and a balanced ventilation system.

Within the full utilization scenarios, the deployable labor was used as a driver of emissions reductions; i.e. all deployable labor is fully utilized to install measures in terraced houses. The years it takes to install a measure completely is calculated by dividing the required labor per measure for the terraced housing stock divided by the deployable labor per measure. The measure that takes the most years to take with all terraced houses is taken as the end-point of the transition. It is assumed that all measures will be implemented at the same rate of that measure. In other words, the most labor-intensive measure sets the pace of the transition; i.e. the number of retrofitted houses per year.

The development of the annual emissions of the total terraced housing stock are calculated by the share of the total housing stock that is retrofitted in each specific year. It is assumed that an average mix of terraced houses are retrofitted each year, thus no preference is given to houses of a specific building period. The cumulative emissions are calculated by summing the emissions of each year between 2018 and 2050.

### 3.2.5. Dispersed Utilization Scenarios Based on Measures

The dispersed utilization scenarios aim to illustrate the effects of different pathways of implementing measures towards carbon neutral heating. The pathways are based on taking single retrofitting measures at a time, each measure needs to be fully installed before the next measure can be taken. This results in ten different pathways which are as follows:

1. PV-panels – Heat Pumps – Insulation
2. PV-panels – Insulation - Heat Pumps
3. Heat Pumps – PV-panels – Insulation
4. Heat Pumps – Insulation – PV-panels
5. Insulation – PV-panels – Heat Pumps
6. Insulation – Heat Pumps – PV-panels
7. Insulation – Heat Districts
8. Heat Districts – Insulation
9. Insulation – Green Gas
10. Green Gas – Insulation

These pathways are aimed to illustrate the effects of different utilizations of labor and might be unfavorable or unfeasible when applied. For example, installing heat pumps before insulation is a highly unrealistic case as this would result in over dimensioned heat pumps making it an economical unfavorable pathway. Furthermore, despite that insulation for high temperature heat districts is unnecessary, a lower heat demand is still assumed to be desirable and thus no distinction is made between high or low temperature heat districts.

Implementing green gas does not require labor within the scope of this research and therefore the years for implementation cannot be determined. In scenario 9, green gas will be implemented after implementation of insulation measures towards 2050. In scenario 10 green gas is implemented before insulation measures are being implemented that are completed by 2050.

### 3.2.6. Dispersed Utilization Scenarios based on Building Age

Labor could also be utilized dispersedly across houses of a certain building period. Two pathways were constructed for the green gas, electrification, heat districts, and the mixed source scenarios: 1) focusing on the oldest buildings first and 2) focusing on the newest buildings first. The results of the full labor utilization provides the years it would take to fully implement a measure in a specific house. The measure that required the most years was taken as the required years to install the full set of measures of a heat source in all houses of a specific building period. Each housing type needs to be completely retrofitted before the next group of terraced houses from a specific building period can be retrofitted.

# Chapter 4: Results

## 4.1. Required Labor

Table 16 shows the hours of labor required per measure per building period of individual houses. There are slight differences in the labor required for insulation measures per house, which are mainly explained by the variation in the surface areas of houses from different building periods. An exception is the floor insulation for houses built before 1946, which require less labor because the average crawl space is lower than the others. The installation of ventilation systems in houses built before 1992 require more labor as these typically require airshafts to be constructed. The rest of all installation measures are identical between all houses. As green gas requires no labor except for the insulation and ventilation measures it is the least labor-intensive carbon neutral heat source. Electrification requires roughly 40 hours more and heat districts roughly 50 hours more than the green gas measures in all cases. These hours can be allocated to the measures required for carbon neutral heat.

TABLE 16 REQUIRED LABOR PER MEASURE FOR INDIVIDUAL HOUSES (*THE MEASURES TAKEN IN THE GREEN GAS SCENARIO ARE IDENTICAL TO THE SUM OF THE INSULATION AND VENTILATION MEASURES)

| (h/house) | <46 | 46-64 | 65-74 | 75-92 | 92> |
|---|---|---|---|---|---|
| Insulation Wall Prefab | 32.5 | 29.1 | 30.3 | 27.6 | 33.2 |
| Insulation Roof Prefab | 40.9 | 38.1 | 43.6 | 45.7 | 37.3 |
| Insulation Floor | 3.3 | 8.6 | 9.5 | 9.3 | 10.2 |
| Ventilation | 16.0 | 16.0 | 16.0 | 16.0 | 4.0 |
| PV-Panels | 8.2 | | | | |
| Heat Pump (air-water) | 22.0 | | | | |
| Electricity Grid Street | 3.1 | | | | |
| Electricity Grid Cables | 4.3 | | | | |
| Electricity Grid Net | 2.1 | | | | |
| Heat District Connection | 5.0 | | | | |
| Heat District Ground | 14.8 | | | | |
| **Heat District Street** | 10.8 | | | | |
| **Heat District Pipes** | 18.7 | | | | |
| **Total Green Gas*** | 92.6 | 91.9 | 99.4 | 98.6 | 84.7 |
| **Total Electrification** | 132.3 | 131.5 | 139.1 | 138.3 | 124.4 |
| **Total Heat District** | 141.9 | 141.2 | 148.7 | 147.9 | 134.0 |

The labor required for the total housing stock per measure is shown in table 17. The greatest amount of labor for each measure is required for houses of the period 75-92 and uncoincidentally, houses from this type are also the most numerous (see table 4 in section 3.1.1). The amount of labor for each of a specific building period is a direct result from the share it has in the total housing stock. The exceptions being floor insulation for houses built before 1946 and ventilation measures for houses built after 92, which require less labor than would be expected from their numbers.

TABLE 17 TOTAL REQUIRED FTE'S PER MEASURE PER BUILDING PERIOD

| (FTE's) | <46 | 46-64 | 65-74 | 75-92 | 92> | Total |
|---|---|---|---|---|---|---|
| Insulation Wall Prefab | 8,808 | 7,190 | 9,521 | 12,538 | 12,553 | 50,610 |
| Insulation Roof Prefab | 11,094 | 9,409 | 13,678 | 20,795 | 14,129 | 69,105 |
| Insulation Floor | 896 | 2,116 | 2,977 | 4,232 | 3,868 | 14,089 |
| Ventilation | 4,343 | 3,948 | 5,019 | 7,275 | 1,514 | 22,099 |
| PV-Panels | 2,220 | 2,019 | 2,567 | 3,720 | 3,096 | 13,622 |
| Heat Pump (air-water) | 5,971 | 5,428 | 6,902 | 10,004 | 8,326 | 36,631 |
| Electricity Grid Net | 571 | 519 | 659 | 956 | 796 | 3,500 |
| Electricity Grid Cables | 1,164 | 1,058 | 1,345 | 1,949 | 1,623 | 7,138 |
| Electricity Grid Street | 845 | 768 | 977 | 1,416 | 1,178 | 5,184 |
| Heat District Connection | 1,357 | 1,234 | 1,569 | 2,274 | 1,892 | 8,325 |
| Heat District Ground | 4,017 | 3,652 | 4,643 | 6,730 | 5,601 | 24,643 |
| **Heat District Street** | 2,931 | 2,665 | 3,388 | 4,911 | 4,087 | 17,983 |
| **Heat District Pipes** | 5,075 | 4,614 | 5,866 | 8,503 | 7,077 | 31,136 |

The aggregate of the required labor per measure that can be taken within the three scenarios is presented in table 18. Insulation is the summation of wall, floor, and roof insulation, and ventilation measures. Within the electrification scenario there are six combinations possible of the three measures that can be taken[15]. Green gas and heat district connection can be taken as single measures or combined with insulation.

The greatest amount of labor in the transition of terraced houses is needed for the insulation measure. Insulation requires 155,904 FTE's, consisting of 133,804 FTE's from the construction sector for insulating and an additional 22,099 FTE's from the installation sector for the required ventilation measures in highly insulated houses. No labor was needed for the implementation of green gas and therefore, the required labor for green gas and insulation is equal to that of the insulation measure.

[15] As stated in the methods, it is assumed that when either heat pumps or PV-panels are installed the grid will be reinforced.

Electrification of the heating system of all terraced houses will require labor from the installation sector to install PV-panels (13,622 FTE's) and heat pumps (36,631 FTE's). The electricity grid will need to be reinforced requiring a total of 15,823 FTE's from a mix of professions from the installation and construction sector. Thus, a total of 66,075 of FTE's is needed for the electrification of all terraced houses in the Netherlands. Electrification and insulation together would require 221,979 FTE's.

Heat districts require 8,325 FTE's from the installation sector to connect houses to a heat district and 73,762 FTE's for constructing the heat districts from multiple professions working in the construction and installation sector. Heat districts are the most labor-intensive option for carbon neutral heat in terraced houses as it requires 82,087 FTE's. It was assumed that all heat districts need to be constructed while 9% of all houses in the Netherlands already have a heat district connection (Menkveld, 2009). Assuming all terraced houses would have access to the existing heat districts, the labor required would be 9% less. Thus, the lowest amount of required labor for heat districts for terraced houses is 74,699 FTE's. Further calculations will be done with the higher value of the labor required for heat districts which results in a total labor requirement of 237,991 FTE's for district heating in terraced houses.

TABLE 18 TOTAL REQUIRED FTE'S PER SET OF MEASURES PER BUILDING PERIOD

| (FTE's) | **<46** | **46-64** | **65-74** | **75-91** | **92>** | **Total** |
|---|---|---|---|---|---|---|
| **Insulation** | 25,140 | 22,663 | 31,195 | 44,841 | 32,064 | 155,904 |
| **Green Gas: Green gas and Insulation** | 25,140 | 22,663 | 31,195 | 44,841 | 32,064 | 155,904 |
| **Green Gas: Green gas** | - | - | - | - | - | - |
| **Electrification: PV-Heat Pump** | 10,771 | 9,792 | 12,449 | 18,045 | 15,019 | 66,075 |
| **Electrification: PV** | 4,800 | 4,363 | 5,548 | 8,041 | 6,693 | 29,444 |
| **Electrification: Heat Pump** | 8,550 | 7,773 | 9,883 | 14,325 | 11,923 | 52,454 |
| **Electrification: Insulation-Heat Pump** | 33,690 | 30,437 | 41,078 | 59,165 | 43,987 | 208,358 |
| **Electrification: Insulation-PV** | 29,940 | 27,027 | 36,743 | 52,882 | 38,757 | 185,348 |
| **Electrification: Insulation-PV-Heat Pump** | 35,911 | 32,455 | 43,645 | 62,885 | 47,083 | 221,979 |
| **Heat District: Connection** | 13,381 | 12,164 | 15,466 | 22,417 | 18,658 | 82,087 |
| **Heat District: Connection and Insulation** | 38,521 | 34,828 | 46,661 | 67,258 | 50,723 | 237,991 |

## 4.2. Potential $CO_2$ Reductions

In table 19 the reductions of the annual emissions due to gas use of individual house per measure are shown. There are only differences between measures when there is either insulation or a carbon neutral source of heat. Only insulating would reduce the annual $CO_2$ emissions of a terraced house with 11,857kg. When a carbon neutral source of heat is available to a house its annual emissions due to heat become zero, which is a reduction of 15,947kg $CO_2$ of the annual emissions of a single terraced house.

TABLE 19 POTENTIAL $CO_2$-REDUCTION OF ANNUAL EMISSIONS OF INDIVIDUAL HOUSES PER SET OF MEASURES PER BUILDING PERIOD

| (kg CO2/year) | <46 | 46-64 | 65-74 | 75-91 | 92> | Total |
|---|---|---|---|---|---|---|
| **Insulation** | 4,005 | 3,354 | 2,337 | 1,335 | 826 | 11,857 |
| **Electrification: Insulation-PV** | | | | | | |
| **Electrification: PV** | - | - | - | - | - | - |
| **Green Gas: Green gas and Insulation** | 4,893 | 4,126 | 3,126 | 2,131 | 1,671 | 15,947 |
| **Green Gas: Green gas** | | | | | | |
| **Electrification: PV-Heat Pump** | | | | | | |
| **Electrification: Heat Pump** | | | | | | |
| **Electrification: Insulation-Heat Pump** | | | | | | |
| **Electrification: Insulation-PV-Heat Pump** | | | | | | |
| **Heat District: Connection** | | | | | | |
| **Heat District: Connection and Insulation** | | | | | | |

The potential emission reduction of each measure per building period and of the total housing stock is shown in table 20. The annual emissions of the total terraced housing stock can be reduced by 6,707 ktonne $CO_2$ when insulation or insulation and PV-panels measures are installed. These two measures are identical as PV-panels do not save natural gas and thus do not reduce the emissions of heat. Carbon neutral heating is provided by the measures including green gas, PV-panels and heat pumps, or district heating. The $CO_2$ reductions of annual emissions for these measures are 9,265 ktonne for the total terraced housing stock. It should be noted that when only heat pumps are installed the electricity use rises, which currently has a higher carbon intensity than natural gas. The emissions due to electricity use with current emission levels were modeled and are included in Appendix E.

TABLE 20 TOTAL $CO_2$-REDUCTION OF ANNUAL EMISSIONS OF THE TERRACED HOUSING STOCK PER SET OF MEASURES PER BUILDING PERIOD

| (ktonne CO2/year) | <46 | 46-64 | 65-74 | 75-91 | 92> | Total |
|---|---|---|---|---|---|---|
| **Insulation** | 2,044 | 1,556 | 1,378 | 1,141 | 588 | 6,707 |
| **Electrification: Insulation-PV** | | | | | | |
| **Electrification: PV** | - | - | - | - | - | - |
| **Green Gas: Green gas and Insulation** | 2,497 | 1,914 | 1,843 | 1,821 | 1,189 | 9,265 |
| **Green Gas: Green gas** | | | | | | |
| **Electrification: PV-Heat Pump** | | | | | | |
| **Electrification: Heat Pump** | | | | | | |
| **Electrification: Insulation-Heat Pump** | | | | | | |
| **Electrification: Insulation-PV-Heat Pump** | | | | | | |
| **Heat District: Connection** | | | | | | |
| **Heat District: Connection and Insulation** | | | | | | |

## 4.3. Labor Efficiency and Potential

The efficiency of labor towards carbon reductions per measure taken in terraced houses is shown in table 21. Labor becomes less efficient in making reductions in each measure the younger the house. Considerable differences in the efficiency of labor can be seen between houses built before and those built after 1975. This can be explained by the level of insulation of the reference houses which reduces the potential for significant savings to be made with further insulation. Implementing green gas requires no adaptations to houses or infrastructures and therefore no labor can be allocated to savings; i.e. the efficiency of labor for green gas cannot be determined. Installing PV-panels on houses does not reduce the natural gas use and thus no savings were allocated to the required labor.

**Table 21 Labor Efficiency in Reducing Annual Emissions due to Heat per set of Measures of Terraced Houses per Building Period**

| (FTE/ktonne $CO_2$) | <46 | 46-64 | 65-74 | 75-91 | 92> | Total |
|---|---|---|---|---|---|---|
| **Insulation** | 12.3 | 14.6 | 22.6 | 39.3 | 54.6 | 31.6 |
| **Green Gas: Green gas and Insulation** | 10.1 | 11.8 | 16.9 | 24.6 | 27.0 | 19.4 |
| **Green Gas: Green gas** | - | - | - | - | - | - |
| **Electrification: PV-Heat Pump** | 4.3 | 5.1 | 6.8 | 9.9 | 12.6 | 8.3 |
| **Electrification: PV** | - | - | - | - | - | - |
| **Electrification: Heat Pump** | 3.4 | 4.1 | 5.4 | 7.9 | 10.0 | 6.6 |
| **Electrification: Insulation-Heat Pump** | 13.5 | 15.9 | 22.3 | 32.5 | 37.0 | 26.0 |
| **Electrification: Insulation-PV** | 14.7 | 17.4 | 26.7 | 46.3 | 66.0 | 37.6 |
| **Electrification: Insulation-PV-Heat Pump** | 14.4 | 17.0 | 23.7 | 34.5 | 39.6 | 27.7 |
| **Heat District: Connection** | 5.4 | 6.4 | 8.4 | 12.3 | 15.7 | 10.3 |
| **Heat District: Connection and Insulation** | 15.4 | 18.2 | 25.3 | 36.9 | 42.7 | 29.8 |

Figure 6 shows the merit order of the measures based on the figures presented in table 18 and 20. The least efficient use of labor towards reducing the emissions of natural gas are insulation and insulation with PV-panels. The most efficient use of labor would be to install heat pumps, although this would lead to a significant rise in electricity demand. The second most efficient use of labor is installing PV-panels and a heat pump followed by a carbon neutral heat district connection. The efficient use of labor diminishes greatly when combined with insulation. The most efficient set of measures including insulation is green gas, followed by heat pumps, and then by PV-panels and heat pumps. The most inefficient use of labor in carbon neutral heat with insulation measures is district heating.

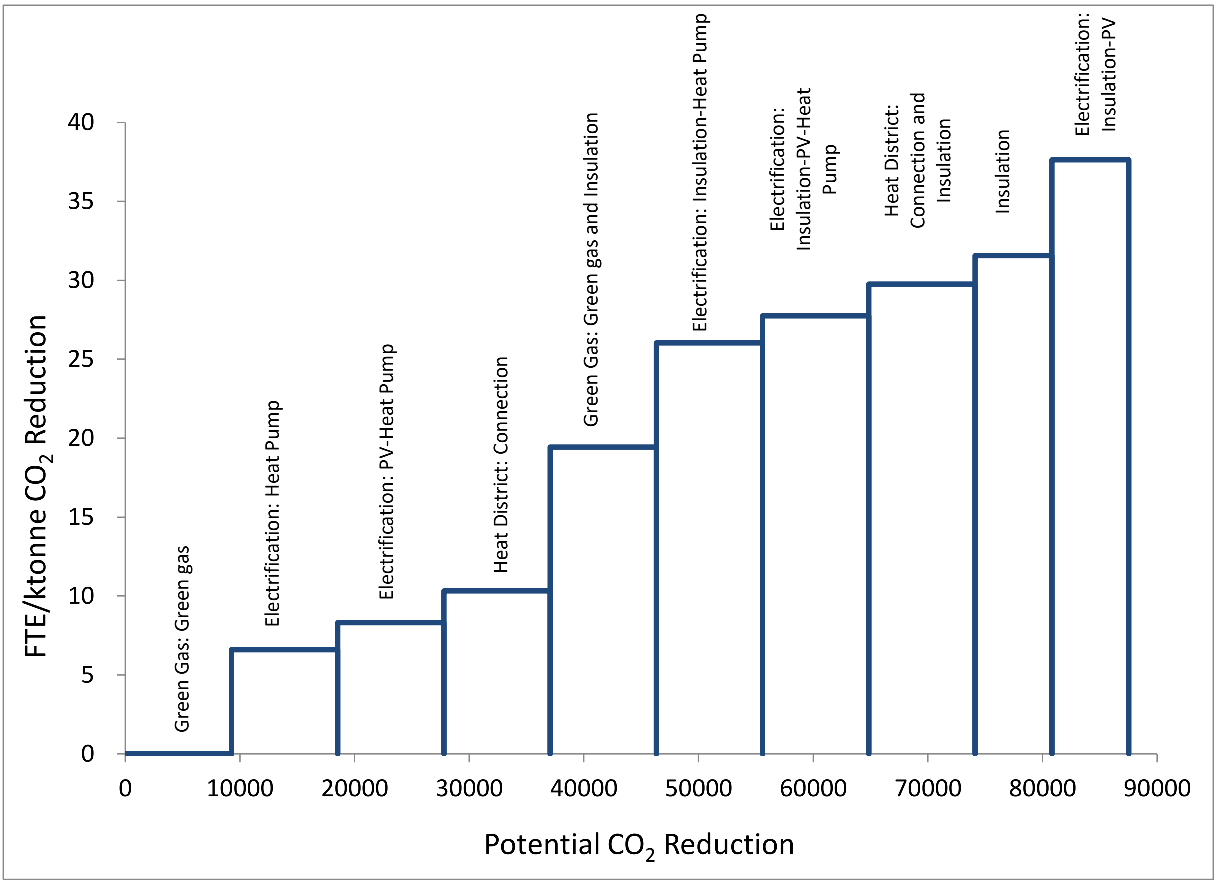


**FIGURE 6 MERIT ORDER OF THE LABOR EFFICIENCY PER SET OF MEASURES, SET OUT TO THE POTENTIAL $CO_2$-REDUCTION PER SET OF MEASURES OF THE TOTAL TERRACED HOUSING STOCK**

## 4.4. Full Utilization Scenarios

### 4.4.1. Green Gas

The required, and deployable labor of the green gas scenario per measure and per profession is shown in table 22. The total deployable labor per measure is the sum of the deployable labor of professions that are indicated with the green cells. For example, the measure 'Insulation Wall' is the sum of the deployable labor of the carpenters, masons, and the other construction workers. It can be seen that the greatest difference between the required and the yearly deployable labor, is for insulating roofs, which also is the most labor intensive measure. Wall insulation and ventilation measures also require more labor than is deployable per year. The required labor for floor insulation measures is closer to the deployable labor than the other insulation measures, suggesting that if there is no labor to be shared all floors could be insulated in a few years. To determine the years that are required for full installation of the measures, the deployable labor needs to be distributed over the measures that share labor.

**Table 22 Total Deployable Labor per Profession and Measure and the Total Required Labor per Green Gas Measure**

| (x1000) | Mechanical Installer | Carpenter | Mason | Roofer | Other Construction Workers | Total required Labor (FTE's) | Total Deployable (FTE/year) |
|---|---|---|---|---|---|---|---|
| **Deployable (FTE/year)** | 4.3 | 5.0 | 0.3 | 0.5 | 2.5 | | |
| **Insulation Wall** | | | | | | 50.6 | 6.9 |
| **Insulation Roof** | | | | | | 69.1 | 6.5 |
| **Insulation Floor** | | | | | | 14.1 | 6.0 |
| **Ventilation** | | | | | | 22.1 | 4.3 |

Table 23 shows how the shortage of labor is distributed across the measures and the years it would take to completely install each measure if the allocated deployable labor is fully utilized. The floor insulation measure is the bottleneck in insulating all building elements of houses. Floor insulation has the lowest share of allocated deployable labor compared to the required labor of the insulation measures. Approximately 22 years are required of full labor utilization to insulate the floors of all terraced houses. The least amount of labor is allocated to the floor insulation measure as it requires the least amount of labor and because it can only utilize shared labor. Ventilation would take slightly more than 5 years and can fully utilize all the deployable labor as there is no competition with other measures. To see how labor is distributed between buildings of different building periods a more detailed table is provided in Appendix F.

TABLE 23 TOTAL REQUIRED, DEPLOYABLE, AND ALLOCATED DEPLOYABLE LABOR, LABOR DISTRIBUTIONS AND REQUIRED YEARS OF MEASURES FOR THE GREEN GAS SCENARIO

| | Total required Labor (FTE) | Total Required Labor to be Shared (FTE) | Share needed of Total Shared Required Labor | Shared Deployable Labor (FTE/Year) | Unique Deployable Labor (FTE/Year) | Allocated Deployable Labor (FTE/year) | Years of full utilization required (year) |
|---|---|---|---|---|---|---|---|
| **Insulation Wall** | 50,610 | 133,805 | 38% | 6,022 | 912 | 3,190 | 15.9 |
| **Insulation Roof** | 69,105 | | 52% | 6,022 | 495 | 3,606 | 19.2 |
| **Insulation Floor** | 14,089 | | 11% | 6,022 | - | 634 | 22.2 |
| **Ventilation** | 22,099 | - | 100% | - | 4,303 | 4,303 | 5.1 |

### 4.4.2. Electrification

In table 24 the required and deployable labor per measure and the deployable labor per professional is shown. As labor for insulation and ventilation measures are identical to that in the green gas scenario these are not discussed here. The most labor of the measures towards a carbon neutral source of heat is required for installing heat pumps, for which the deployable labor is comparatively low. Deployable labor from mechanical installers for heat pumps is partly shared with the ventilation measure but can utilize HVAC technicians as well. The required labor for installing PV-panels is roughly three times higher than the total deployable labor for this measure. PV-panels can be installed by electrotechnical installers, which are also needed for the activities required for the electricity grid net measure. The required labor for the infrastructural measures is relatively low compared to the other measures as well as the relative differences between the required and deployable labor. Indicating that the greatest bottlenecks for electrification will be in the insulation measures or the installation of heat pumps which both share labor with other measures.

**Table 24 Total Deployable Labor per Profession and Measure and the Total Required per Electrification Measure**

| (x1000) | Mechanical Installer | Electrotechnical Installer | | HVAC technicians | Carpenter | Mason | Line installer | Road Construction (Electricity Grid) | Paviour (Electricity Grid) | Roofer | Other Construction Workers | Required (FTE's) | Total Deployable (FTE/year) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Deployable (FTE/year** | 4.3 | 5.0 | 0.8 | 0.3 | 3.6 | 0.9 | 0.6 | 1.9 | 0.8 | 0.5 | 2.4 | | |
| **Insulation Wall** | | | | | ■ | ■ | | | | | ■ | 50.6 | 6.9 |
| **Insulation Roof** | | | | | ■ | | | | | ■ | ■ | 69.1 | 6.5 |
| **Insulation Floor** | | | | | ■ | | | | | | ■ | 14.1 | 6.0 |
| **Ventilation** | ■ | | | | | | | | | | | 22.1 | 4.3 |
| **PV-Panels** | | ■ | | | | | | | | | | 15.0 | 5.0 |
| **Heat Pumps** | ■ | | | ■ | | | | | | | | 36.6 | 4.6 |
| **Electricity Grid Net** | | | ■ | | | | | | | | | 3.5 | 0.8 |
| **Electricity Grid Cables** | | | | | | | ■ | ■ | | | | 7.1 | 2.5 |
| **Electricity Grid Street** | | | | | | | | | ■ | | | 5.2 | 0.8 |

Table 25 shows how the required and deployable labor is distributed among measures. Identical with the green gas scenario, the floor insulation measure is the bottleneck requiring 22.2 years. Installing the ventilation systems require more time than in the green gas scenario, because the required labor is shared with installing heat pumps. The ventilation measure requires almost 13 years to complete and as heat pumps can utilize labor from HVAC technicians it can be completed in roughly 12 years. The deployable labor from electrotechnical installers for installing the PV-panels and the adaptations to the grid is sufficiently available and require 2.7 and 4.4 years of full labor utilization respectively. Despite the relative low amount of deployable labor from paviours, line installers, and road constructors compared to other professions all required work on the grid could be done in 6.4 years when assuming full utilization of the deployable labor. The activities required on the streets is the bottleneck in the infrastructural measures. A more detailed table of labor distribution between buildings of different ages is provided in Appendix F.

**TABLE 25 TOTAL REQUIRED, DEPLOYABLE, AND ALLOCATED DEPLOYABLE LABOR, LABOR DISTRIBUTIONS AND REQUIRED YEARS OF MEASURES FOR THE ELECTRIFICATION SCENARIO**

<table>
<tr><th></th><th>Total Required Labor (FTE)</th><th>Total Required Labor to be Shared (FTE)</th><th>Share Labor Required of Shared Labor</th><th>Shared Deployable Labor (FTE/Year)</th><th>Unique Deployable Labor (FTE/Year)</th><th>Allocated Deployable Labor (FTE/year)</th><th>Years Required</th></tr>
<tr><td>**Insulation Wall**</td><td>50,610</td><td rowspan="3">133,805</td><td>38%</td><td>15,056</td><td>912</td><td>3,190</td><td>15.9</td></tr>
<tr><td>**Insulation Roof**</td><td>69,105</td><td>52%</td><td>15,056</td><td>495</td><td>3,606</td><td>19.2</td></tr>
<tr><td>**Insulation Floor**</td><td>14,089</td><td>11%</td><td>15,056</td><td>-</td><td>634</td><td>22.2</td></tr>
<tr><td>**Ventilation**</td><td>22,099</td><td rowspan="2">58,730</td><td>38%</td><td>4,303</td><td></td><td>1,719</td><td>12.9</td></tr>
<tr><td>**Heat Pumps**</td><td>36,631</td><td>62%</td><td>4,303</td><td>265</td><td>3,115</td><td>11.8</td></tr>
<tr><td>**PV-panels**</td><td>13,622</td><td>-</td><td>100%</td><td>-</td><td>5,016</td><td>5,016</td><td>2.7</td></tr>
<tr><td>**Electricity Grid Net**</td><td>3,500</td><td>-</td><td>100%</td><td>-</td><td>792</td><td>792</td><td>4.4</td></tr>
<tr><td>**Electricity Grid Cable**</td><td>7,138</td><td>-</td><td>100%</td><td>-</td><td>2,517</td><td>2,517</td><td>2.8</td></tr>
<tr><td>**Electricity Grid Street**</td><td>5,184</td><td>-</td><td>100%</td><td>-</td><td>810</td><td>810</td><td>6.4</td></tr>
</table>

### 4.4.3. Heat District

Table 26 shows the required and deployable labor per measure as well as the deployable labor per profession for heat districts. The results for the insulation and ventilation measures are identical to the green gas and electrification scenarios. The greatest amount of labor for carbon neutral through heat districts is required for the infrastructural work while the least amount of labor is deployable for that end. This suggests that the greatest barrier to overcome for the implementation of heat districts is the scarcity of labor for the infrastructural work, most notably the labor from pipe layers. The labor required for the heat district connection is relatively low compared to the other measures and the deployable labor relatively high. Although, mechanical installers are needed for both the heat district connection and the ventilation measures and the ventilation measure requires considerably more labor than the heat district connection.

**TABLE 26 TOTAL DEPLOYABLE LABOR PER PROFESSION AND MEASURE AND THE TOTAL REQUIRED PER DISTRICT HEATING MEASURE**

| (x1000) | Mechanical Installer | Carpenter | Mason | Pipe Layer | Road Construction (District heating) | Paviour (District Heating) | Roofer | Other Construction Workers | Required (FTE's) | Deployable (FTE/year) |
|---|---|---|---|---|---|---|---|---|---|---|
| Deployable (FTE/year | 4.3 | 3.6 | 0.9 | 0.8 | 1.1 | 1.4 | 0.5 | 2.4 | | |
| Insulation Wall | | ■ | ■ | | | | | ■ | 50.6 | 6.9 |
| Insulation Roof | | ■ | | | | | ■ | ■ | 69.1 | 6.5 |
| Insulation Floor | | ■ | | | | | | ■ | 14.1 | 6.0 |
| Ventilation | ■ | | | | | | | | 22.1 | 4.3 |
| Heat District Connection | ■ | | | | | | | | 8.3 | 4.3 |
| Heat District Ground | | | | | ■ | | | | 24.6 | 1.1 |
| Heat District Street | | | | | | ■ | | | 18.0 | 1.4 |
| Heat District Pipes | | | | ■ | | | | | 31.1 | 0.8 |

Table 27 shows how the deployable and required labor are distributed between measures of district heating. Again, the insulation measures are identical to the green gas and electrification scenario. However, the years of full labor utilization required for the ventilation measure differs from the other two scenarios as labor from mechanical installers is to be shared with the heat district connection measure. 7.1 years of full labor utilization is required for the ventilation and heat district connection measure. The bottleneck for heat districts is the labor required for welding and laying the pipes, which require roughly 41 years of full labor utilization for all houses to be connected. The ground work needed during the construction of the heat districts approximately 22 years of full labor utilization, which is similar to the floor insulation measure. In Appendix F a more detailed distribution of labor between buildings of different ages can be found.

TABLE 27 REQUIRED, DEPLOYABLE, AND ALLOCATED DEPLOYABLE LABOR, LABOR DISTRIBUTIONS AND REQUIRED YEARS OF MEASURES FOR THE DISTRICT HEATING SCENARIO

| | Total Required Labor (FTE) | Total Required Labor to be Shared (FTE) | Share Labor Required of Shared Labor | Shared Deployable Labor (FTE/Year) | Unique Deployable Labor (FTE/Year) | Allocated Deployable Labor (FTE/year) | Years Required |
|---|---|---|---|---|---|---|---|
| **Insulation Wall** | 50,610 | 133,805 | 38% | 15,056 | 912 | 3,190 | 15.9 |
| **Insulation Roof** | 69,105 | | 52% | 15,056 | 495 | 3,606 | 19.2 |
| **Insulation Floor** | 14,089 | | 11% | 15,056 | - | 634 | 22.2 |
| **Ventilation** | 22,099 | 30,424 | 73% | 4,303 | - | 3,126 | 7.1 |
| **Heat District Connection** | 8,325 | | 27% | 4,303 | - | 1,178 | 7.1 |
| **Heat District Ground** | 24,643 | - | 100% | - | 1,111 | 1,111 | 22.2 |
| **Heat District Street** | 17,983 | - | 100% | - | 1,378 | 1,378 | 13.0 |
| **Heat District Pipes** | 31,136 | - | 100% | - | 756 | 756 | 41.2 |

#### 4.4.4. Mixed Sources

Table 28 shows the required and deployable labor per measure as well as the deployable labor per profession for the mixed sources. Each of the three carbon neutral heat sources has an equal share in the total retrofitted housing stock. The deployable and required labor for the insulation and ventilation measures is identical to each of the other scenarios. The deployable labor from each profession and for each measure is identical to the previously presented deployable labor as well. However, the required labor for the electrification and district heating measures differs. The differences between the deployable and required labor for the PV-panels and measures for the electricity grid are relatively small. The labor required for heat pumps is a few factors higher than the yearly deployable labor. In this scenario the labor from mechanical installers is shared between ventilation, heat pumps, and the heat district connection measures. The infrastructural measures for electrification and heat districts both need labor from road constructers and paviours, but these come from different sectors. Electrification requires labor from the reconstruction and renovation sector and heat districts require labor from the new construction sector (see section 3.1.2). Therefore, there is no direct competition for road constructors and paviours between electrification and heat districts measures in this scenario. Heat district require considerably more labor than is deployable for the infrastructural work.

**Table 28 Total Deployable Labor per Profession and Measure and the Total Required Labor per Measure**

| (x1000) | Mechanical Installer | Electrotechnical Installer (PV-panels) | Electrotechnical Installer (Electricity Grid Net) | HVAC technicians | Carpenter | Mason | Line installer | Road Construction (Electricity grid) | Road Construction (District Heating) | Paviour (Electricity grid) | Paviour (District Heating) | Pipe Layer | Roofer | Other Construction Workers | Required (FTE's) | Total Deployable (FTE/year) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Deployable Labor (FTE/year)** | 4.3 | 5.0 | 0.8 | 0.3 | 3.6 | 0.9 | 1.9 | 0.6 | 1.1 | 0.8 | 1.4 | 0.8 | 0.5 | 2.4 | | |
| **Insulation Wall** | | | | | | | | | | | | | | | 50.6 | 6.9 |
| **Insulation Roof** | | | | | | | | | | | | | | | 69.1 | 6.5 |
| **Insulation Floor** | | | | | | | | | | | | | | | 14.1 | 6.0 |
| **Ventilation** | | | | | | | | | | | | | | | 22.1 | 4.3 |
| **PV-Panels** | | | | | | | | | | | | | | | 4.5 | 5.0 |
| **Heat Pumps** | | | | | | | | | | | | | | | 12.2 | 4.6 |
| **Electricity Grid Net** | | | | | | | | | | | | | | | 1.2 | 0.8 |
| **Electricity Grid Cables** | | | | | | | | | | | | | | | 2.4 | 2.5 |
| **Electricity Grid Street** | | | | | | | | | | | | | | | 1.7 | 0.8 |
| **Heat District Connection** | | | | | | | | | | | | | | | 2.8 | 4.3 |
| **Heat District Ground** | | | | | | | | | | | | | | | 8.2 | 1.1 |
| **Heat District Street** | | | | | | | | | | | | | | | 6.0 | 1.4 |
| **Heat District Pipes** | | | | | | | | | | | | | | | 10.4 | 0.7 |

Table 29 shows the required and deployable labor, and the required years per measure of the mixed sources. Again, the insulation measures are identical to the others. When all three carbon neutral heat sources are installed simultaneously they compete for labor from mechanical installers (see tables 28). Most mechanical installers are needed for ventilation measures followed by heat pumps and the least number of mechanical installers are required for the heat district connection. Ventilation and heat district connection will require 8.6 years to complete. Heat pumps require slightly less time, 7.3 years, as these can utilize HVAC technicians. The PV-panels and electricity grid measures require considerable less time to be completed, the street work requires the most time, 2.1 years. The infrastructural measures for district heating requires 7.4 years for the ground work, 4.3 years for the street work, and 13.7 years for the work on the pipes. As stated before, green gas requires no extra labor within the scope of this research. The bottleneck of the mixed scenario is the floor insulation measure requiring 22.2 years to be completed, which is the same as the green gas and electrification scenario.

TABLE 29 REQUIRED, DEPLOYABLE, AND ALLOCATED DEPLOYABLE LABOR, LABOR DISTRIBUTIONS AND REQUIRED YEARS OF MEASURES FOR THE MIXED SOURCES SCENARIO

| | Total Required Labor (FTE) | Total Required Labor to be Shared (FTE) | Share Labor Required of Shared Labor | Shared Deployable Labor (FTE/Year) | Unique Deployable Labor (FTE/Year) | Allocated Deployable Labor (FTE/year) | Years Required |
|---|---|---|---|---|---|---|---|
| **Insulation Wall** | 50,610 | 133,805 | 38% | 6,022 | 912 | 3,190 | 15.9 |
| **Insulation Roof** | 69,105 | | 52% | 6,022 | 495 | 3,606 | 19.2 |
| **Insulation Floor** | 14,089 | | 11% | 6,022 | - | 634 | 22.2 |
| **Ventilation** | 22,099 | 37,085 | 60% | 4,303 | - | 2,564 | 8.6 |
| **Heat Pumps** | 12,210 | | 33% | 4,303 | 265 | 1,682 | 7.3 |
| **Heat District Connection** | 2,775 | | 7% | 4,303 | - | 322 | 8.6 |
| **PV-Panels** | 4,541 | - | 100% | - | 5,016 | 5,016 | 0.9 |
| **Electricity Grid** | 1,167 | - | 100% | - | 792 | 792 | 1.5 |
| **Electricity Grid Cables** | 2,379 | - | 100% | - | 2,517 | 2,517 | 0.9 |
| **Electricity Grid Street** | 1,728 | - | 100% | - | 810 | 810 | 2.1 |
| **Heat District Ground** | 8,214 | - | 100% | - | 1,111 | 1,111 | 7.4 |
| **Heat District Street** | 5,994 | - | 100% | - | 1,378 | 1,378 | 4.3 |
| **Heat District Pipes** | 10,379 | - | 100% | - | 756 | 756 | 13.7 |

### 4.4.4. Timeline of Possible Scenarios

This section will show the development of the annual $CO_2$ emissions of all terraced houses in the heat transition determined by the full utilization of the deployable labor. Figure 7, shows how annual emissions reduce over time in each scenario towards 100% emission reduction (absolute values given in table 20). Both the green gas, electrification, and the mixed sources measures will take 22.2 years to fully implement in all terraced houses; 100% reduction of annual emissions will be reached in 2040. Heat districts however, will not be fully implemented before 2050 as 41 years of full labor utilization is required. By 2050 the total annual emissions will be at approximately 22% of 2018 levels, which in this case means that 22% of the terraced housing stock has not been retrofitted. When considering the cumulative $CO_2$ emissions, shown in table 30, the least amount of emissions, 106,546ktonne CO2, will be when the measures for green gas, electrification, or mixed sources are installed. The heat district scenario will result in 186,428ktonne of cumulative $CO_2$ emissions and is therefore the least favorable option in terms of cumulative emissions.

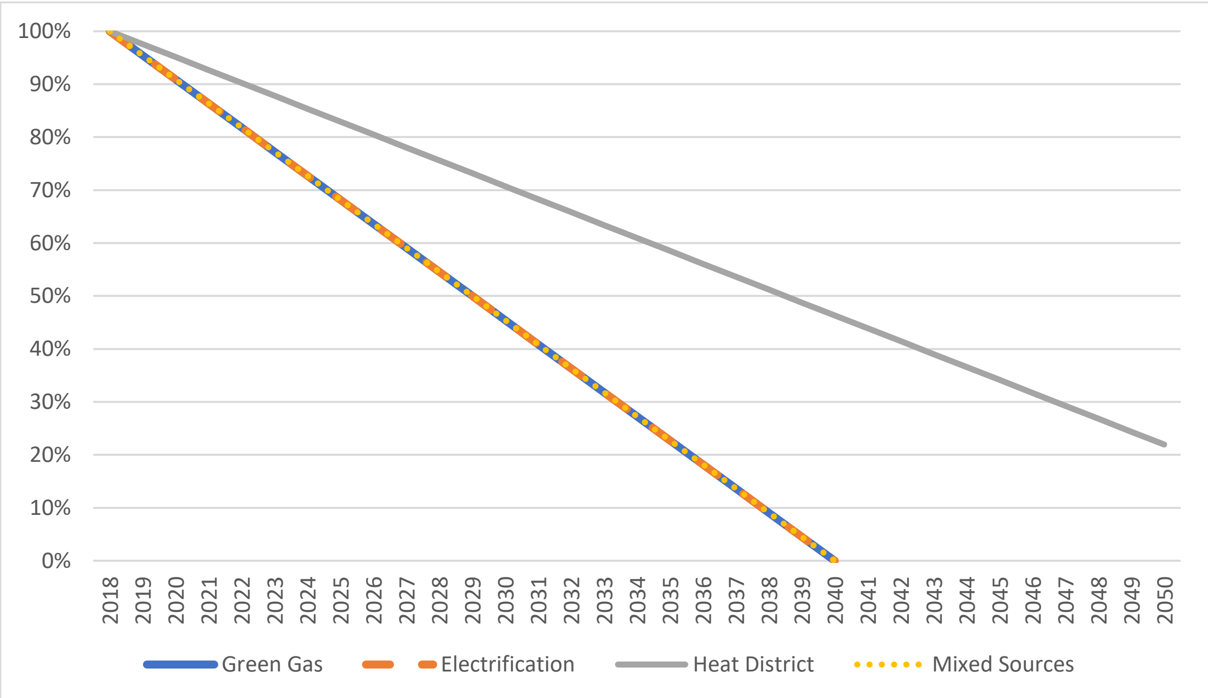


**FIGURE 7 $CO_2$ EMISSION LEVELS: FULL UTILIZATION OF LABOR**

**TABLE 30 CUMULATIVE $CO_2$ EMISSION: FULL UTILIZATION OF LABOR**

| (ktonne $CO_2$ Emissions) | **Cumulative Emissions** |
|---|---|
| **Green Gas** | 106,546 |
| **Electrification** | 106,546 |
| **Heat District** | 186,428 |
| **Mixed Sources** | 106,546 |

## 4.5. Dispersed Utilization

### 4.5.1. Dispersion based on Measures

Figure 8 shows the development of annual $CO_2$ emissions of all terraced houses when other measures than insulation are taken first. Implementing green gas is not determined by labor and the 10 years that are presented are based on the required years for insulation measures. The implementation rate of green gas would largely be determined by the availability of it and therefore an apt comparison cannot be made with the other pathways. The fastest pathway, to a natural gas free house is the implementation of heat pumps first (pathways 3 and 4). During the 12 years needed for installing heat pumps the infrastructural work will be done as well. Although, these pathways will lead to an increase in electricity use from the grid. Pathway 3 will have PV-panels installed after 3 years and is thus the fastest pathway to carbon neutral heat independently from the electricity grid. Pathway 4 will take insulation measures after the installation of heat pumps and thus remains dependent on the electricity grid for its heat. Pathways 1 and 2 install PV-panels first, which requires adaptations to the grid and thus roughly 6 years is required for these measures to be fully completed. Pathway 1 will install heat pumps in the following 12 years and is the second fastest pathway towards carbon neutral heat independent from the electricity grid. Pathway 2 will install insulation before installing heat pumps and will reach 17% of the total potential emission reduction in 2050 (see table 20 for the total potential reductions). Pathway 8, where heat districts are installed before insulation measures, will have reduced annual emissions in 2050 to 22% of the total potential emission reductions.

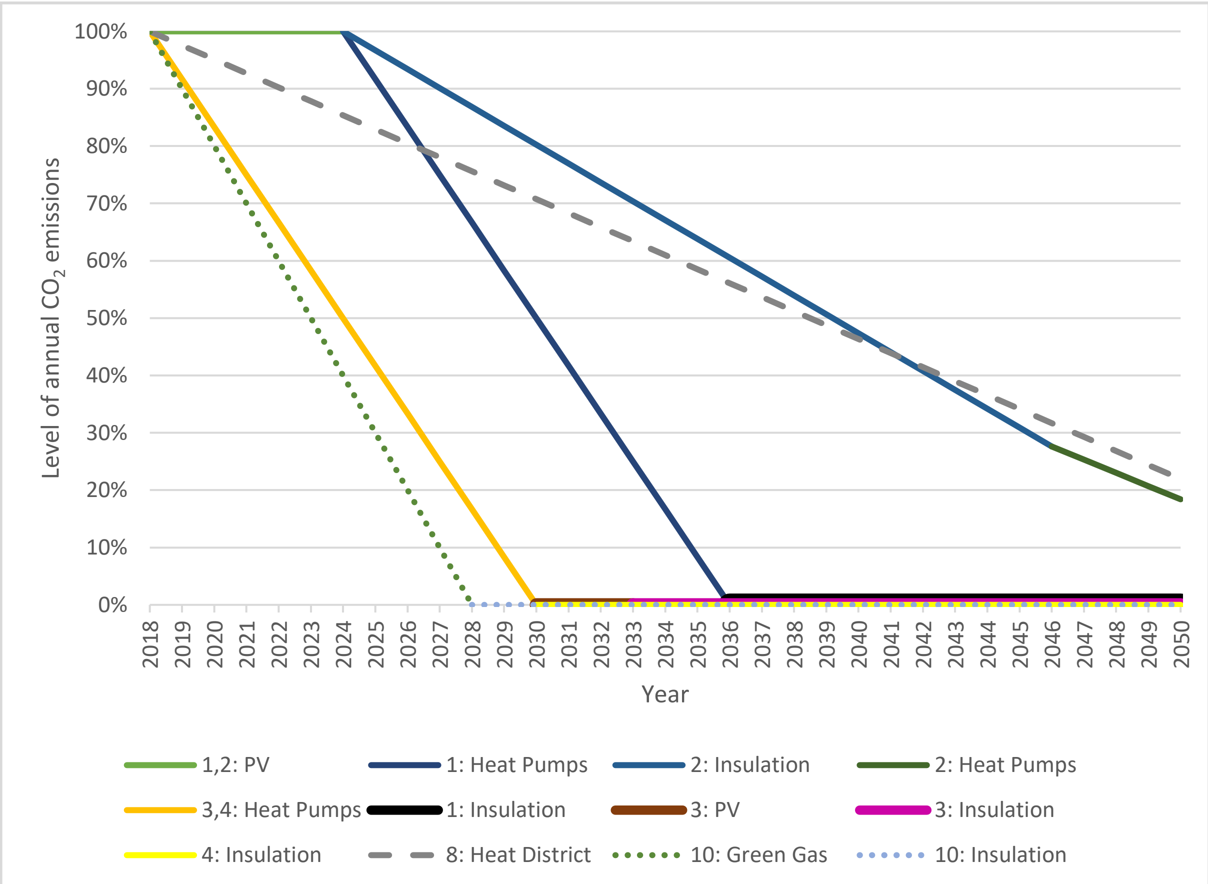


**FIGURE 8 $CO_2$ EMISSION LEVELS OVER TIME: CARBON NEUTRAL HEAT MEASURES FIRST**

Figure 9 shows the $CO_2$ reduction of annual emissions over time when insulation measures are taken before the others which include pathways 5,6,7, and 9. In all these pathways 22 years of full labor utilization is required before insulation is installed in all houses. In pathway 9, green gas is assumed to fully implemented by 2050, again this is an assumption as the implementation of green gas is dependent on availability, not on labor and thus a comparison cannot be made with the other pathways. Pathway 6, spends the years between 2040 and 2050 on installing heat pumps which require 12 years to fully install. It will have reduced the annual emissions to 5% of the total potential reductions to be made (see table 20, for the total potential emission reductions). Pathway 5 will install PV-panels after the insulation measure, which requires roughly 6 years as the electricity grid requires adaptations as well. The remaining years are spent on installing heat pumps and with that annual emissions can be reduced to 17% of the total potential reductions to be made. In pathway 7, heat districts are installed after 2040 which result in a reduction of annual emissions to 21% of the total potential emission reductions.

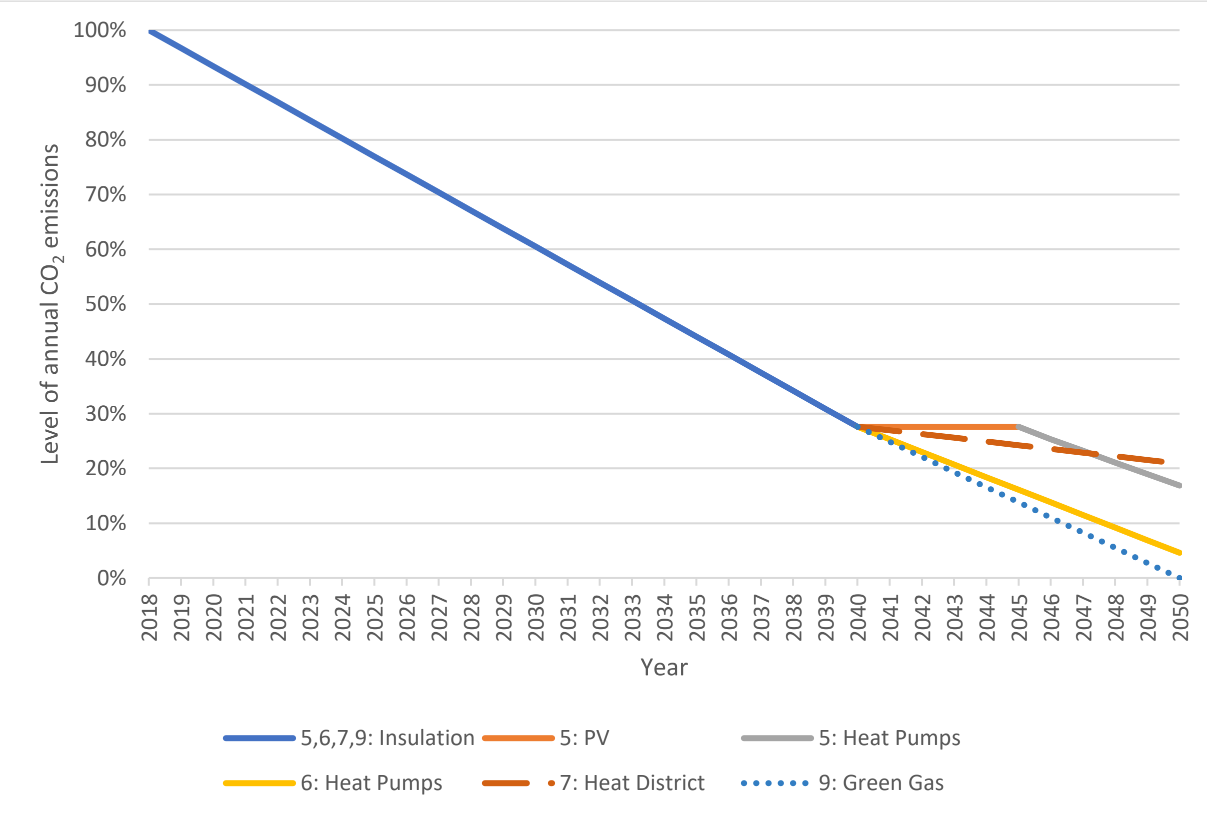


**FIGURE 9 $CO_2$ EMISSION LEVELS OVER TIME: INSULATION MEASURES FIRST**

Table 31 shows the cumulative emissions of all 10 pathways. Pathway 10, where green gas is fully implemented in all terraced houses in the first 10 years results in the least amount of emissions (50,957ktonne $CO_2$). But again, as the implementation of green gas does not depend on labor a correct comparison cannot be made between pathways 9 and 10 and the other pathways. Therefore, these will not be discussed further in this section. After pathway 10, the most favorable pathways in terms of cumulative emissions are number 3 and 4 with 60,222 ktonne $CO_2$ each. In these pathways heat pumps are installed before the other measures, which results in a higher electricity demand. Pathway 3 will become self-sufficient in the production of electricity for heat, as it will install PV-panels before 2050. Whereas, pathway 4 will not install PV-panels before 2050 and thus its true emissions depend on the development of the electricity mix in the Netherlands. Pathway 1, where PV-panels are installed first, followed by heat pumps and insulation measures respectively, results in a total of 115,811 ktonne $CO_2$ emissions. Pathway 2, which also install PV-panels first, results in the highest amount of $CO_2$ emissions (199,659 ktonne). In this pathway heat pumps are postponed to the final years of the transition and thus carbon neutral heat is not provided until that time. It is because of this reason that heat districts emit less $CO_2$ (186,428 ktonne) despite the higher levels of annual emissions in 2050 compared to pathway 2. The pathways where insulation measures are taken before the other measures result in similar cumulative emissions. Pathway 5, where after insulation measures PV-panels and heat pumps are installed consecutively, result in 158,532 ktonne of cumulative $CO_2$ emissions. Pathway 6, where heat pumps and PV-panels are installed successively after the insulation measures, result in cumulative $CO_2$ emissions of 149,826 ktonne. Again, it should be noted that when heat pumps are installed before PV-panels emissions due to the increased electricity demand are not considered. Pathway 7, where insulation is followed by the installation of heat districts results in 158,120 ktonne of cumulative $CO_2$ emissions.

TABLE 31 CUMULATIVE $CO_2$ EMISSIONS: DISPERSED UTILIZATION OF LABOR BASED ON MEASURES

| (ktonne $CO_2$) | Cumulative Emissions |
|---|---|
| **1. PV-panels – Heat Pumps – Insulation** | 115,811 |
| **2. PV-panels – Insulation - Heat Pumps** | 199,659 |
| **3. Heat Pumps – PV-panels – Insulation** | 60,222 |
| **4. Heat Pumps – Insulation – PV-panels** | 60,222 |
| **5. Insulation – PV-panels – Heat Pumps** | 158,532 |
| **6. Insulation – Heat Pumps – PV-panels** | 149,826 |
| **7. Insulation – Heat Districts** | 158,120 |
| **8. Heat Districts – Insulation** | 186,428 |
| **9. Insulation – Green Gas** | 144,923 |
| **10. Green Gas – Insulation** | 50,957 |

### 4.5.2. Dispersion based on Building Age

Figure 10 shows a pathway where priority is given to the oldest houses in implementing the entire set of measures of each scenario. The green gas, electrification, and mixed source scenario have an identical pathway as their retrofitting pace is determined by the insulation measures (see table 23, 25, and 29). After 3.5 years all terraced houses built before 1946 can be retrofitted, reducing the total emissions by almost 27%. The following 3 years are spent on houses built between 1946-1964 reduce the total emissions by roughly 20%. Terraced houses built between 1965-1974 require 4.3 years to all be retrofitted and lead to a 20% emissions reduction. Retrofitting the terraced houses built between 1975 and 1992 requires the most time, 6.2 years, and reduces the annual emissions by almost 20%. The final 13% emission reduction can be attained by retrofitting houses built after 1992 which requires roughly 5 years.

Heat districts requires roughly 41 years to be constructed and connected to all terraced houses and can thus not reach carbon neutrality before 2050. Terraced houses from before 1946 require almost 7 years and reduce the annual emissions by 27%. Roughly 6 years are needed for heat districts to be installed for houses built between 1946 and 1964, and lead to a reduction of roughly 20%. The next 8 years are required for houses from the building period 1965-1974 and lead to a reduction of 20%. The most time, approximately 11 years, are required for houses built between 1975 and 1992, which account for almost 20% of the total emissions reductions. Terraced houses built after 1992 will not all be connected to a heat district before 2050, as only a fraction of the last year remains for the transition. Annual emissions in 2050 will be reduced to 13% of the 2018 levels when heat districts are implemented in the oldest houses first.

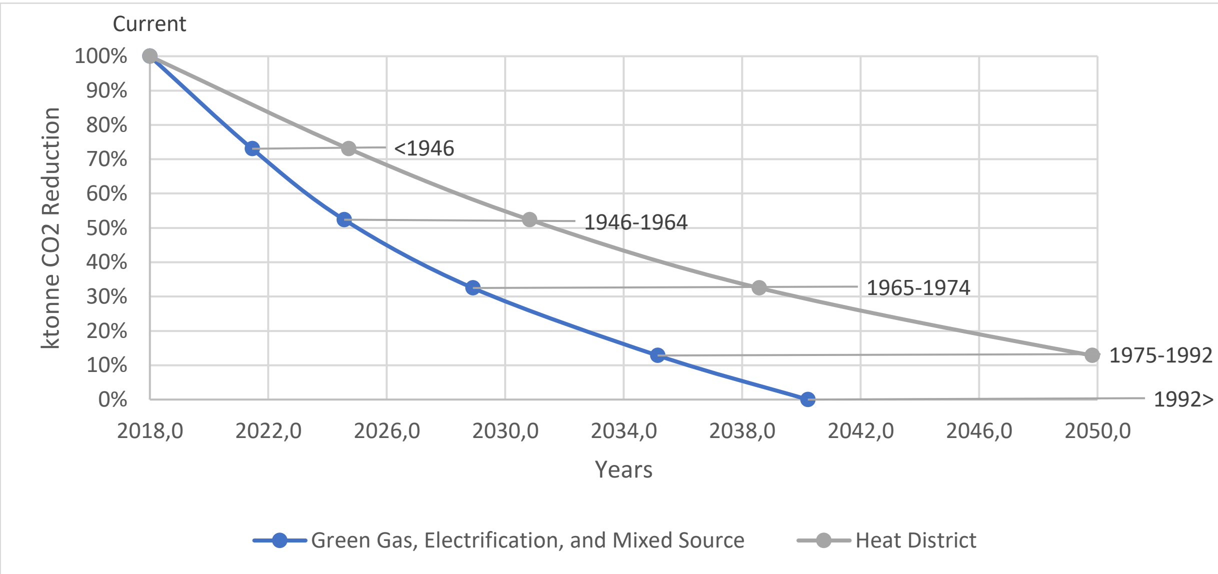


**FIGURE 10 $CO_2$ EMISSION LEVELS OVER TIME: OLD HOUSES FIRST.** THE DOTS MARK THE RETROFITTING OF TERRACED HOUSES PER BUILDING PERIOD: **1)** CURRENT SITUATION, **2) <1946, 3) 1946-1964, 4) 1965-1974, 5) 1975-1992, 6) 1992>**

Figure 11 shows the pathway where priority is given to the newest houses. Green gas, electrification, and mixed source have identical emission reduction paces, reaching 100% reduction in 2040. The first 13% of reductions are made in 5 years by retrofitting houses built after 1992. Houses from between 1975 and 1992 will lead to 20% reductions in roughly 6.2 years. After which, houses built in the period 1965-1974 will lead to another 20% emission reduction within approximately 4.3 years. Followed by houses built between 1946 and 1964, which reduce the annual emissions by roughly 20% in 3 years. The final 3.5 years are spent on the houses built before 1946, and with that the final 27% of the emission reductions are made.

Heat districts require too many years to be constructed and will not reach full carbon neutrality for heat by 2050. Almost 9.5 years is needed for terraced houses built after 1992 which would reduce the annual emissions by 13%. The most time, roughly 11 years, is required for terraced houses built between 1975 and 1992, which account 20% of the total emission reductions. Terraced houses from the building period 1965-1974 will require almost 8 years to be retrofitted with district heating and will lead to an emission reduction of 20%. Approximately 6 years is needed for the houses built between 1946 and 1964 and as only 3.5 years remained until 2050 only 58% of these terraced houses can be retrofitted. Thus, of the 20% potential emissions reductions of 1946-1964 terraced houses only 12% can be made before 2050. The potential 27% reductions of the emissions of retrofitting houses built before 1946 cannot be made when priority is given to the newest houses first. The level of $CO_2$ emissions in 2050 by installing heat districts in the newest houses first is approximately 35% of 2018 levels.

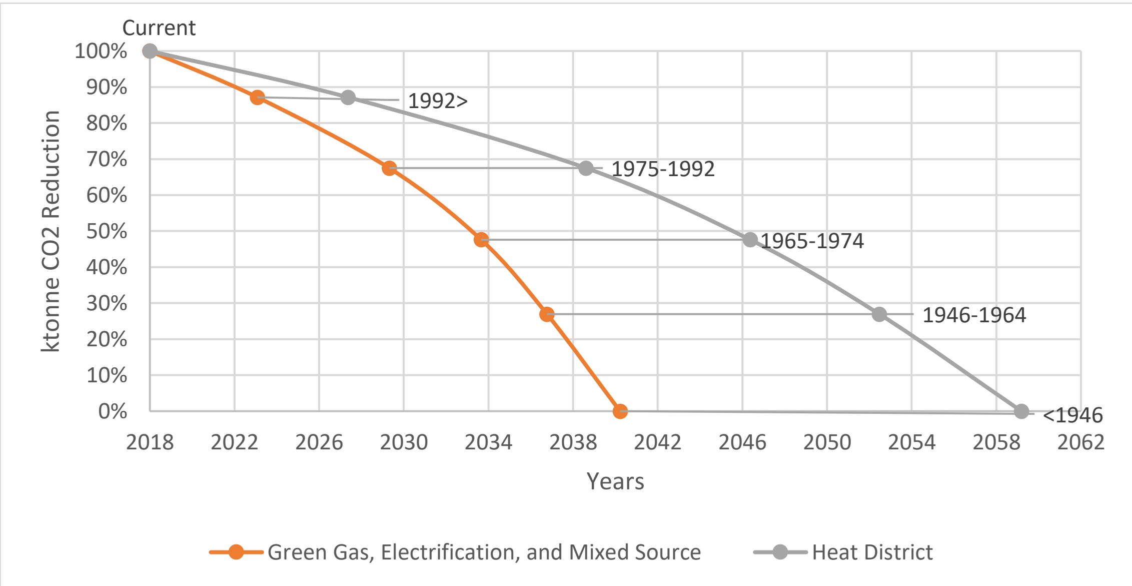


**FIGURE 11 $CO_2$ EMISSION LEVELS OVER TIME: NEW HOUSES FIRST.** THE DOTS MARK THE RETROFITTING OF TERRACED HOUSES PER BUILDING PERIOD: 1) CURRENT SITUATION, 2) 1992>, 3) 1975-1992, 4) 1965-1974, 5) 1946-1964, 6) <1946

Table 32, shows the cumulative emissions of the different pathways. It is no surprise that the focus on the older houses leads to a greater savings than the focus on newer houses. The green gas, electrification, and mixed source scenarios have the same retrofitting pace; their cumulative emissions are identical in both pathways. The 'Old First' pathway will lead to 78,949 ktonne $CO_2$ of emissions and the 'New First' pathway will emit 126,897 ktonne $CO_2$. The implementation of heat districts will result in greater emissions than green gas and electrification regardless of the pathway chosen. For heat districts the 'Old First' pathway will lead to cumulative emissions of 132,164 ktonne $CO_2$ and the 'New First' pathway will emit a total of 217,083 ktonne $CO_2$. Thus, the electrification, green gas, and mixed source scenario with a focus on the oldest buildings first will lead to least amount of $CO_2$ emissions.

TABLE 32 CUMULATIVE $CO_2$ EMISSIONS: OLD HOUSES AND NEW HOUSES FIRST

| (ktonne $CO_2$) | **Old First** | **New First** |
|---|---|---|
| **Green Gas** | 78,949 | 126,897 |
| **Electrification** | 78,949 | 126,897 |
| **Heat Districts** | 132,164 | 217,083 |
| **Mixed Source** | 78,949 | 126,897 |

# Chapter 5: Discussion

## 5.1. Research Limitations

In this research assumptions were made which could have led to under- or overestimations of the $CO_2$ reductions and emissions/savings, as well as the deployable and required labor for measures. First the assumptions and their effects on the $CO_2$ reductions will be discussed. Followed by the assumptions and their effects on the labor. Finally, the assumptions influencing the results of the different utilizations of labor will be discussed.

### 5.1.1. $CO_2$ Reductions

The measures considered might not be applicable to all terraced houses. It was assumed that houses would be insulated by an extra building shell and that PV-panels can be installed. Installation of these measures could be limited due to construction constraints, cultural property, or aesthetics. These could be limiting factor on the implementation of specific measures and thus the potentials given might be overestimated.

The $CO_2$-emission reductions of houses were determined using average characteristics of houses from specific building periods that were constructed in 2010 (RVO, 2011). Average housing characteristics could have changed since then which would lead to an overestimation of the emission reductions. Although, 8 years is a relatively short period for a significant transformation of the existing housing stock to occur and thus the overestimation will be insignificant.

In this research district heating is assumed to provide carbon neutral heat. However, current district heating is not carbon neutral (see table 11). The possibility of carbon neutral heat districts depends on the sources as well as the emission allocation methods used. Thus, the results of this research are more likely to have overestimated the potential emission reductions and underestimated the total cumulative emissions of heat districts.

The emissions due to electricity use were not within the scope of this research. Currently heat in houses is not strongly linked the electricity use; as a relatively small amount of auxiliary electricity is needed for the heating installations. While in the future the electricity and heat supply will be more strongly connected when heat pumps become more dominant. As the RVO model included electricity use these were extrapolated to the entire terraced housing stock, the results of which are included in appendix E. From that data it can be derived that PV-panels will result in considerable emissions reductions, and heat pumps will lead to a significant increase of emissions due to electricity use. The considered balanced ventilation system in this research led to an increase of electricity use. When electricity use would be considered, the most favorable pathways in terms of overall $CO_2$ emissions would be those which install PV-panels early in the transition. The inclusion of electricity use in the green gas and the heat district scenarios would results in more cumulative $CO_2$ emissions than the electrification scenario.

### 5.1.2. Required and Deployable Labor

As previously stated in the method section the considered professions, their activities, and their skills, have been categorized and approximated with the best knowledge that the researcher had. It should be noted that all results regarding labor should be considered more as indicative than as absolute figures on labor availability, deployability, and requirements.

Furthermore, it has been assumed that all professionals were available full-time for installing the measures. In other words, the time required for secondary labor activities (e.g. driving, planning) are not considered. Which leads to an overestimation of the deployable labor and an underestimation of the required labor.

The time required for the wall and roof insulation measures does not include the labor requirements to produce the prefab building elements. The production of the prefab elements will need labor from the same professionals working on the building sites, most notably carpenters. Thus, the required labor for insulation measures is most likely an underestimation and the deployable labor for insulation measures an overestimation.

The variance of the labor required for measures was not considered in this research. A considerable variance is for the figures regarding the installation of prefab façade elements, heat pumps, and infrastructural work on the electricity grid. Thus, the presented required labor for insulation and electrification could be over- or underestimated.

The deployable labor for heat districts is based on the expected investments for the new construction of infrastructures, but some activities could be considered as re-construction activities. Existing streets will need to be opened and closed to construct heat districts. Thus, it is more likely that the construction of heat districts is combined with planned reconstructions of other infrastructures. Laying and welding pipelines require highly specialized welders and as these were categorized with the line installers it is most likely and overestimation of the deployable labor.

Labor development over time has not been included in this research. Thus, deployability was assumed to be static over time. There are multiple in- and outflows of the labor supply such as: retirement, competition with other sectors, import, and education. Education is considered as the greatest source of new labor which follows the labor demand because professionals need to be educated, and as such supply will always lag behind the demand. The future labor demand is most likely to be a mix of all professions as there is no one-size-fits-all set of retrofitting measures. Currently, knowledge of heat districts is not widely available in education systems or courses, whereas knowledge on PV-systems, heat pumps, and insulation measures are widely available (ISSO, 2018). Therefore, it is more likely that electrification will be a more dominant measure than district heating in the short term. Besides the interaction between labor demand and supply, there are many other factors to consider within the complex system surrounding specific measures determining the knowledge distribution (i.e. the labor supply) (Hekkert et al., 2007). Overall, the presented deployable labor over time is considered an underestimation and with that the required years to implement the measures are likely overestimated.

### 5.1.3. Scenarios

In all scenarios the implementation of heat pumps and PV-panels will lead to a rise in labor required for maintenance and replacement throughout the transition as these have a lifetime of approximately 15 years. This increase of required labor could reduce the deployability of the professionals for installing heat pumps and PV-panels if labor from the installation sector does not increase in line with the increase in demand for maintenance and replacement.

In the dispersed scenarios, when heat pumps are applied before insulation measures, heat pumps are over dimensioned which would make it an economically unfavorable option. The pathways 1, 3, and 4 are therefore highly unlikely to be implemented.

It should also be mentioned that a dispersed implementation of some measures might lead to a greater time needed for secondary labor activities (e.g. driving, planning). Thus, it is likely that a more disperse utilization the labor will lead to an increase of the required labor and a decrease of the deployable labor.

Overall, the utilization of labor presented in the scenarios was based on possible overestimations of deployable labor and possible underestimations of the required labor. Thus, the total years required and with that the cumulative emissions are more likely to be underestimated than overestimated.

## 5.2. Contribution to Literature

Labor as a unit of time has received little attention within sustainability sciences and no explicit links between labor and CO2 savings exist in scientific literature to the best knowledge of the author. Within sustainability sciences, sustainability is divided in environmental, economic, and social dimensions which are to be analyzed in consideration of the time dimension (Lozano, 2008). Labor is commonly expressed in monetary value or in more qualitative terms (mostly reflecting aspects of the social dimension). Expressing labor in a unit of time and linking it explicitly to $CO_2$ emissions provides a new relationship between the sustainability categories to be studied. Furthermore, efficiency expressed in labor per unit of $CO_2$ could prove to be a useful concept for policy makers for programs addressing climate and economic issues and can aid in guiding educational programs.

To the best knowledge of the author, assessing the required labor through a bottom-up approach where labor required per house is used to determine the overall labor requirements for a transition has not been done before. This method allows for more detailed insights in labor requirements than top-down approaches and approaches where money is used as indirect indicator for labor.

## 5.3. Recommendations for Further Research

The number of data sources collected to determine the required labor of retrofitting measures and infrastructural adaptations per terraced houses were limited. More research should be done on the labor requirements of the measures in this research before statements can be made regarding the representativeness and robustness of the figures presented in this research.

This research could be extended by including labor development over time, which would consider in- and outflows as well as changes in the skills of workers. Labor efficiency in terms of time per measure could also develop over time which could influence the results of this research.

This research assumed that all deployable labor could be utilized without geographical limitations. Addressing the competition for labor between regions in scenarios will provide useful information for guiding the transition on more local levels.

Further research should be done on the labor requirements for other housing types. Some measures might differ in the required time when installed in the other housing types. Terraced housing consists of 40% of the total Dutch housing stock, semi-detached and detached houses are roughly 30% of the housing stock, and the various types of flats 30% as well. When assuming all factors are equal for the rest of the housing stock labor requirements would be a factor 2.5 higher. The knowledge to what degree labor requirements between housing types differ might be useful for policy makers.

This research did not include the labor that is required for the construction of prefab building elements. A study on the professions and time required for constructing prefab building elements should be done as this could influence the deployable labor considered in this research.

The scenarios in this research included only emissions due to heat, the scope could be broadened to include emissions of electricity. Electricity is roughly 30% of the energy demand of houses and in case of electrification all energy demands will be met by electricity. Future energy systems are likely to be more interconnected and thus future studies on the energy use of houses should consider the relationships between energy systems.

# Chapter 6: Conclusion

This research aimed to show how labor can be utilized most efficiently in terms of annual $CO_2$ emissions and reductions between measures and building periods of terraced houses. The cumulative $CO_2$ emissions of the heat transition were considered as well. The required labor and the potential reduction of annual $CO_2$ emissions of heat were determined for multiple retrofitting measures installed in terraced houses from five different building periods. Five scenarios were constructed to determine the most favorable utilization of labor in terms of cumulative $CO_2$ emissions. Only the emissions in fulfilling the heat demand and emissions bound to the terraced houses were considered. The current labor supply of the Netherlands was assumed to be static over time. For this research three sources of carbon neutral heat were considered: 1) green gas, 2) electrification through PV-panels and air-water heat pumps, 3) heat from heat districts. In all cases these heat sources were complemented by insulation measures. The main research question is as follows:

'How can the current Dutch labor supply be utilized most efficiently towards achieving carbon neutral heating before 2050 in all Dutch terraced houses?'

To answer the main research question the following five sub-research questions were posed:

1. What is the required labor for retrofitting terraced houses towards carbon neutral heating?
2. What are the potential reductions of annual $CO_2$ emissions of various retrofitting measures in terraced houses?
3. What is the efficiency of each retrofitting measure in terms of FTE per ktonne $CO_2$ emission reduction of annual $CO_2$ emissions due to heat in terraced houses?
4. What are the total $CO_2$ emissions of all terraced houses when current labor is fully utilized in the heat transition?
5. What are the total $CO_2$ emissions of all terraced houses when labor is utilized dispersedly over measures and terraced houses in the heat transition?

In the following sections the results of each sub-research question will be discussed before answering the main research question.

## 6.1. Required Labor

It was found that the greatest amount of labor in the transition of terraced houses is required for insulating houses. Insulation measures consisted of prefab roof and wall elements as an extra building shell, insulation of the crawl spaces, and the installation of a balanced ventilation system. Green gas required no extra labor to be implemented within the system boundaries of this research. The electrification of terraced houses was found to be the least labor-intensive source of carbon neutral heat. Although, it should be mentioned that the source data on the required work for the infrastructures and heat pumps had a wide variance. Heat districts are a more labor-intensive carbon neutral heat source than electrification. For all measures it was found that the greatest amount of labor was needed for terraced houses built between 1974 and 1992. Followed successively to the least amount of labor by terraced houses from the following building periods: built after 1992, 1965-1974, built before 1946, and built between 1946 and 1964.

## 6.2. $CO_2$ Emission Reductions

The potential emissions reduction of carbon neutral heat sources is identical between retrofitting measures in terraced houses from specific building periods. Insulation measures can significantly reduce the annual $CO_2$ emissions due to the heat demand of terraced houses. The potential reductions are the greatest in the oldest terraced houses and decrease the more recent the building period.

## 6.3. Labor Efficiency

The most efficient use of labor in terms of FTE's per ktonne $CO_2$ reduction of annual emissions for a single measure was to install a heat pump. Although, without PV-panels this would lead to a shift in emissions to the electricity grid. Installing heat pumps combined with PV-panels is the most efficient use of labor for a carbon neutral heat source, followed by heat districts. As green gas requires no labor this cannot be expressed in terms of labor efficiency. As a single measure, insulation is the second least efficient use of labor, followed by insulation and PV-panels. Combining a carbon neutral source of heat with insulation significantly reduces the efficiency when compared to the efficiency of labor for carbon neutral heat sources.

## 6.4. Full Utilization Scenarios

Scenarios focusing on each potential carbon neutral source of heat combined with insulation measures were constructed assuming full utilization of the deployable labor in retrofitting terraced houses. These full utilization scenarios showed that the measures from green gas, electrification, or a mix of sources can be installed in all terraced houses by 2040 with the current deployable labor. Labor in these three scenarios is most scarce for the insulation measures and as a result the deployable labor needs to be fully utilized for 22 years. It should be noted that the availability of green gas is most likely to be limited and implementation of green gas depends on the availability of it and not on any labor requirements. The greatest labor scarcity is for district heating, most notably the labor for laying and welding the pipes, and as such 41 years of full utilization of the deployable labor is needed. District heating cannot be installed in all terraced houses before 2050 with full utilization of the current deployable labor. If heat districts were the only carbon neutral source of heat 22% of the terraced housing stock will be unretrofitted in 2050 if the deployable will not increase.

## 6.5. Dispersed Utilization Scenarios

Two scenarios were also constructed where labor was dispersedly utilized over time with different focusses on specific measures and on building periods. For the scenarios focusing on measures 10 pathways were constructed which varied in the order of measures taken. It was found that implementation of heat pumps would be the fastest pathway to reduce annual $CO_2$ emissions. Although, solely installing heat pumps would displace these emissions to the electricity grid which could to an overall increase of annual $CO_2$ emissions. The combination of heat pumps and PV-panels was found to be the second fastest pathway to reducing the annual $CO_2$ emissions for heat in terraced houses. However, heat pumps require a highly insulated house with low temperature heating systems to comfortably heat houses cost effectively. Thus, electrification without insulating houses first is unlikely to be a realistic case. Implementing green gas early in the transition could lead to low cumulative $CO_2$ emissions. But the extent to which green gas can be implemented is highly dependent on its availability, which is most likely to be limited. Implementing heat districts before insulating is the pathway with the second highest $CO_2$ emissions because heat districts require a long time to be constructed. The pathways where terraced houses are insulated before natural gas is replaced are the most realistic and favorable pathways in terms of $CO_2$ emissions.

Within the scenario of dispersed utilization of labor based on the building periods of terraced houses, two pathways were constructed where priority was given to either the oldest or the newest houses. The pathway which focused on the oldest terraced houses first had the lowest cumulative $CO_2$ emissions for all three carbon neutral sources of heat. Where green gas, electrification, and the mixed sources had identical and lower cumulative $CO_2$ emissions than heat districts. Within the green gas, electrification, and mixed source pathways all the terraced houses were retrofitted by 2040. Whereas, within the heat district pathway only the houses built before 1992 can be retrofitted before 2050. Thus, leaving the emissions for heating in terraced houses at 13% of 2018 annual $CO_2$ emission levels. When priority is given to the newest houses first, all retrofitting measures of green gas, electrification, and mixed sources can be installed in terraced houses by 2040. Unsurprisingly, when installing heat districts in the newest houses first, not all terraced houses can be retrofitted before 2050. Only a part of the houses built in the period 1946-1964 can be connected to a heat district and the houses built before 1946 are left unretrofitted and the emissions for heating in terraced houses remain at 35% of current levels.

## 6.6. Conclusion

It is unlikely that all terraced houses will be retrofitted with one type of carbon neutral heat because there is no one-size-fits-all solution for all terraced houses. Instead it is more likely that a mix of heat districts, electrification, and green gas will be used to reach carbon neutrality of heat in terraced houses before 2050. Green gas requires no extra labor from the construction or installation sector within the bounds of this research. The shared type of labor between the electrification and district heating is mostly limited to mechanical installers and infrastructural labor for street and groundwork. Thus, when a mix of heat sources is installed a greater share of the labor supply is utilized compared to a scenario with a focus on only one heat source. Although, electrification is the most efficient measure in terms of FTE's per ktonne $CO_2$ reduction and it currently has more labor to utilize and as such electrification will most likely have a more prominent place in transition than heat districts. For which the current labor supply is scarce. Insulation measures are an integral part of the heat transition as it is a requirement for electrification of houses or for heat from low temperature heat districts. Furthermore, insulation can significantly reduce the heat demand of houses thus increasing the potential number of houses that can be heated with the same amount of energy. Which is particularly relevant for green gas as this is most likely be a limited available source of heat for houses. In conclusion, the current Dutch labor supply can be utilized most efficiently in the transition towards carbon neutral heating in terraced houses by 2050, by insulating terraced houses while simultaneously replacing natural gas with a mix of carbon neutral heat sources. Which in the short-term will mainly be green gas and heat from heat pumps and PV-panels and to a lesser extent by connecting houses to heat districts. Priority should be given to the oldest houses as these have the greatest reduction potential, while not requiring considerably more time than other houses for the installation of the required measures considered in this research.

# References

Aalst, van der, M., Beukel, van den, L., 2017. Kansrijke beroepen, waar is de arbeidsmarkt te krap. Landelijk overzicht. *UWV Afdeling Arbeidsmarktinformatie en -advies.*

BuildUpSkills, 2012. The Netherlands - Analysis of the national status quo.

BZK, 2011a. Brochure Voorbeeldwoningen 2011 bestaande bouw. *Agentschap NL.*

BZK, 2011b. Voorbeeldwoningen 2011 Onderzoeksverantwoording. *Agentschap NL.*

BZK, 2011c. Voorbeeldwoningen 2011 – EPA Detailgegevens per woningtype, subtype en bouwperiode. *Agentschap NL*

BZK, 2016. Cijfers over Wonen en Bouwen 2016. Ministerie van Binnelandse Zaken en Koninkrijksrelaties.

CBS, 2017. Banen van Werknemers naar SBI (tot en met 5 digit).

CBS, 2018a. Retrieved 8 July 2018 from:
http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=83704ned&D1=0&D2=a&D3=0-8&D4=0&D5=a&HDR=T,G1,G2&STB=G3,G4&VW=T

CBS, 2018b. Retrieved 8 July 2018 from:
http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=82235ned&D1=0-4,7&D2=82-96&HDR=T&STB=G1&VW=T

EIB, 2017. Trends op Bouwarbeidsmarkt 2017-2022. *Economisch Instituut voor de Bouw.*

EIB, 2018. Verwachtingen bouwproductie en werkgelegenheid 2018. *Economisch Instituut voor de Bouw.*

Eurostat, 2013. Glossary: Full-time equivalent (FTE). Retrieved 15 March 2018 from:
http://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Full-time_equivalent_%28FTE%29

FNV, 2018. Vakantie Vrij Verlof. Retrieved 15 July 2018 from: https://www.fnv.nl/themas/vakantie-vrij-verlof/

Geerlings, R., Hofman, M., 2015a, March. BCP+ Dossier - Aanvullende Eisen aan vakmanschap - Dakdekken. *BuildUpSkillsNL.*

Geerlings, R., Hofman, M., 2015b, March. BCP+ Dossier - Aanvullende Eisen aan vakmanschap – Elektrotechnisch Installeren. *BuildUpSkillsNL.*

Geerlings, R., Hofman, M., 2015c, March. BCP+ Dossier - Aanvullende Eisen aan vakmanschap - Koudetechnisch Installeren. *BuildUpSkillsNL.*

Geerlings, R., Hofman, M., 2015d, March. BCP+ Dossier - Aanvullende Eisen aan vakmanschap - Metselen. *BuildUpSkillsNL.*

Geerlings, R., Hofman, M., 2015e, March. BCP+ Dossier - Aanvullende Eisen aan vakmanschap - Timmeren. *BuildUpSkillsNL.*

Geerlings, R., Hofman, M., 2015f, March. BCP+ Dossier - Aanvullende Eisen aan vakmanschap -Werken als Zelfstandige. *BuildUpSkillsNL.*

Geerlings, R., Hofman, M., 2015g, March. BCP+ Dossier - Aanvullende Eisen aan vakmanschap - Werktuigkundig Installeren. *BuildUpSkillsNL.*

Groen Gas Forum, 2014. Routekaart Hernieuwbaar Gas. *De Gemeynt, ECN, Groen Gas Nederland, RVO.*

Grootenboer, A., Koning, M., Saitua, R., Vrolijk, M., Zuidema, M., 2013. SER Energieakkoord Macro-economische doorwerking. *EIB.*

Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., Smits, R.E.H.M., 2007. Functions of innovation systems: A new approach for analysing technological change. *Technological Forecasting & Social Change. 74 413-432.*

IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

ISSO, 2018. WKI-Inventarisatie Technishe Innovaties en Bijscholingsaanbod. Provided by J. Cromwijk at request.

Koning, M., Smit, N., van Dril, T., 2016. Energieakkoord Effecten van de energietransitie op de inzet en kwaliteit van arbeid. *EIB, ECN & CBS.*

Lozano, R., 2008. Envisioning sustainability three-dimensionally. *Journal of Cleaner Production. 16 138-1846*

Ma, Z., Cooper, P., Daly, D., Ledo, L., 2012. Existing building retrofits: Methodology and state-of-the-art. *Energy and Buildings. 55 889–902.*

Majcen, D. Itard, L., Visscher, H., 2013. Actual and theoretical gas consumption in Dutch dwellings: What causes the differences?. *Energy Policy. 61 460-471.*

Menkveld, M., 2009. Kentallen warmtevraag woningen. *ECN*.

MEZ, 2016. Energieagenda Naar een $CO_2$-arme energievoorziening. *Ministerie van Economische Zaken.* December 2016.

Milieucentraal, 2018. Duurzaam en zuinig verwarmen. Retrieved 12 April 2018 from: https://www.milieucentraal.nl/energie-besparen/energiezuinig-huis/energiezuinig-verwarmen-en-warm-water/

OTIB, 2016. Trends en Ontwikkelingen in de Technische Installatiebranche 2016. *Radboud Universiteit Nijmegen.*

Regeling Bouwbesluit, 2012. Regeling van de Minister van Binnenlandse Zaken en Koninkrijksrelaties van 22 december 2011, nr. 2011-2000589667, tot vaststelling van nadere voorschriften voor bouwwerken. Retrieved 15 March 2018 from: *http://wetten.overheid.nl/BWBR0031022/2018-01-01#Opschrift*

RVO, 2014a. Technieken Energie Neutrale Woningen. *Rijksdienst voor Ondernemend Nederland.*

RVO, 2014b. Infoblad Energieneutraal Bouwen: Definitie en Ambitie. *Rijksdienst voor Ondermenend Nederland.*

RVO, 2016. Vragen en antwoorden methodiek definitief energielabel voor woningen update juli 2016. *Rijksdienst voor Ondernemen Nederland.*

RVO, 2017. Monitor Energiebesparing Gebouwde Omgeving 2016. *Rijksdienst voor Ondernemend Nederland.*

RVO, 2018a. Energiemix. *Rijksdienst voor Ondernemend Nederland.* Retrieved 14 February 2018 from: https://energiecijfers.databank.nl/dashboard/Energiemix/

RVO, 2018b. Referentiewoningen EPC. *Rijksdienst voor Ondernemend Nederland.* Retrieved 8 March 2018 from: https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/gebouwen/wetten-en-regels-gebouwen/nieuwbouw/energieprestatie-epc/referentiewoningen-epc

RVO, 2018c. Verschil Energie-Index (EI) en Energie Prestatie Co ëfficiënt (EPC). *Rijksdienst voor Ondernemend Nederland.* Retrieved 4 April 2018 from: https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/gebouwen/wetten-en-regels-gebouwen/bestaande-bouw/energie-index/verschil-energie-index-en-epc

RVO, 2018d. Energiebesparingsverkenner voor woningen (regulier en hoge ambities) – Achtergronddocument. Innax Bouwkundig adviseurs B.V..

Sartori, I., Napolitano, A., Voss, K., 2012. Net zero energy buildings: A consistent definition framework. *Energy Buildings. 48 220-232.*

Sastresa, E.L., Usón, A.A., Bribián I. Z., Scarpellini, S., 2009. Local impact of renewables on employment: assessment methodology and case study. *Renewable and Sustainable Energy Reviews. 14 679-690.*

Schepers, B.L., Scholten, T., 2016. Ketenemissies warmtelevering – directe en indirecte $CO_2$-emissies van warmtetechnieken. CE Delft.

Schoots, K., Hekkenberg, M., Hammingh, P., 2017, Nationale Energieverkenning 2017. *ECN*-O--17-018. Petten: Energieonderzoek Centrum Nederland.

SER, 2013. Energieakkoord voor duurzame groei. *Sociaal-Economische Raad*.

SER, 2016. Uitvoeringsagenda Energieakkoord 2016. *Sociaal-Economische Raad.*

SER, 2017. Uitvoeringsagenda Energieakkoord 2017. *Sociaal-Economische Raad.*

SER, 2018. Ontwerpadvies Energietransitie en werkgelegenheid. *Sociaal-Economische Raad.* Retrieved 19 April from: https://www.ser.nl/~/media/db_adviezen/2010_2019/2018/energietransitie-werkgelegenheid.ashx

Simmelink, V.I., 1996. Lassen in Nederland: Sectoren en beroepsprofielen. DIJK 12.

Slingerland, E., Terlouw, W. Oude Lohuis, J., 2016. Kwantificering van toekomstscenario's voor de gebouwde omgeving Eindrapport. *Ecofys.*

Straatmeijer, J.L., Koning, M.A., 2015. Energiebesparende technieken en kwalificaties bouwpersoneel. *EIB.*

Stroomversnelling, 2013. Akte van oprichting. Retrieved 15 February from: http://stroomversnelling.nl/wp-content/uploads/2017/03/afschrift-akte-van-oprichting-Vereniging-DeBredeStroomversnelling.pdf

Tigchelaar, C., Leidelmeijer, K., 2013. Energiebesparing: Een samenspel van woning en bewoner – Analyse van de module Energie WoON 2012. *ECN & RIGO.*

UNETO-VNI, 2016. Economische vooruitzichten Installatiebranche 2017 en verder.

UNFCCC, 2018*a*. Summary of the Paris Agreement. Retrieved 14 February 2018 from: http://bigpicture.unfccc.int/#content-the-paris-agreemen

UNFCCC, 2018*b*. Status of Ratification. Retrieved 14 February 2018 from: http://unfccc.int/paris_agreement/items/9444.php

Volandis. (2018, May). Beroepen. Retrieved June, 2018, from http://www.arbocatalogus-bouweninfra.nl/beroepen/index.htm

Wijngaart, R. van den., Folkert, R., Middelkoop, van, M., 2014. Op weg naar een klimaatneutrale woningvoorraad in 2050. *Planbureau voor de Leefomgeving.*

# Appendix A

TABLE 33 DUTCH HOUSING STOCK, NUMBERS (ADAPTED FROM BZK, 2011; CBS, 2018A, 2018D)

<table>
<tr><th>Housing Type</th><th>< 1946</th><th>1946-1964</th><th>1965-1974</th><th>1975-1991</th><th>1992></th><th>Total</th></tr>
<tr><td>Detached</td><td colspan="2">430,741</td><td>119,282</td><td>218,684</td><td>355,757</td><td>1,124,464</td></tr>
<tr><td>Semi-Detached</td><td colspan="2">278,325</td><td>139,162</td><td>218,684</td><td>355,757</td><td>991,928</td></tr>
<tr><td>Terraced</td><td>510,262</td><td>463,875</td><td>589,784</td><td>854,855</td><td>711,514</td><td>3.130.290</td></tr>
<tr><td>Maisonette</td><td colspan="2">218,684</td><td>19,880</td><td>92,775</td><td>82,098</td><td>413,437</td></tr>
<tr><td>Gallery Flat</td><td colspan="2">66,268</td><td>172,296</td><td>106,029</td><td>232,610</td><td>577,203</td></tr>
<tr><td>Porch Flat</td><td>251,818</td><td>258,445</td><td>112,655</td><td>139,162</td><td>136,830</td><td>898.910</td></tr>
<tr><td>Other Flat</td><td colspan="2">99,402</td><td>119,282</td><td>119,282</td><td>273,659</td><td>611,625</td></tr>
<tr><td>Total</td><td colspan="2">2,571,192</td><td>1,265,716</td><td>1,749,471</td><td>2,134,542</td><td>7,720,920</td></tr>
</table>

TABLE 34 DUTCH HOUSING STOCK, SHARES (ADAPTED FROM BZK, 2011; CBS, 2018A, 2018D)

<table>
<tr><th>Housing Type</th><th>< 1946</th><th>1946-1964</th><th>1965-1974</th><th>1975-1991</th><th>1992></th><th>Total</th></tr>
<tr><td>Detached</td><td colspan="2">6%</td><td>2%</td><td>3%</td><td>5%</td><td>15%</td></tr>
<tr><td>Semi-Detached</td><td colspan="2">4%</td><td>2%</td><td>3%</td><td>5%</td><td>13%</td></tr>
<tr><td>Terraced</td><td>7%</td><td>6%</td><td>8%</td><td>11%</td><td>9%</td><td>41%</td></tr>
<tr><td>Maisonette</td><td colspan="2">3%</td><td>0%</td><td>1%</td><td>1%</td><td>5%</td></tr>
<tr><td>Gallery Flat</td><td colspan="2">1%</td><td>2%</td><td>1%</td><td>3%</td><td>7%</td></tr>
<tr><td>Porch Flat</td><td>3%</td><td>3%</td><td>1%</td><td>2%</td><td>2%</td><td>12%</td></tr>
<tr><td>Other Flat</td><td colspan="2">1%</td><td>2%</td><td>2%</td><td>4%</td><td>8%</td></tr>
<tr><td>Total</td><td colspan="2">33%</td><td>16%</td><td>23%</td><td>28%</td><td>100%</td></tr>
</table>

# Appendix B

| MATRIX SPECIALISMEN EN BEROEPSBEELDEN | Timmerman | Metselaar | Dakdekker | Glaszetter | Stukadoor | Plafond- en wandmonte | Opzichter Bouw | Calculator Bouw | Werkvoor. Bouw | Tekenaar / Ontw. Bouw | Zelfstandig ondern. | Ontwerper inst. | Werkvoorbereider inst. | Monteur E-installatie | Service monteur E-inst. | Monteur W-installatie | Service monteur W-inst. | Monteur Koudetechniek | Service monteur K | Stroomversnelling huur | Stroomversnelling koop | Urgenda | Kleur Uw Gemeente Gro |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ENERGY MANAGEMENT** | | | | | | | | | | | | | | | | | | | | | | | |
| Domotica | | | | | | | | | | | X | | | X | X | | X | | X | X | X | O | O |
| Power quality | | | | | | | | | | | | | | | X | | | | | O | O | O | O |
| Installatie-optimalisatie W | | | | | | | | | | | | | | | | X | X | | | | | X | X |
| Installatie-optimalisatie E | | | | | | | | | | | | | | | | | | X | X | | | X | X |
| Energiemonitoring | | | | | | | | | | | | | | | X | | X | | X | X | X | X | O |
| Grijswatersysteem | | | | | | | | | | | | | | | | X | X | | | O | O | O | O |
| **ENERGY PRODUCTION** | | | | | | | | | | | | | | | | | | | | | | | |
| Bodemenergie | | | | | | | | | | | | | | | | X | X | X | X | O | O | O | O |
| Pelletkachels (biomassa) | | | | | | | | | | | X | | | | | X | X | | | | | O | O |
| Stadsverwarming | | | | | | | | | | | | | | | | X | X | | | | | O | O |
| Warmtepompen woningbouw | | | | | | | | | | | | | | | | X | X | X | X | O | O | O | O |
| Warmtepompen utiliteitsbouw | | | | | | | | | | | | | | | | X | X | X | X | | | | O |
| Airconditioning | | | | | | | | | | | X | | | | | | | X | X | | | | |
| Montage zonnepanelen (zonnestroom) | X | | X | | | | | | | | X | | | X | X | | | X | X | X | X | X | X |
| Montage zonnepanelen (zonnewarmte & zonkoeling) | | | X | | | | | | | | X | | | | | X | X | X | X | X | X | X | X |
| Montage kleine windmolens | | | X | | | | | | | | X | | | X | X | | | | | | | O | O |
| Zonnestroom | | | | | | | | | | | | | | X | X | | | | | X | X | X | O |
| Zonnewarmte | | | | | | | | | | | | | | | | X | X | | | X | X | X | O |
| Ventilatie woningbouw | | | | | | | | | | | | | | | | X | X | | | X | X | O | O |
| Ventilatie utiliteitsbouw | | | | | | | | | | | | | | | | X | X | | | | | | O |
| Zonkoeling | | | | | | | | | | | | | | | | | | X | X | | | | |
| **ENERGY REDUCTION** | | | | | | | | | | | | | | | | | | | | | | | |
| Renovatie (houten) vloeren | X | | | | | | | | | | X | | | | | | | | | O | O | O | O |
| Na-isolatie kruipruimten (bodemisolatie) | | | | | | | | | | | X | | | | | | | | | | | | O |
| Na-isolatie in begane grond vloeren | X | | | | | | | | | | X | | | | | | | | | | | | |
| Vloerisolatie PUR | | | | | | | | | | | X | | | | | | | | | O | O | O | O |
| Vloerisolatie Folie | | | | | | | | | | | X | | | | | | | | | O | O | O | O |
| Na-isolatie spouwmuren | | | | | | | | | | | X | | | | | | | | | | | O | O |
| Na-isolatie in voorzetwand (met stuclaag) | X | | | | | X | | | | | X | | | | | | | | | | | O | O |
| Na-isolatie daken binnenzijde | X | | | | | X | | | | | X | | | | | | | | | | | X | X |
| Na-isolatie hellend dak (vervanging) | X | | X | | | | | | | | X | | | | | | | | | X | X | O | O |
| Na-isolatie hellend dak (materiaal onder dakpan) | | | X | | | | | | | | X | | | | | | | | | | | O | O |
| Isolatie plat dak | | | X | | | | | | | | X | | | | | | | | | ? | ? | O | O |
| Isolatie onder maaiveld | | | | | | | | | | | X | | | | | | | | | X | X | O | O |
| Isolatie met drukvaste stenen KIM | | X | | | | | | | | | X | | | | | | | | | | | ? | ? |
| Gevelisolatie (met betimmering) | X | | | | | | | | | | X | | | | | | | | | O | O | O | O |
| Gevelisolatie (met stuclaag) | | | | | X | | | | | | X | | | | | | | | | O | O | O | O |
| Gevelisolatie (met metselwerk) | | X | | | | | | | | | X | | | | | | | | | O | O | O | O |
| Gevelisolatie (met steenstrips) | | X | | | X | | | | | | X | | | | | | | | | O | O | O | O |
| Gevelisolatie isolerend binnenspouwblad | | X | | | | | | | | | X | | | | | | | | | | | | |
| Isolerende tussenwanden | X | | | | | X | | | | | X | | | | | | | | | O | O | O | O |
| Zonwerende glasfolie | | | | X | | | | | | | X | | | | | | | | | O | O | O | O |
| Hoogwaardig geisoleerd glas | | | | X | | | | | | | | | | | | | | | | X | X | X | X |
| Schakelbaar glas/ smart glas | | | | X | | | | | | | | | | | | | | | | | | | |
| Laag temperatuur verwarming | | | | | | | | | | | | | | | | X | X | | | X | X | X | O |
| Duurzaam licht | | | | | | | | | | | X | | | X | X | | | | | X | X | X | X |
| Hoog temperatuurkoeling | | | | | | | | | | | | | | | | | | X | X | O | O | O | O |
| Montage prefab vloeren | X | | | | | | | | | | X | | | | | | | | | | | | |
| Montage prefab gevel elementen beton | | | | | | | | | | | X | | | | | | | | | X | X | O | O |
| Montage prefab gevel elementen hout | X | | | | | | | | | | X | | | | | | | | | X | X | O | O |
| Montage kozijnen, ramen, deuren | X | | | | | | | | | | X | | | | | | | | | | | X | X |
| Montage prefab daken | X | | X | | | | | | | | X | | | | | | | | | X | X | O | O |
| Montage tuimelvensters | X | | | | | | | | | | X | | | | | | | | | | | X | X |
| Montage prefab dakkapellen | X | | | | | | | | | | X | | | | | | | | | | | O | O |
| Montage vegetatiedak en -gevel | | | X | | | | | | | | X | | | | | | | | | ? | ? | O | O |
| Luchtdicht bouwen | X | | | | | | | | | | X | | | | | | | | | X | X | X | O |
| Bewaken energetische kwaliteit gebouwschil | | | | | | | X | | | | X | | | X | X | | | | | X | X | X | X |
| Thermografie bij installaties | | | | | | | | | | | X | | | X | X | | | | | | | | O |

**FIGURE 12 MATRIX OF PROFESSIONS AND SPECIALIZATIONS (STRAATMEIJER AND KONING, 2015)**

# Appendix C

TABLE 35 EXPECTED INVESTMENTS IN THE INSTALLATION SECTOR IN 2017 PER PROFESSION PER SECTOR (ADAPTED FROM UNETO-VNI, 2016)

| | Million € | Share per profession |
|---|---|---|
| **Housing Total** | 8,875 | |
| Electro | 3,714 | 50% |
| Climate | 2,797 | 46% |
| Plumbing | 2,364 | 59% |
| **Utility Total** | 7,935 | |
| Electro | 3,300 | 45% |
| Climate | 2,987 | 49% |
| Plumbing | 1,638 | 41% |
| **Infrastructure Total (ground, water, road)** | 680 | |
| Electro | 375 | 5% |
| Climate | 305 | 5% |
| **Total** | 17,490 | |

TABLE 36 EXPECTED INVESTMENTS IN THE INSTALLATION SECTOR IN 2017 PER USE PER SECTOR (ADAPTED FROM UNETO-VNI, 2016)

| | Million € | Share |
|---|---|---|
| **Housing Total** | 8,875 | |
| New Construction | 3,961 | 45% |
| Reconstruction and renovation | 3,307 | 37% |
| Maintenance | 1,607 | 18% |
| **Utility Total** | 7,935 | |
| New Construction | 4,111 | 52% |
| Reconstruction and renovation | 2,124 | 27% |
| Maintenance | 1,700 | 21% |
| **Infrastructure Total (ground, water, road)** | 680 | |
| New construction and reconstruction | 387 | 57% |
| Maintenance | 293 | 43% |
| **Total** | 17,490 | |

# Appendix D

**ENERGETISCH NIVEAU**

| | |
|---|---|
| pakket maatregelen | oorspronkelijk |

**ALGEMEEN**

| | |
|---|---|
| type woning | hoekwoning / twee-onder-een-kap |
| type dak | hellend |
| aantal bewoners (-) | 3,0 |
| gebruiksoppervlak (m2) | 102,0 |
| serre | - |

| BOUWKUNDIG | begrenzing | ZTA | oppervlak | Rc | U-waarde |
|---|---|---|---|---|---|
| | [-] | [-] | [m2] | [m2K/W] | [W/m2K] |
| begane grondvloer | kruipruimte/grond | - | 55,0 | 0,15 | 2,44 |
| plat dak | buiten | - | 17,7 | 0,22 | 2,08 |
| hellend dak | buiten | - | 55,9 | 0,22 | 2,08 |
| voor-/achtergevel | | | | | |
| gesloten | buiten | - | 49,0 | 0,19 | 2,22 |
| enkelglas | buiten | 0,8 | 21,1 | - | 5,20 |
| dubbelglas | buiten | 0,7 | - | - | - |
| HR++glas | buiten | 0,6 | - | - | - |
| zijgevel | | | | | |
| gesloten | buiten | | 17,4 | 0,19 | 2,22 |
| enkelglas | buiten | 0,8 | 0,6 | - | 5,20 |
| dubbelglas | buiten | 0,7 | - | - | - |
| HR++glas | buiten | 0,6 | - | - | - |

NB oriëntatie glas is oost/west

| VENTILATIE | naam |
|---|---|
| ventilatiesysteem | natuurlijke ventilatie |
| type warmteterugwinning | geen |
| eigen waarde rendement warmteterugwinning | - |
| gelijkstroomventilatoren | nee |
| kierdichting | nee |

**PV CELLEN**

| | |
|---|---|
| PV cellen aanwezig | nee |
| PV type | - |
| PV oppervlak (m2) | - |
| hellingshoek PV (°) | - |
| orientatie PV (°) | - |

| RUIMTEVERWARMING | naam |
|---|---|
| type ruimteverwarming | individueel |
| individueel: toestel ruimteverwarming | lokaal gas of olie |
| collectief: preferent toestel ruimteverwarming | - |
| vermogen preferent toestel (kW) | - |
| niet preferent toestel | - |
| vermogen niet preferent toestel (kW) | - |
| plaats perwarmingstoestel | binnen thermische schil |
| temperatuurniveau | > 55 graden Celsius |
| afgiftesysteem | radiatoren |
| pompregeling | - |
| waakvlam | nee |
| leidingen in onverwarmde ruimten | ja |
| leidingisolatie van leidingen in o.r. | nee |
| individuele bemetering | ja |
| optimale afregeling | nee |

| WARMTAPWATER | naam |
|---|---|
| toestel warmtapwater | keukengeiser |
| HRww aanwezig | nee |
| keukenboiler aanwezig | nee |
| douche aanwezig | ja |
| bad aanwezig | ja |
| vaatwasser aanwezig | nee |
| spaardouchekop aanwezig | nee |
| beperkte leidinglengte | nee |
| douchewater warmteterugwinning aanwezig | nee |
| circulatieleiding aanwezig | nee |
| isolatie van circulatieleiding | - |
| zonneboilertype | geen |
| zonnekeurlabel | - |
| oppervlak collectieve collector (m2) | - |
| hellingshoek collector (°) | - |
| orientatie collector (°) | - |

**ENERGIEPRESTATIE**

| | |
|---|---|
| EI (-) | 4,25 |
| energielabel | G |
| totaal primair energiegebruik EI (MJ) | 198.936 |
| m3 gas 1) | 5.094 |
| kWh hulpenergie, verlichting, PV 1) | 612 |
| CO2 emissie (kg/jaar) | 9.414 |

**INVESTERINGSKOSTEN 2)**

| | |
|---|---|
| projectmatige investeringskosten t.o.v. huidig pakket | |
| investeringskosten t.o.v. huidig pakket voor enkele woning | |

**ENERGIELASTEN 3)**

| | | |
|---|---|---|
| vaste kosten gas (€ / jaar) | | 152 |
| gasverbruik (€ / jaar) | (€ 0,4411 per m3) | 2.247 |
| vaste kosten elektriciteit (€ / jaar) | | 197 |
| elektriciteitsverbruik (€ / jaar) | (€ 0,1866 per kWh) | 114 |
| energielasten (€ / jaar) | | 2.710 |
| besparing energielasten t.o.v. huidig pakket (€ / jaar) | | |

1) op basis van de EI-berekening, maar met een binnentempertuur van 16,5°C i.p.v. 18°C, zonder comfortcorrectie bij lokal

2) de investeringen van 'Huidig' naar 'Comfort' zijn exclusief btw en en het prijspeil van 1 maart 2010

3) prijspeildatum januari 2010, inclusief energiebelasting, exclusief btw

**FIGURE 13 EXAMPLE OF RELEVANT CHARACTERISTICS TO DETERMINE THE ENERGY PERFORMANCE OF A HOUSE (BZK, 2011C)**

# Appendix E

TABLE 37 REDUCTIONS OF ANNUAL $CO_2$ EMISSIONS OF ELECTRICITY USE PER MEASURE PER BUILDING PERIOD PER INDIVIDUAL TERRACED HOUSE

| (kg $CO_2$) | <46 | 46-64 | 65-74 | 75-91 | 92> |
|---|---|---|---|---|---|
| **Insulation** | -336 | -288 | -348 | -348 | -176 |
| **Green Gas: Green gas and Insulation** | -336 | -288 | -348 | -348 | -176 |
| **Green Gas: Green gas** | - | - | - | - | - |
| **Electrification: PV-Heat Pump** | -2,170 | -1,649 | -1,010 | -389 | -148 |
| **Electrification: PV** | 1,410 | 1,410 | 1,410 | 1,410 | 1,410 |
| **Electrification: Heat Pump** | -3,579 | -3,059 | -2,420 | -1,799 | -1,558 |
| **Electrification: Insulation-Heat Pump** | -1,413 | -1,250 | -1,308 | -1,313 | -1,218 |
| **Electrification: Insulation-PV** | 1,074 | 1,122 | 1,061 | 1,061 | 1,234 |
| **Electrification: Insulation-PV-Heat Pump** | -3 | 159 | 101 | 96 | 192 |
| **Heat District: Connection** | 61 | 62 | 61 | 61 | 61 |
| **Heat District: Connection and Insulation** | -275 | -227 | -288 | -288 | -115 |

TABLE 38 REDUCTIONS OF ANNUAL $CO_2$ EMISSIONS OF ELECTRICITY USE PER MEASURE PER BUILDING PERIOD OF THE TERRACED HOUSING STOCK

| (ktonne $CO_2$) | <46 | 46-64 | 65-74 | 75-91 | 92> |
|---|---|---|---|---|---|
| **Insulation** | -171 | -134 | -206 | -298 | -125 |
| **Green Gas: Green gas and Insulation** | -171 | -134 | -206 | -298 | -125 |
| **Green Gas: Green gas** | - | - | - | - | - |
| **Electrification: PV-Heat Pump** | -1,107 | -765 | -596 | -333 | -106 |
| **Electrification: PV** | 719 | 654 | 831 | 1,205 | 1,003 |
| **Electrification: Heat Pump** | -1,826 | -1,419 | -1,427 | -1,538 | -1,109 |
| **Electrification: Insulation-Heat Pump** | -721 | -580 | -772 | -1,123 | -866 |
| **Electrification: Insulation-PV** | 548 | 520 | 626 | 907 | 878 |
| **Electrification: Insulation-PV-Heat Pump** | -1 | 74 | 60 | 82 | 137 |
| **Heat District: Connection** | 31 | 29 | 36 | 52 | 43 |
| **Heat District: Connection and Insulation** | -140 | -105 | -170 | -246 | -82 |

Table 39 Labor Efficiency per set of Measures per Terraced Housing Type of Reducing Emissions of Electricity use

| (FTE/ktonne $CO_2$) | **<46** | **46-64** | **65-74** | **75-91** | **92>** |
|---|---|---|---|---|---|
| **Insulation** | -147.0 | -169.1 | -151.4 | -150.5 | -256.5 |
| **Green Gas: Green gas and Insulation** | -147.0 | -169.1 | -151.4 | -150.5 | -256.5 |
| **Green Gas: Green gas** | - | - | - | - | - |
| **Electrification: PV-Heat Pump** | -9.7 | -12.8 | -20.9 | -54.2 | -141.7 |
| **Electrification: PV** | 6.7 | 6.7 | 6.7 | 6.7 | 6.7 |
| **Electrification: Heat Pump** | -4.7 | -5.5 | -6.9 | -9.3 | -10.8 |
| **Electrification: Insulation-Heat Pump** | -46.7 | -52.5 | -53.2 | -52.7 | -50.8 |
| **Electrification: Insulation-PV** | 54.6 | 52.0 | 58.7 | 58.3 | 44.1 |
| **Electrification: Insulation-PV-Heat Pump** | -35,910.9 | 438.6 | 727.4 | 766.9 | 343.7 |
| **Heat District: Connection** | 431.6 | 419.5 | 429.6 | 431.1 | 433.9 |
| **Heat District: Connection and Insulation** | -275.1 | -331.7 | -274.5 | -273.4 | -618.6 |

# Appendix F

TABLE 40 REQUIRED, DEPLOYABLE, AND DISTRIBUTED DEPLOYABLE LABOR, AND THE REQUIRED YEARS PER MEASURE PER TERRACED HOUSING TYPE

| Building Period | Scenario | Measure | Required FTE's | Deployable Labor | Distributed Deployable (FTE's/Year) | Years Required (years) |
|---|---|---|---|---|---|---|
| <46 | **Insulation** | Insulation Wall | 8,808 | 6,934 | 3,463 | 2.5 |
| | | Insulation Roof | 11,094 | 6,518 | 3,708 | 3.0 |
| | | Insulation Floor | 896 | 6,022 | 259 | 3.5 |
| | **Green Gas** | Ventilation (Green Gas) | 4,343 | 4,303 | 4,303 | 1.0 |
| | **Electrification** | Ventilation (Electrification) | 4,343 | 4,303 | 1,812 | 2.4 |
| | | PV-Panels | 2,220 | 5,016 | 5,016 | 0.4 |
| | | Heat Pumps | 5,971 | 4,568 | 2,757 | 2.2 |
| | | Electricity Grid | 571 | 792 | 792 | 0.7 |
| | | Electricity Grid Cables | 1,164 | 2,517 | 2,517 | 0.5 |
| | | Electricity Grid Street | 845 | 810 | 810 | 1.0 |
| | **District Heating** | Ventilation (Heat District) | 4,343 | 4,303 | 3,279 | 1.3 |
| | | Heat District Connection | 1,357 | 4,303 | 1,025 | 1.3 |
| | | Heat District Ground | 4,017 | 1,111 | 1,111 | 3.6 |
| | | Heat District Street | 2,931 | 1,378 | 1,378 | 2.1 |
| | | Heat District Pipes | 5,075 | 756 | 756 | 6.7 |
| | **Mixed Sources** | Ventilation (Mixed Scenario) | 4,343 | 4,303 | 2,754 | 1.6 |
| | | PV-Panels | 740 | 5,016 | 5,016 | 0.1 |
| | | Heat Pumps | 1,990 | 4,568 | 1,527 | 1.3 |
| | | Electricity Grid | 190 | 792 | 792 | 0.2 |
| | | Electricity Grid Cables | 388 | 2,517 | 2,517 | 0.2 |
| | | Electricity Grid Street | 282 | 810 | 810 | 0.3 |
| | | Heat District Connection | 452 | 4,303 | 287 | 1.6 |
| | | Heat District Ground | 1,339 | 1,111 | 1,111 | 1.2 |
| | | Heat District Street | 977 | 1,378 | 1,378 | 0.7 |
| | | Heat District Pipes | 1,692 | 756 | 756 | 2.2 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **46-64** | **Insulation** | Insulation Wall | 7,190 | 6,934 | 3,226 | 2.2 |
| | | Insulation Roof | 9,409 | 6,518 | 3,523 | 2.7 |
| | | Insulation Floor | 2,116 | 6,022 | 681 | 3.1 |
| | **Green Gas** | Ventilation (Green Gas) | 3,948 | 4,303 | 4,303 | 0.9 |
| | **Electrification** | Ventilation (Electrification) | 3,948 | 4,303 | 2,884 | 1.4 |
| | | PV-Panels | 2.019 | 5.016 | 5.016 | 2.1 |
| | | Heat Pumps | 5.428 | 4.568 | 2.757 | 0.4 |
| | | Electricity Grid | 519 | 792 | 792 | 2.0 |
| | | Electricity Grid Cables | 1.058 | 2.517 | 2.517 | 0.7 |
| | | Electricity Grid Street | 768 | 810 | 810 | 0.4 |
| | **District Heating** | Ventilation (Heat District) | 3,948 | 4,303 | 2,884 | 1.4 |
| | | Heat District Connection | 1,234 | 4,303 | 1,025 | 1.2 |
| | | Heat District Ground | 3,652 | 1,111 | 1,111 | 3.3 |
| | | Heat District Street | 2,665 | 1,378 | 1,378 | 1.9 |
| | | Heat District Pipes | 4,614 | 756 | 756 | 6.1 |
| | **Mixed Sources** | Ventilation (Mixed Scenario) | 3,948 | 4,303 | 2,754 | 1.4 |
| | | PV-Panels | 673 | 5,016 | 5,016 | 0.1 |
| | | Heat Pumps | 1,809 | 4,568 | 1,527 | 1.2 |
| | | Electricity Grid | 173 | 792 | 792 | 0.2 |
| | | Electricity Grid Cables | 353 | 2,517 | 2,517 | 0.1 |
| | | Electricity Grid Street | 256 | 810 | 810 | 0.3 |
| | | Heat District Connection | 411 | 4,303 | 287 | 1.4 |
| | | Heat District Ground | 1,217 | 1,111 | 1,111 | 1.1 |
| | | Heat District Street | 888 | 1,378 | 1,378 | 0.6 |
| | | Heat District Pipes | 1,538 | 756 | 756 | 2.0 |
| **65-74** | **Insulation (Green Gas, Electrification, District Heating)** | Insulation Wall | 9,521 | 6,934 | 3,102 | 3.1 |
| | | Insulation Roof | 13,678 | 6,518 | 3,642 | 3.8 |
| | | Insulation Floor | 2,977 | 6,022 | 685 | 4.3 |
| | **Green Gas** | Ventilation (Green Gas) | 5,019 | 4,303 | 4,303 | 1.2 |
| | **Electrification** | Ventilation (Electrification) | 5,019 | 4,303 | 3,955 | 1.3 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | PV-Panels | 2.567 | 5.016 | 5.016 | 0,5 |
| | | Heat Pumps | 6.902 | 4.568 | 2757 | 2,5 |
| | | Electricity Grid | 659 | 792 | 792 | 0,8 |
| | | Electricity Grid Cables | 1.345 | 2.517 | 2.517 | 0,5 |
| | | Electricity Grid Street | 977 | 810 | 810 | 1,2 |
| | **District Heating** | Ventilation (Heat District) | 5,019 | 4,303 | 3,955 | 1.3 |
| | | Heat District Connection | 1,569 | 4,303 | 1,025 | 1.5 |
| | | Heat District Ground | 4,643 | 1,111 | 1,111 | 4.2 |
| | | Heat District Street | 3,388 | 1,378 | 1,378 | 2.5 |
| | | Heat District Pipes | 5,866 | 756 | 756 | 7.8 |
| | **Mixed Sources** | Ventilation (Mixed Scenario) | 5,019 | 4,303 | 2,754 | 1.8 |
| | | PV-Panels | 856 | 5,016 | 5,016 | 0.2 |
| | | Heat Pumps | 2,301 | 4,568 | 1,527 | 1.5 |
| | | Electricity Grid | 220 | 792 | 792 | 0.3 |
| | | Electricity Grid Cables | 448 | 2,517 | 2,517 | 0.2 |
| | | Electricity Grid Street | 326 | 810 | 810 | 0.4 |
| | | Heat District Connection | 523 | 4,303 | 287 | 1.8 |
| | | Heat District Ground | 1,548 | 1,111 | 1,111 | 1.4 |
| | | Heat District Street | 1,129 | 1,378 | 1,378 | 0.8 |
| | | Heat District Pipes | 1,955 | 756 | 756 | 2.6 |
| **75-92** | **Insulation (Green Gas, Electrification, District Heating)** | Insulation Wall | 12,538 | 6,934 | 2,922 | 4.3 |
| | | Insulation Roof | 20,795 | 6,518 | 3,829 | 5.4 |
| | | Insulation Floor | 4,232 | 6,022 | 678 | 6.2 |
| | **Green Gas** | Ventilation (Green Gas) | 7,275 | 4,303 | 4,303 | 1.7 |
| | **Electrification** | Ventilation (Electrification) | 7,275 | 4,303 | 6,211 | 1.2 |
| | | PV-Panels | 3.720 | 5.016 | 5.016 | 0,7 |
| | | Heat Pumps | 10.004 | 4.568 | 2757 | 3,6 |
| | | Electricity Grid | 956 | 792 | 792 | 1,2 |
| | | Electricity Grid Cables | 1.949 | 2.517 | 2.517 | 0,8 |
| | | Electricity Grid Street | 1.416 | 810 | 810 | 1,7 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | **District Heating** | Ventilation (Heat District) | 7,275 | 4,303 | 6,211 | 1.2 |
| | | Heat District Connection | 2,274 | 4,303 | 1,025 | 2.2 |
| | | Heat District Ground | 6,730 | 1,111 | 1,111 | 6.1 |
| | | Heat District Street | 4,911 | 1,378 | 1,378 | 3.6 |
| | | Heat District Pipes | 8,503 | 756 | 756 | 11.2 |
| | **Mixed Sources** | Ventilation (Mixed Scenario) | 7,275 | 4,303 | 2,754 | 2.6 |
| | | PV-Panels | 1,240 | 5,016 | 5,016 | 0.2 |
| | | Heat Pumps | 3,335 | 4,568 | 1,527 | 2.2 |
| | | Electricity Grid | 319 | 792 | 792 | 0.4 |
| | | Electricity Grid Cables | 650 | 2,517 | 2,517 | 0.3 |
| | | Electricity Grid Street | 472 | 810 | 810 | 0.6 |
| | | Heat District Connection | 758 | 4,303 | 287 | 2.6 |
| | | Heat District Ground | 2,243 | 1,111 | 1,111 | 2.0 |
| | | Heat District Street | 1,637 | 1,378 | 1,378 | 1.2 |
| | | Heat District Pipes | 2,834 | 756 | 756 | 3.7 |
| **92-99** | **Insulation (Green Gas, Electrification, District Heating)** | Insulation Wall | 12,553 | 6,934 | 3,387 | 3.7 |
| | | Insulation Roof | 14,129 | 6,518 | 3,281 | 4.3 |
| | | Insulation Floor | 3,868 | 6,022 | 762 | 5.1 |
| | **Green Gas** | Ventilation (Green Gas) | 1,514 | 4,303 | 4,303 | 0.4 |
| | **Electrification** | Ventilation (Electrification) | 1,514 | 4,303 | 662 | 2.3 |
| | | PV-Panels | 3,096 | 5,016 | 5,016 | 0.6 |
| | | Heat Pumps | 8,326 | 4,568 | 3,906 | 2.1 |
| | | Electricity Grid | 796 | 792 | 792 | 1.0 |
| | | Electricity Grid Cables | 1,623 | 2,517 | 2,517 | 0.6 |
| | | Electricity Grid Street | 1,178 | 810 | 810 | 1.5 |
| | **District Heating** | Ventilation (Heat District) | 1,514 | 4,303 | 893 | 1.7 |
| | | Heat District Connection | 1,892 | 4,303 | 2,391 | 0.8 |
| | | Heat District Ground | 5,601 | 1,111 | 1,111 | 5.0 |
| | | Heat District Street | 4,087 | 1,378 | 1,378 | 3.0 |
| | | Heat District Pipes | 7,077 | 756 | 756 | 9.4 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | **Mixed Sources** | Ventilation (Mixed Scenario) | 1,514 | 4,303 | 1,324 | 1.1 |
| | | PV-Panels | 1,032 | 5,016 | 5,016 | 0.2 |
| | | Heat Pumps | 2,775 | 4,568 | 2,693 | 1.0 |
| | | Electricity Grid | 265 | 792 | 792 | 0.3 |
| | | Electricity Grid Cables | 541 | 2,517 | 2,517 | 0.2 |
| | | Electricity Grid Street | 393 | 810 | 810 | 0.5 |
| | | Heat District Connection | 631 | 4,303 | 552 | 1.1 |
| | | Heat District Ground | 1,867 | 1,111 | 1,111 | 1.7 |
| | | Heat District Street | 1,362 | 1,378 | 1,378 | 1.0 |
| | | Heat District Pipes | 2,359 | 756 | 756 | 3.1 |