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Spatial energy model for the reduction in CO₂ by district heating systems within the built environment in the Netherlands

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Spatial energy model for the reduction in CO₂ by district heating systems within the built environment in the Netherlands

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ABSTRACT

A more sustainable heat supply of the built environment is needed to reach the policy goal of a climate-neutral economy in the Netherlands by 2050. This paper presents a method using a spatial energy model to calculate the most cost-effective CO₂-reduction potential of a sustainable heat supply in the energy-demanding built environment in the Netherlands. The model can be used to evaluate national energy outlooks and to advise policymakers, to improve policy decision-making in the field of energy. Objects of analysis are the CO₂-reduction potential and the costs of energy measures. There are two main model options concerning the types of measures that can be run separately or together. These options refer to a reduction in heat demand (energy conservation) achieved through certain building measures, and/or through district heating measures. Options for district heating consist of: waste heat for electricity and industrial plants, geothermal heating, combined heat and power district heating (CHPDH), and systems for ground source heat pumps (GSHP). The potential of district heating systems depends on the local availability of heat sources, on the one hand, and the intensity and extent of heat demand, on the other. For this purpose, the spatial energy model uses highly detailed geographical data on residential buildings and the services sector. With the aid of energy characteristics for the different types of buildings, the heat demand is calculated in each postcode-4 area of the Netherlands. Next the cost-effectiveness of district heating to the nearest option (heat source) of district heating for each postcode-4 area is calculated by the net present value (NPV), viewed from the perspective of the heat supplier. By considering in the calculation algorithm only the nearest heat source for each postcode-4 area calculation time is limited. A disadvantage of this algorithm is that the cost-effectiveness of the postcode-4 area to a heat source at larger distances could be better, in some cases. So the used algorithm yields the locally optimal solution but gives no absolute guarantee to find the general optimal solution for all heat sources. Nevertheless, we conclude that this heuristic approach approximates the globally optimal solution. Therefore, it is what is known as a 'greedy' algorithm. The paper also discusses methods to improve this greedy algorithm. Finally, it presents some results of an analysis made with the aid of the model. The cost-effective CO₂-reduction potential in a business as usual scenario of energy conservation and district heating, by 2050, will be 15% to 30% of the emissions related to the built environment. This range depends on the assumed energy prices and investment costs of the energy conservation measures. The contribution of district heating is 10 to 15 percentage points.

Key words

District heating, energy model, greedy algorithm, CO₂ reduction, waste heat, built environment, energy conservation, energy policy, heat supply, GIS.

1. INTRODUCTION

One of the main long-term goals of the Dutch Government is to achieve a climate-neutral Dutch economy by the year 2050 [15]. A more sustainable heat supply in the built environment (residential housing, service sector, greenhouse horticulture) may contribute to achieving this goal. At this moment, the share of natural gas in the heat supply is 90% [5] in the Netherlands. As the concern about energy supply is growing there is also an increasing interest in studies concerning energy transitions in a real and integrated way. One of the ways to achieve such better integration would be by taking the possibilities of district heating more into consideration. Since the 1970s, waste heat, one of the options for district heating, has been an established technique in the Netherlands. In other European countries, such as Denmark [4], waste heat also contributes significantly to district heating systems.

Vesta, the energy model described in this paper, is a model that matches future projected demand for energy in the built environment to options for energy savings in buildings and sustainable district energy production. The new built environment for the year 2050 for Vesta is calculated by the Land Use Scanner [6, 8]. Distinction is made in new housing development districts and redevelopment areas. The energy demand for heat is around 684 PJ in the Netherlands in 2008 [15]. Dwellings takes up around 49% of this figure. In general, district heating will be more profitable and successful as energy prices rise, which they are generally expected to do in the future. The potential for waste heat will be growing in the Netherlands, as four large new power plants are becoming in operation in the Netherlands in the near future. Also relatively new options for district heating are coming up. In the last year, the first two projects of geothermal heating have been implemented for the heat supply of current and newly built dwellings. In dozens of projects, ground source heat pumps have been installed, mainly for newly built offices and residential properties.

The next chapter considers the purpose of the energy model. Subsequently, the input of the energy model is described (Chapter 3). Chapter 4 focuses on the matching of heat demand and supply, and, Chapter 5 presents some results from an analysis made with the aid of the energy model. Finally, Chapter 6 discusses the method used and draws some conclusions.

2. Purpose of the energy model

The purpose of the newly created Vesta energy model is to calculate the cost-effective CO₂-reduction potential of a sustainable heat supply in the energy-demanding built environment of the Netherlands. The model can be used to evaluate national energy outlooks and to advise policymakers to improve policy decision-making in the field of energy. Objects of analysis are the CO₂-reduction potential and the costs of energy measures. The considered options are divided into two main categories: reduction in the heat demand (energy conservation) of buildings, and district heating. One of the problems which can be analysed by the model is the risk of cannibalisation of the options: if the cost-effective potential of energy conservation in buildings would be realised at some time in the future, the cost-effective potential of district heating would be lower than without energy conservation, and vice versa. Therefore, the effect at energy conservation of both categories is less than when calculated separately.

3. Input of the energy model

3.1 Introduction

The Vesta model can be used to project energy use and CO₂ emissions related to the built environment, including greenhouse horticulture, for the period from 2010 to 2050. Figure 1 presents an overview of the model's main processing blocks. The main focus in this paper is on matching algorithms between energy demand and supply for the district measures (Chapter 4 and beyond). The other blocks are discussed briefly, to explain the matching algorithms. Possible district measures consist of:

1. Waste heat from electricity and industrial plants.
2. Geothermal heating
3. Combined Heat and Power District Heating (CHDPH), local cogeneration of heat and electric power from gas.
4. Ground source heat pump (GSHP); sometimes called geothermal heat pump.

In Vesta model, it is possible to run only district heating options, or user-specified building-specific options such as insulation, as well as both types of options together. Building options to reduce the heat demand consist of thermal insulation, high efficiency condensed boilers, solar water heaters, and electrical heat pumps. The demand for energy is modelled, geographically specific, for: residential buildings, the service sector (excluding industrial usage, agriculture and transportation) and greenhouse horticulture. To simulate future land use, which is the input data for the model, the Land Use Scanner (Dutch: *Ruimtescanner*) has been used; a GIS-based spatial model. In this respect, the Vesta model is part of a model chain. The Land Use Scanner is based on demand–supply interaction with respect to land use, with sectors competing for allocation within suitability and policy constraints. Since its development in 1997, the Land Use Scanner has been applied in many policy-related land-use projects. Applications include the simulation of future land use, following various scenarios [7, 13]. The model results consist of 100 x 100 metre grids, and are also used in the Vesta model. Figure 2 provides an impression of this, showing the western part of the Netherlands, which is used as input data (newly built environment) for the Vesta model [11]. In addition, it would be worth mentioning that GSHP is the only option of the four district heating options that could not be applied

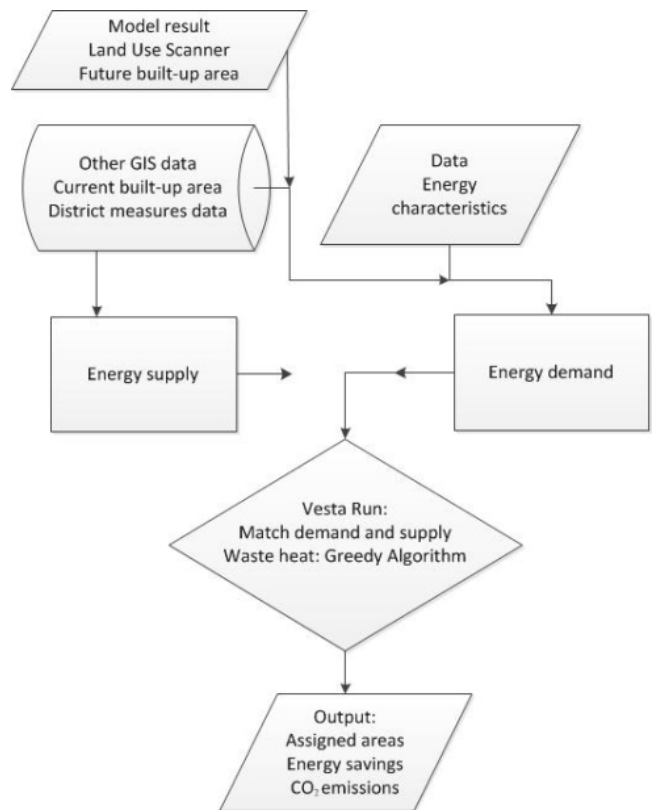


Figure 1: Flowchart processing-blocks Vesta

in the current built environment; it could only be used in future residential areas or redevelopment areas. The Vesta model and the Land Use Scanner both run on the Geo Data and Model Server (GeoDMS) modelling framework [10] which is mainly written in C⁺⁺. Also the Land Use Scanner runs on this framework. The Declarative Model Script (the so-called .dms files) is used for model scripting.

3.2 Composition of the built environment

The built environment is built up in the Vesta model by six layers of GIS data with a high level of spatial detail:

- Residential buildings: current and future houses per postcode-6 area;
- Service sector: current and future buildings per address;
- Greenhouse horticulture: current and future locations per grid area.

In the Vesta model, for each layer, the energy demand is calculated by means of energy characteristics. By summing the energy demand for each layer, the total energy demand can be determined for a certain area.

3.2.1 Current built environment

The Vesta model includes residential buildings in 458,841 (Data source: WDM Geomarktprofiel) postcode-6 areas, representing 7,140,101 households. Each residential postcode 6, on average, consists of 15.6 ($\sigma=13.7$) households, representing a street or part of a street. A geometric point is placed at the weight point of the residential area. For each postcode-6 area, the dominant housing type (one of 14 types) and construction period (one of 12 periods)

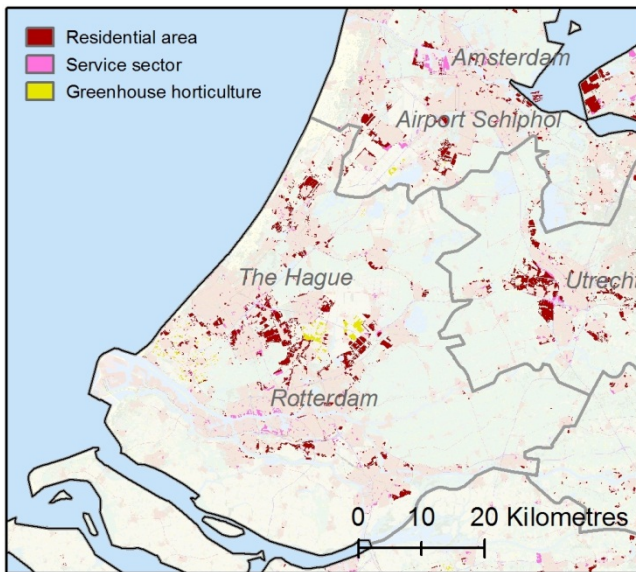


Figure 2: New build-up area in western Netherlands in 2050

is known. Characteristics of the particular energy demand are known for each combination of housing type and construction period. The most common housing type is the family home from the 1970–1979 construction period. The buildings in the service sector are located at 395,789 different addresses (Data source: LISA), divided into 8 classes of economic activity. For each location, the number of employees is also known. Energy demand is calculated by means of average floor space, in square metres per employee and economic activity type. In contrast to residential buildings, construction periods for the service sector are not known. The most common housing type in the service sector is the office building. Also in terms of energy demand, offices are the most important housing type in the service sector in the Netherlands. Greenhouse horticulture is quite common in some parts of the Netherlands and this, therefore, is an important sector from the perspective of energy demand and thereby the cost effectiveness of district heating systems. In the Vesta model, current greenhouse horticulture consists of 68,056 points, representing as many plots of land. Energy demand is determined by plot size in square metres and the type of greenhouse (heated versus unheated, and lighted versus unlit). Figure 3 provides an impression of the built environment used in the western part of Utrecht, in the Vesta model.

3.2.2 Future built environment

The future built environment for 2050 is calculated by means of the Land Use Scanner, which models the transformation of land use over a period of time [8]. New residential areas with their housing densities are directly extracted as output from the Land Use Scanner and can be used in the Vesta model. Demolition and redevelopment will take place in a certain geographical sequence defined by the degree of social deprivation and condition of the buildings. Redevelopment is implemented in the Vesta model by changing the number and the construction period of existing residential houses. By changing the construction period, the energy demand, as well as other energy characteristics used. For the Netherlands, the total additional amount of houses in 2050 will be 1,137,933 relative to the year 2010, according to a trend projection of population, houses, economy and employment [5]. Also according to this projection and with the aid of future service sector areas, job numbers for 2050 are distributed over these new

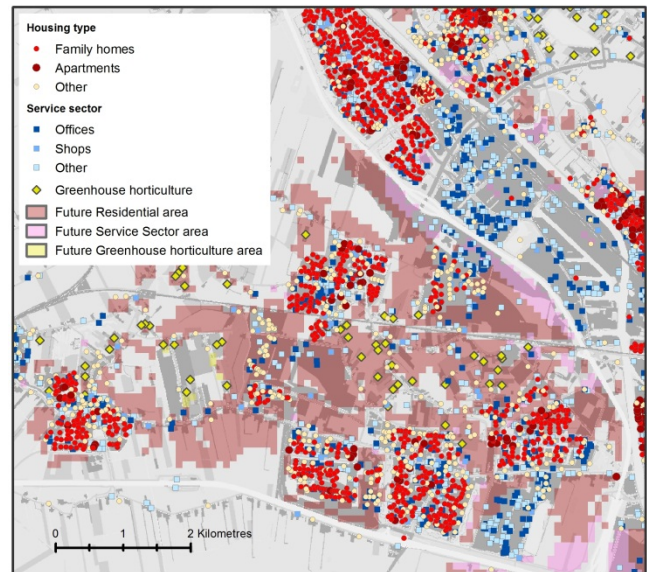


Figure 3: Built environment in the west of Utrecht (in the Vesta model)

building locations. As the exact type of service sector is not known for a new location, jobs for each service sector class are allocated according to a distribution key, based on the current ratio of classes in a certain area. Demolition of business locations is not included in the Vesta model. Instead, the number of employees per service sector location is reduced in shrinking regions. The number of jobs will rise with 420,700 by 2050, according to the trend projection [5]. Future development of the greenhouse horticulture area is taken directly from the Land Use Scanner results, as the energy demand is determined by the size of greenhouses, in square metres. The greenhouse area in the Netherlands is projected to have grown by 7% by 2050, according to the Land Use Scanner model-results.

3.3 Energy demand and building measures

In the Vesta model, the energy demand for heat per home is based on functional demand (domestic hot water, space heating and cooling) and energy efficiency of the building and energy installations [9]. Seven sample houses – data of NL Agency [1] – with seven possible construction periods were used as a basis for determining the functional heat demand characteristics. When it appeared that direct use of these sample houses overestimated the totally aggregated energy demand in the Netherlands, these characteristics were scaled. The sample houses are matched with the 14 housing types used in the Vesta model. Building measures used are according to the Dutch Energy Performance Certificates, and houses are improved to Label B (from a scale range from B to G). The functional energy demand is based on the long-term average climatic conditions (1975–2005) at De Bilt, a location in the centre of the Netherlands. For the possible future development of the climate in 2050, climate scenarios of the Royal Netherlands Meteorological Institute (KNMI) have been used. Under the default scenario (the G⁺-scenario), the average annual temperature in De Bilt will rise from 10.0 °C to 11.3 °C by 2050. In general, this increase will have a moderating effect on future heat demand. In 2008 (reference year) the total energy demand for heating, in the Vesta model, was 684 PJ, 49% of which for residential buildings, 38% for the service sector and 13% for greenhouse horticulture.

3.4 District heat measures

3.4.1 Waste heat

Waste heat is heat from point sources, such as power plants, waste incinerators and industrial companies, which is delivered to homes, the service sector or greenhouse horticulture [14] by means of pipelines. The heat is used in most cases for space heating and hot water. The network generally includes also one or more additional heat boilers and substations. The temperature of the heat supplied, generally, is between 70 °C and 120 °C. The economic feasibility of waste heat depends mainly on distribution distance and the required density of the heat supply network, which depends on the number and geographical configuration of consumers.

Currently, the Netherlands counts 13 large heating networks, with a total of 227,000 consumers connected to terminals of less than 1,000 kilowatts [2]. The energy saving related to the use of waste heat ranges from 20% to 60% for residential housing. If the waste heat is delivered by power plants, this leads to a decrease in electricity production. For each GigaJoule of waste heat, 0.18 GigaJoule less electricity is produced. To maintain production levels, these plants need to generate more energy, which in turn results in additional costs and emissions. Figure 4 gives an impression of the current heat supply network in the Netherlands.

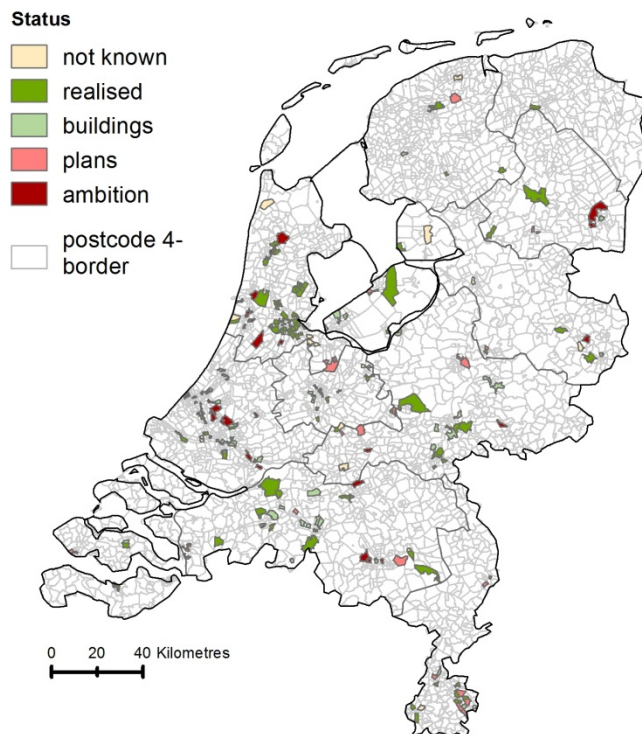


Figure 4: Heat supply network in the Netherlands in 2011 (Source: CE Delft)

3.4.2 Geothermal heating

Geothermal heating is the heat stored in the ground, directly used for heating applications. In practice, it will almost always involve heat from depths of 1,500 metres or more. In the Netherlands, the average groundwater temperature is about 31 °C per vertical kilometre. At depths of more than two kilometres, the temperature of the groundwater varies between 40 and 120 °C. The energy saving related to heating according to ECN is 60% to 70% [3]; and according to the Platform Geothermal Energy [12] this would even be 70% to 80%. The Vesta model assumes the capacity of

geothermal heating not to be a limiting factor to deliveries to postcode-4 service areas. In 2007, the first deep geothermal doublet was realised for greenhouse horticulture in the Netherlands. The first residential houses were connected to geothermal heating in 2012 in The Hague. Figure 5 shows the probabilities of successful drilling for geothermal heating in the Netherlands. Only at a few locations this probability is greater than 70%, the contour used in the Vesta model. This involves locations in Rotterdam, Alkmaar, Hoorn (blue spots in the north-western part of the country) and some areas in the north and north-east of the Netherlands.

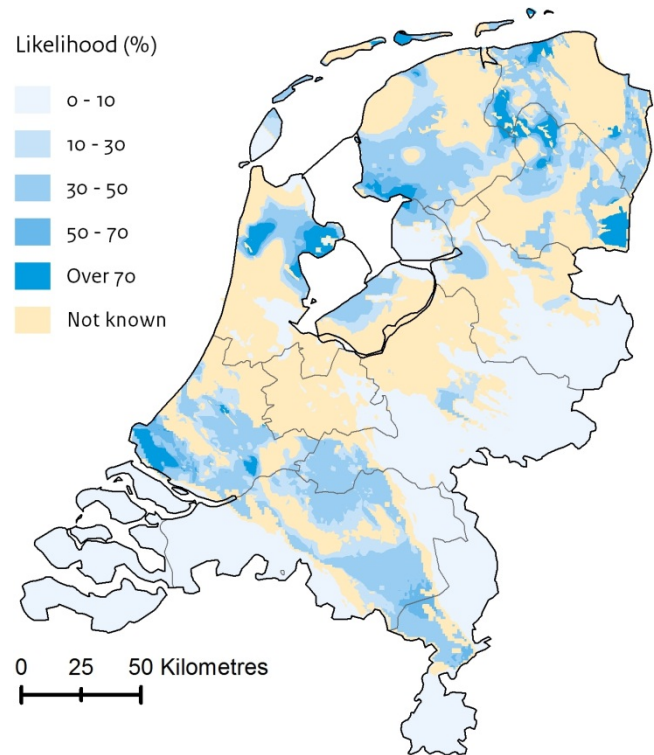


Figure 5: Likelihood of exploitable geothermal energy being present in the Netherlands (source: TNO)

3.4.3 GSHP: Ground Source Heat Pump

Ground source heat pumps (GSHPs) enable the use of heat or cold in the ground; from the shallow underground to several hundreds of metres deep. The Vesta model only considers direct exchange systems that are suitable for large offices and housing blocks. Currently, there are about 1,000 direct exchange systems operational in the Netherlands. Almost the whole of the Netherlands is suitable for the use of geothermal heat pumps, except the Wadden Islands, Zeelandic Flanders and some eastern parts of the country. In summer, cool water (approximately 7 °C) is pumped up and used directly for cooling. After cooling, this water, now heated, is returned to a hot spring (15 to 25 °C). In winter, this heated water is re-used to heat buildings in combination with a heat pump. The now cooled down water is returned to a cold source. The heat pump brings the temperature of the water at a level of 40 to 55 °C [14]. In the Vesta model, the postcode-6 level (458,841 points) is the allocation level to determine if a GSHP system would be profitable and suitable or not.

3.4.4 CHDPH: Combined Heat and Power District Heating

With CHDPH, electricity and heat are generated in the vicinity of the consumption location, by using energy installations. Losses during the transport of heat and electricity are thus reduced to a minimum. In the Netherlands, natural gas is often used in cogeneration, but basically every type of fuel could be used. For the heating of buildings, cogeneration is cost-efficient at current energy prices, and can make an important contribution to CO₂ emission reduction. It is expected that the application of cogeneration will decrease with rising fuel prices. Especially as the electricity prices rise more than the price of natural gas. Mainly because of the extensive natural gas network, the application of cogeneration would be possible anywhere in the Netherlands, geographically speaking. Cogeneration, currently, is still limited to larger energy consumers, such as hospitals and universities.

4. Matching energy demand and supply

4.1 Introduction

District heating is considered at the postcode-4 level, which consists of 4043 areas in the Netherlands. On average, a postcode-4 area is 8.7 km² and contains 1,766 households. Current district heating by waste heat, in the Netherlands, takes place roughly on this scale. In addition, postcode-4 borders closely match district borders, with similar building ages and socio-economic characteristics. In general, the defined areas are mono-functional and form homogeneous residential areas. Only for GSHP the postcode-6 level is considered for district heating, consisting of a total of 458,841 residential cluster-points representing an area.

In the Vesta model, a predefined default order is given for the different possible district measures which can be changed by the researcher. For our analysis, we used: 1. Waste heat; 2. Geothermal heating; 3. GSHP; and 4. CHDPH. This order follows the order in which expected national total specific energy and CO₂ emissions could be avoided through the implementation of these district measures. This is a robust approach for the Netherlands, but it is dependent on several specific and local conditions. In this regard, calculating district measures in a Vesta model run is not a real optimisation which is taken place as the order is fixed. The user may change the preference sequence of the supply options, or even define fewer options in the software. For each option, a cost-benefit analysis is done. For each postcode-4 area the first calculated option in which benefits would outweigh costs and where sufficient capacity is available, this heat supply option would be assigned to this a particular postcode-4 area. A precondition in the Vesta model is that only one district heating option may be identified for each postcode-4 area. This is not the case with GSHP which is allocated at postcode-6 level and may be applied within the same area as waste heat. When none of the four options would be cost-effective, the Vesta model reverts back to default natural gas delivery. This is for most locations in the Netherlands the present situation. The delivery of waste heat in the Vesta model is limited by the maximum capacity of the point source. In contrast to waste heat, the other heat supply options are not limited to a maximum capacity.

4.2 Costs and benefits

In the model, for each postcode-4 area, cost-effectiveness is determined by heat sales and distribution costs [9]. To compare district areas for profitability the difference between the revenue

and the costs is determined and divided by the heat demand in a postcode-4 area. The revenue is defined by:

$$Revenue_{post} = sc + cc + sh$$

sc = standing charge in euros/year

cc = connection contribution in euros

sh = heat sales in euros/year

Those revenues are summarised for the three sectors in the model: residential buildings, the service sector and greenhouse horticulture. One of the main factors for possible allocation of waste heat to a postcode-4 area is the cost involved in the construction of the heat supply network. The components are visualised in Figure 6 and consist of: Construction of the primary heat supply network, the main and side pipelines of the secondary network within a district, Heat Transfer Stations (HTS) and aid heat boilers (AHB). Also costs are made by additional burning of fuel of the peak boiler and the large scale purchase of heat.

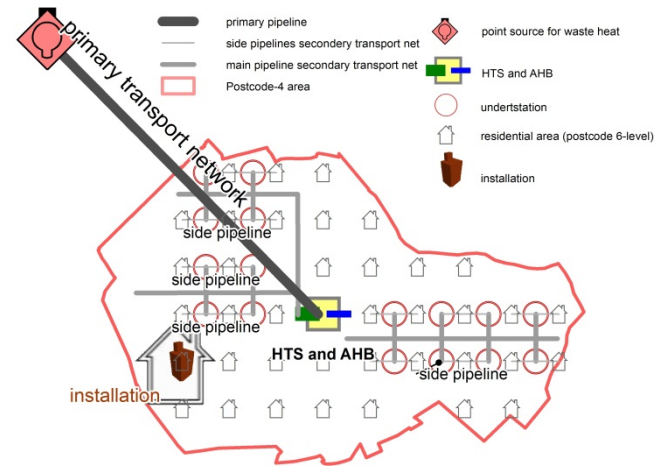


Figure 6: Schematic representation of the components of the heat supply network within a postcode-4 area

Formulas are used to calculate the cost per metre within the heat-supply network, depending on the heat output to be transported. The costs of construction of the primary network are:

$$C_{pri_Total} = l * \alpha * C_{step_m} * C_{marg_m} * P$$

with:

l = length of line from point source to centroid postcode-4 area, in metres

α = assumption of the detour factor of 1.25

Empirically determined constants:

$$C_{step_m} = 3,309 - (0.1917 * 120 * 120) = 548.52 \text{ euros}$$

$$C_{marg_m} = 3,309 - (0.1917 * 5 * 5) - C_{step_m} = 23.96 \text{ euros}$$

$$P = (n_1 + n_2) * P_{const}$$

with

n_1 = number of substations for not collectively heated houses

n_2 = number of substations for collectively heated houses

P_{const} = the power of a standard substation = 0.825 MW

In the existing built environment, the formula for the costs of a secondary heat network in a postcode-4 area is:

$$C_{sec_Total} = C_{mainpipe} + C_{sidepipe} + C_{hts}$$

$$C_{mainpipe} = \alpha * \sqrt{2} * \sqrt{surface_post} * C_{pipe}$$

α = assumption of the detour factor of 1.25

surface_post = surface area of postcode-4 area in metres²

$$C_{pipe} = 3,309 - 0.1917 * (P-120)^2 \text{ euros/metre valid until 115 MW}$$

Formula in euros for the cost of secondary side branches pipeline network:

$$C_{sidepipe} = 1.25 * (n_1 + n_2) * \frac{1}{4} * \frac{1}{2} \sqrt{2} * \sqrt{surface_post} * C_{pipe}$$

Costs for the Heat Transfer Station (HTS) in euros:

$$C_{hts} = 0.5 * (n_1 + n_2) * 0.825 \text{ MW} * \text{€ } 65,000$$

Costs, revenues and net heat are discounted at a specified discount rate. It is assumed that the investment in the disposable connection will be recovered after two years. The annual revenue from standing charges and heat sales as well as the net present value are all taking into account over the lifetime of the project – default 30 years minus a lead time of two years.

4.3 Greedy algorithm for Waste Heat

Waste heat is allocated with the aid of a geographically oriented greedy algorithm. Using a greedy algorithm is more or less required, in this case, as the numbers of combinations of point sources for waste heat and postcode-4 areas are enormous. This greedy algorithm attempts to construct an optimal solution in iteration steps and is characterised by providing relatively easy solutions for a rather complex, multi-step problem. At each iteration, the choice is made for what appears to be the best solution under the given conditions as well as the most straightforward. One of the characteristics of this algorithm is that once a postcode-4 area is allocated for waste heat, it cannot be changed in later iteration steps. In general, allocation depends, among other things, on the costs of creating a heat supply network and on energy demand. Further explanation of the used algorithm is provided with the aid of Figures 7, 8 and 9. The greedy algorithm consists of the following steps:

1. At the first iteration i_0 of the algorithm potential, service areas for waste heat are determined according to the nearest point source for each postcode-4 area. This is done by calculating the perpendicular distance between the point source and the centroid of the postcode-4 area. In Figure 7 this is visualised for the whole of the Netherlands at the starting state of the iteration. Also relatively small point sources can have substantially sized service areas.

2. A ranking in euros/MW is calculated with the aid of the net present value (NPV) for each postcode-4 area

$$Ranking = (DF_{28} * I_{y_post} - C_{i_post}) / C_d$$

DF_{28} = DurationFactor_28 of 11.9 Year. The number of years to double an amount at a discount rate of 6.0%.

I_{y_post} = Annual income for each postcode-4 area in euros/year

C_{i_post} = Investment costs for each postcode-4 area in euros

C_d = Capacity demand in MW

3. For each point source, the list of values from step 2 is sorted in descending order. Thereafter, a value is chosen from this list

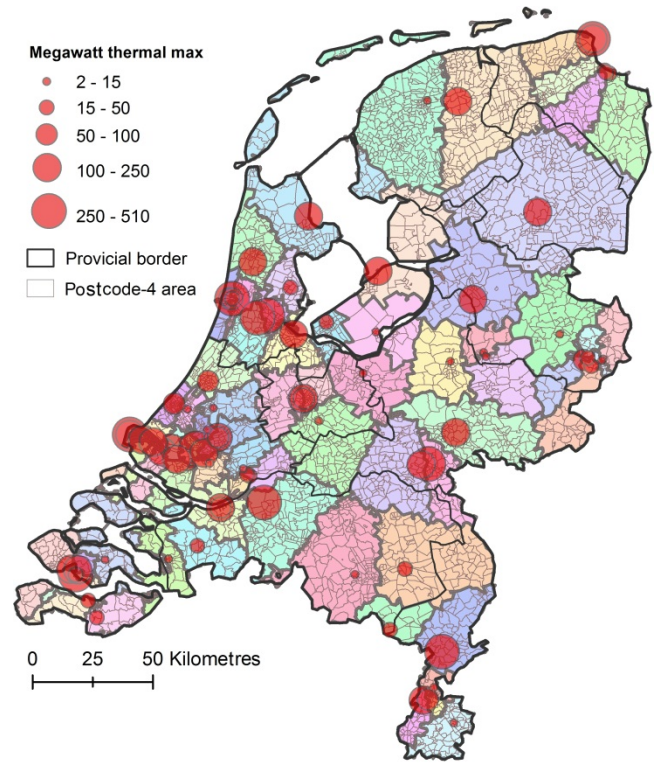


Figure 7: Starting state of point sources of waste heat with allocation areas

which acts as a threshold according to:

$-nth_element_weighted(-rank, target\ weight, weight)$

with:

-rank: sorting of the revenue per MW capacity

target weight: the maximum capacity of the point source

weight: the capacity demand of an individual postcode-4 area according to its ranking.

The weight capacity values are subsequently summed according to this order until the maximum capacity of the point source is reached. The ranking value for this element is the result of the $nth_element_weighted$ function.

4. Selection of postcode-4 areas for actual allocation to waste heat according to:

$$Ranking > ThresHold \text{ AND } Ranking > 0$$

The ranking needs to be positive, as these areas are cost-effective to exploit. Figure 8 shows the light gray postcode-4 areas identified in step 1. Most of the time, the largest number of areas typically are assigned to a point source, in this step.

5. Steps 1 to 4 are repeated with the difference that, this time, the newly assigned waste heat areas are being taken into account by determining the nearest point source. The new areas act as a new 'point source' themselves, from which the remaining capacity can be distributed further. This remaining capacity is determined by summing the capacity used in the previous iteration steps. The costs of constructing a pipeline from these areas to other users would also be lower, as the distance would be shorter, compared to constructing a new pipeline from the original point source all the way to a postcode-4 area. This is illustrated in Figure 8 by

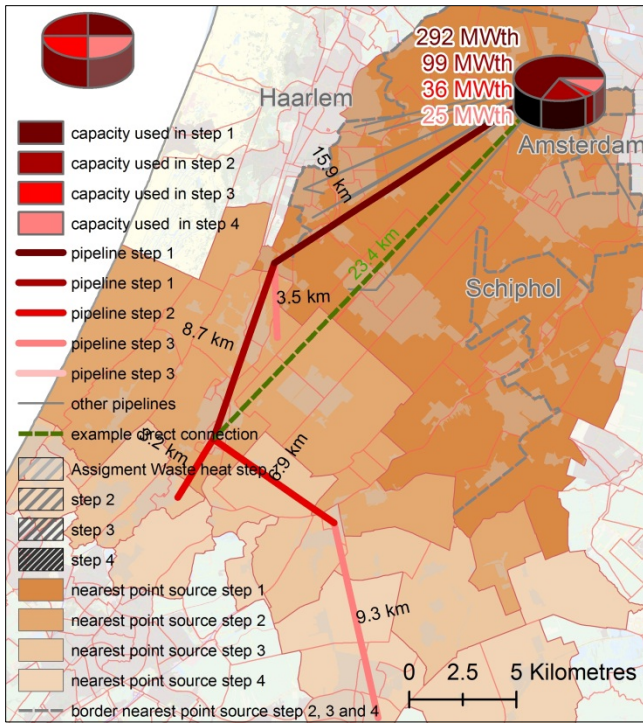


Figure 8: schematic representation of the expansion of the heat supply network for one pipe during the iteration steps

means of the green dotted line. Where an increasing number of areas are connected to a point source, the pipeline could be under-dimensioned. In the Vesta model, this is taken into account by increasing the diameter of pipelines and thus the capacity of the pipelines. The increasing diameter has a step-wise increasing influence on costs. Recapitulating the above, the potential servicing area of a point source for waste heat could be expanded during the iteration steps as new assignment areas to waste heat of the former step are taking into account. As a consequence other servicing areas of a point sources could be shrinking during the iteration steps.

A good example of a shrinking potential service area is given in the map-series of figure 9 by means of the yellow area in the south of the Netherlands. In this case the capacity of the point source is too low to compete with other point sources. Examples of expanding potential service areas, in Figure 9, are the areas surrounding three point sources in the south-westernmost part of the Netherlands. The iteration steps will be repeated until all capacity has been used, or if energy demand is too low to be exploited cost-effectively. It is not possible, in the Vesta model, to allocate only part of a postcode-4 area to waste heat. As a consequence some residual capacity of the point source will almost always be left, as the capacity demand from a (new potential) postcode-4 area will never exactly match this residual capacity. A maximum of 12 iterations is set in the VESTA-software. After five steps, the Vesta model typically indicates the expansion limit of the network has been reached; at that point, the thermal capacity will be used up, for most of the point sources, or the remaining energy demand is too low for profitable cost-effective exploitation. The regions with such remaining capacity at the point sources are characterised by rural conditions, the energy demand is too far from the point sources for the thermal capacity to be used in a cost-effective way. Furthermore, areas with many large point sources within a relatively small area, such

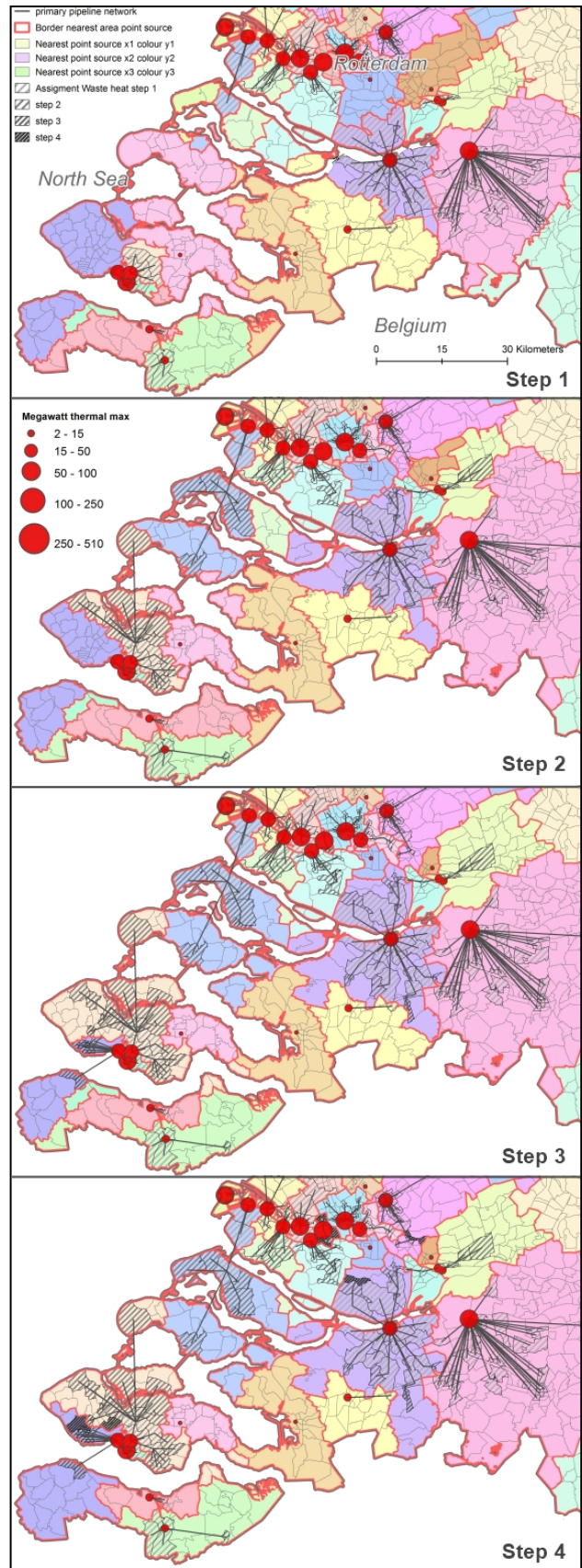


Figure 9: Iteration steps greedy algorithm for waste heat in 2050 for the southwest of The Netherlands

as in Rotterdam and near Vlissingen, also have shows not unused capacity remaining. In these situations there is a risk of capacity being used from other point sources, because of the specific spatial configuration of the point sources. There are some shortcomings of the above described greedy algorithm. This is for example the case in areas where there are a lot of smaller point sources in the vicinity of a large point source. Small point sources occupy the postcode-4 area if their capacity is too low to meet the demand in their own postcode-4 area. This postcode-4 area is then blocked to be able to act as a service area for other point sources. As a consequence the large point source is only capable of get rid of its capacity by finding a route of high energy demand, if even present, along the adjacent already occupied postcode-4 areas. So jumping over other potential service areas is not possible. Thus, it is possible that although a large point source is in the direct vicinity, it would not be possible to connect to this point source.

The possible assignment of a postcode-4 area of the other three district heat options are more straightforward compared to the above described waste heat option. Geothermal heating is possible within the 70% contour (Figure 5) with only installation costs. Additional pipeline costs outside this contour are based on the distance from the boundary of the contour to the centroids of the postcode-4 areas. GSHP works in the same manner, with the exception that it is only possible within the contour although this would be the case for most of the Netherlands. Moreover, the allocation is based on the detailed postcode-6 level, instead of the much larger postcode-4 areas. CHDPH is not location-dependent in terms of source, because gas pipelines are already available almost everywhere in the Netherlands. The costs of GSHP differ for installations above and below ground. In contrast to waste heat, geothermal heating, GSHP and CHDPH are not limited to a maximum capacity.

5. Results

The Vesta model can be used to calculate a large number of combinations of options, such as variations in energy prices, different orders of district measures, and applying different characteristics for building measures. The scenario used in Vesta is a Business As Usual scenario (BAU), also called Trend-scenario. [5]. In Figure 10, the results for district heating measures are projected back to individual residential houses. In this manner, a more realistic image is presented of where exactly the energy is needed, compared to a global visualisation at the postcode-4 level. In the western part of the Netherlands (Randstad), waste heat and GSHP are quite common. CHDPH only occurs around the city of the Hague and uses only 0.9% of the postcode-6 level points. Geothermal heating, with 0.5% of the available points, only is being used in a few places in the north-west (Alkmaar), whereby 1668 of the 2434 (69%) points are within the 70% contour. The maximum distance from the contour boundary is around 2.4 kilometres. GSHP is only being used in new residential areas, but still uses 5.1% of the available points. Heating in the rest of the Netherlands falls back on the default delivery of gas. This generally concerns less populated areas, although certain quite large cities are also supplied with gas. GSHP is allocated on postcode-6 level, and cannot be present at the same time in allocated waste heat and geothermal areas, as it is ranked below those two options in the order of heat supply options. In addition GSHP can only be applied in new residential and reconstruction areas, and not within the current built environment. To be made suitable, current buildings would need to be refurbished first, and those costs, including those for the construction of GSHP, are considered too high.

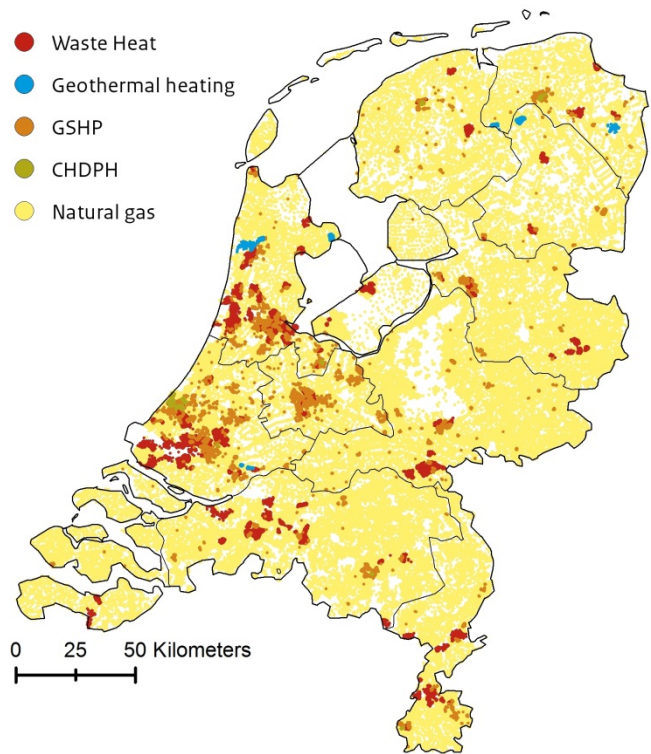


Figure 10: Cost-effective district measures for residential buildings in 2050, at high energy prices

Although the Vesta model is not intended for modelling the current network, it is interesting to compare the results against Figure 4, which shows the current waste heat areas. These areas may be assumed to have once been developed under profitable conditions. Overall, the same kinds of areas appear to be connected to waste-heat providing sources; these areas are mainly in and around large cities and industrial complexes, where energy demand is high. As the model calculates locations where waste heat exploitation would be profitable under certain conditions, factors such as social and governance processes have not been taken into account. But these factors, in the past, may have been deciding factors for connecting areas to sources of waste heat. This is the exact reason why validation of the model cannot be performed with the aid of Figure 4. However, validation of energy demand for the reference year 2008 was partly possible as energy consumption data was available for this year, for some areas. It appeared that the modelled energy use of dwellings was reasonably correct. Validation of the energy-demand of the service sector proved to be quite difficult because of the diversity within this sector.

Figure 11 shows the depletion of the capacity of point sources of waste heat as is discussed in paragraph 4.3. The pace of depletion is slightly slower when energy prices are lower. Remarkably, some point sources remain totally untapped (for example north of The Netherlands). When doubling the energy price (also called technical reduction potential) the modelled remaining capacity in the Netherlands is around 30%. It should be emphasized this percentage does not mean that there is not enough energy-demand in the Netherlands to use this capacity. The spatial configuration of the point sources merely has not been optimal to distribute the heat in a cost-effectiveway. As Figure 12 shows, with increasing energy prices in two steps, the number of postcode-4 areas increases from 364 to 599 (15%) from a potential 4043 areas.

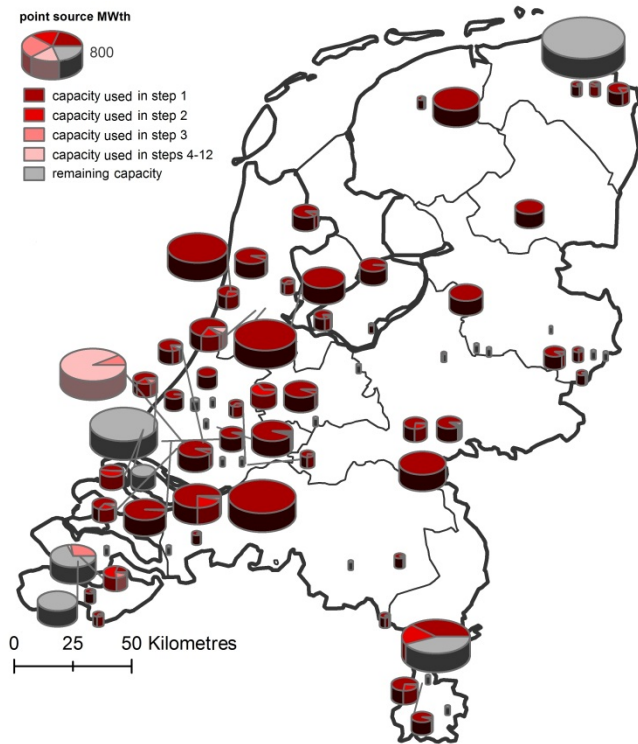


Figure 11: Development of used capacity for point sources during iteration with double energy prices in 2050

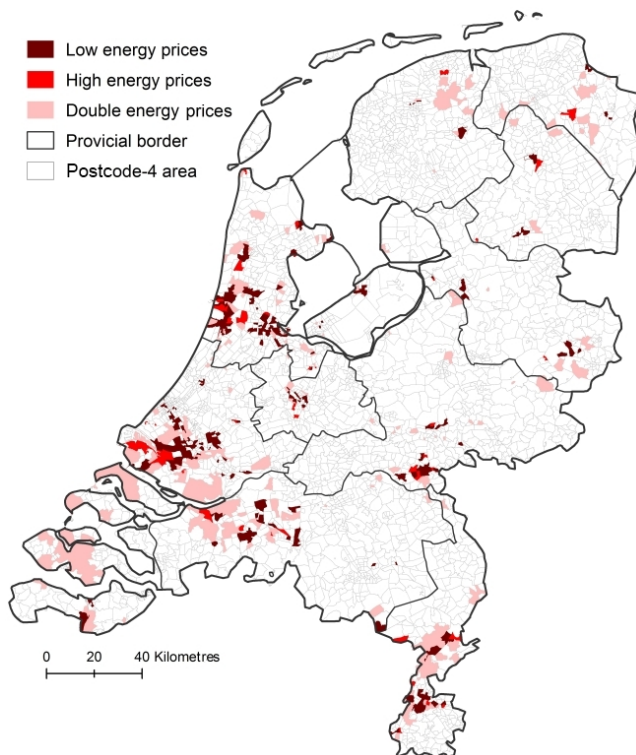


Figure 12. Allocation of waste heat at increasing energy prices
 These 599 areas represent 25% of all residential houses currently in the Netherlands; 47% of which are family homes and 16% were built in the 1970–1979 period. In particular, the south-west of the

Netherlands and the middle of the province of Limburg show a large potential for waste heat exploitation. For all sectors together, waste heat would deliver a CO₂ reduction of 3.8 megatons at double the energy prices compared to the scenario with low energy prices. At high energy prices this reduction would be 0.8 megatons less compared to double energy prices. Geographically speaking the waste areas for double energy prices in figure 12 not always overlaps the areas which are visible at low energy prices. This considerable number of areas (71) mainly are located around The Hague in the west of the Netherlands, and are characterised by falling back on gas delivery. From an investor's perspective, these areas are more risky, because other measures besides waste heat application are coming into view if energy prices would rise.

6. Discussion and conclusion

This paper presents a methodology to determine the potential of district heating measures for CO₂ reduction with an highly detailed spatial energy model. To reduce CO₂ emissions from the built environment, a combination of building and area district measures would be the most efficient. This provides a greater reduction in CO₂ emissions than taking only building measures or heat district measures. Taking all cost-effective building and area measures together would prevent 15% to 30% of CO₂ emissions from the built environment by 2050. The percentage range is caused by uncertainties about future energy prices and the investment costs of energy saving measures. Although the Vesta model uses highly detailed data, in particular, on the built environment, the model is most valid when used on a national or subnational scale. This has to do with the GIS-data and with the way the greedy algorithm works. On smaller scales, the local specific situations will increasingly deviate from the modelled results, which are based on data with national characteristics and

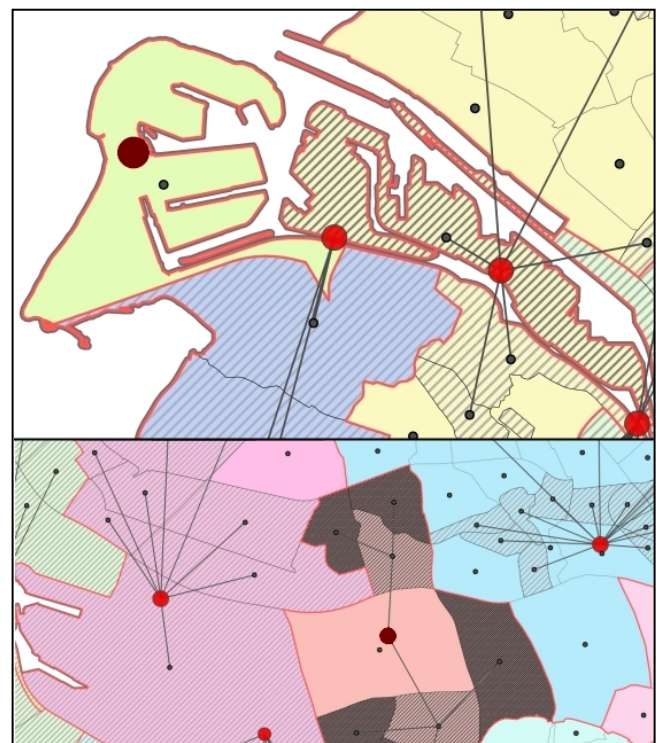


Figure 13: Effect of algorithm at isolated point (upper), and large point source surrounded by smaller point sources (lower)

assumptions. Also, the greedy algorithm is not always capable of correctly dealing with lower scales. Smaller point sources will be discarded in the Vesta model, as they are not capable of meeting the relatively high energy demand in their own postcode area. As a consequence, these areas are not considered anymore by larger point sources. In very specific situations, the used greedy algorithm in Vesta even has some shortcomings on a subnational scale. Large point sources at isolated locations like peninsulas, such as those shown in Figure 13 (upper), in combination with relatively large neighbouring districts can result in blocking of the ability to get rid of its capacity. This has to do with the fact that model technically it is not possible to jump over other postcode 4-areas which are already assigned to other (smaller) point sources. At peninsulas this is further reinforced by the absence of possible geographical corridors to escape. Also, a large source almost totally surrounded by other smaller point sources, shown in Figure 13(lower), can result in an inability to supply their capacity, although high energy demanding areas are nearby. From the 101 point sources included in the Vesta model only the 2 described in Figure 13 represent situations that show the shortcomings of the algorithm. This number is too low to undermine conclusions on a national scale.

Experiments, as presented in Figure 14, with Vesta model-runs with smaller regular shaped districts show more used capacity on a smaller land area. After intensive use of the model the size of the chosen district-level (postcode-4) seems slightly too large. Interestingly, the problem outlined in Figure 13 (lower) is resolved by using smaller regular shaped districts instead of using bigger irregular areas. The problem represented by figure 13 (above) is however only partly resolved by using regular shaped areas. Attention must also be paid to the number of points sources in relation to the number of districts. The Vesta model, preferably, should be run with a substantially larger number of point sources

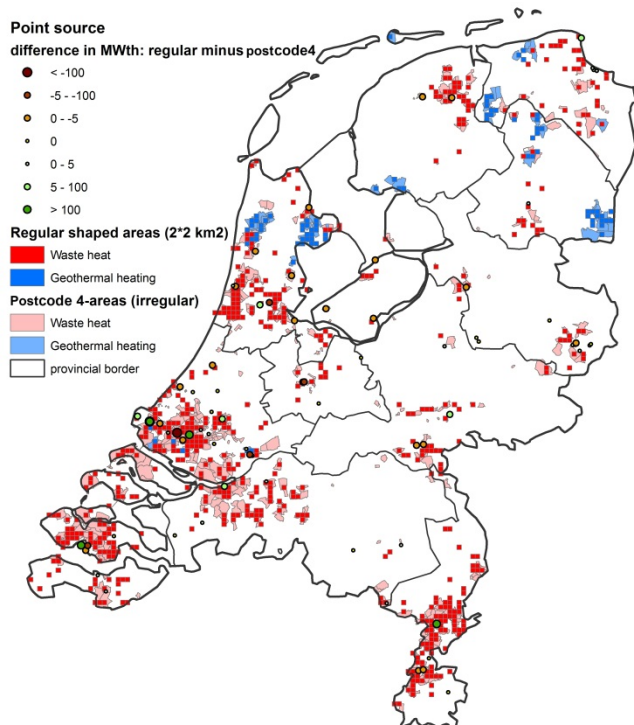


Figure 14: Effect of regular shaped assignment areas compared to irregular shaped postcode 4-areas

than districts (currently 101 versus 4043). The results in combination with the current heat supply network clearly shows that, in the past, not only economic motives have determined the construction of heat supply networks. In practice, also governance and social factors seem to be playing a role. One of the shortcomings of the Vesta model is the absence of this current network. The spatial configuration of the heat supply net for waste heat in the Vesta model clearly shows similarities with the real world situation, areas around and in cities, with most of the time a large point source within a ten kilometre distance. At double the current energy price, distances from point source to waste heat areas may become several dozen kilometres; a situation that is currently not occurring. The Vesta model could be adjusted by connecting it to the present network, and then only model the possible future network extensions. Cost variations for the network were not carried out in this study, in contrast to variations in energy prices, for which a sensitivity analysis was carried out (Figure 12).

Other more obvious improvements or extensions of the Vesta model could be the following:

Include the capability of an area to use more than one heat supply option and the ability for an area to use more than one point source; enable the implementation of point sources across the border (Belgium and Germany) to better represent the European energy market; improve the method to determine the costs of the secondary supply net by not only taking the land area of the postcode-4 area into account, but also the real spatial configuration of the buildings. Use of the capacity distribution point in a postcode-4 area based on the weight point of buildings not on geometrical shape. This could have a profound effect in some special situations of very irregular shaped postcode-4 areas. The Vesta model could also be interesting to use for other parts of the world. The most crucial factors to do this successfully seem to be the availability of highly detailed geospatial information about the (future) built environment and heat district options, and a thorough knowledge of the characteristics of the energy demand.

7. ACKNOWLEDGMENTS

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