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Accelerating the urban energy transition by data analytics

A method for enriching and exploiting fine-grained city data to enable informed decision
making on the transformation of cities towards low carbon cities

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Abstract

The aim of this study is to express the impacts of building-related sustainability measures in a generic set of performance indicators, exploiting fine-grained city data. A data enrichment method is described for energy consumption data and municipal administration data, that gives accurate estimations of the current energy performance of buildings in a city. The impacts of 11 building-related sustainability measures are approximated using these enriched data. These impacts are then expressed in the four KPIs (1) CO₂ emissions, (2) energy efficiency, (3) share of renewables and (4) costs, which enables comparison between the 11 sustainability measures, while taking into account local conditions. In combination with a decision support tool developed within the EU's TRANSFORM programme, it enables city stakeholders to focus their efforts more effectively, accelerating the transformation of our cities into low carbon cities.

Key words: CO₂ emissions, low carbon cities, fine-grained data, open energy data, data enrichment, data analytics, sustainable buildings, impact model, bottom-up, decision support tool

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Executive summary

Cities play a major role in the transition towards a low carbon society, since they consume about three-quarters of the global energy demand. In order to help city decision makers choose cost-effective low carbon scenarios instead of business-as-usual scenarios, better insights into the opportunities for sustainable development are needed. The current study demonstrates the role of city data in gaining these insights. The goal of this research is to accurately express the impacts of building-related sustainability measures in a generic set of performance indicators, using fine-grained city data. The hypothesis is that proper comparison between intervention alternatives, on four generic key performance indicators (KPIs), enables city stakeholders to focus their efforts more effectively for becoming a low carbon city. With this, the study aims to be a contribution to the urban energy transition.

This master thesis demonstrates that statistics and generally available city data can be used to give accurate estimations of building dimensions, insulation degrees of walls, roof, floor and windows, and of the division of energy consumption into eight different purposes depending on energy label. An initial dataset containing 10 data points per building can be extended into a dataset with 34 data points per building, by using the enrichment method as described in section 5.

The 34 data points that represent reported and approximated building properties can be used to determine the potential impact that sustainability measures have on the energy performance of buildings. From stakeholder interviews, 11 measures of interest (MOIs) are identified that city stakeholders deem important building-related measures for becoming a low carbon city. It turns out that within the larger energy-supply system, these measures have an impact on either final energy consumption or local production of electricity. On a building-level, energy efficiencies can be improved. The magnitude of impact of each measure is dependent on building-related properties such as roof area, façade area, geographical location, insulation thickness of the building envelope, and current energy consumption for certain purposes. Investment costs are converted into yearly costs of capital, which enables a direct and simple comparison between the costs and benefits (in terms of cost savings) of measures, i.e. the economic feasibility. This provides insights into the cost-effectiveness of sustainability measures on building level, based on real city data.

For actually comparing all costs and benefits, also in light of the 20-20-20 climate targets, a set of four KPIs is defined within the TRANSFORM project to assess the overall sustainability performance of a city. These KPIs are CO₂ emissions, energy efficiency, share of renewables and costs. The current status of a city relates to certain baseline values of these KPIs. While affecting the city's performance by implementing sustainability measures, changes in energy consumption and production break-down determine the evolution of these KPIs in the future. Comprehensive formulas of the KPIs are defined that relate the building-related data, in combination with city parameters, to the four KPIs.

The accuracy of the KPI calculations depends for a large part on the city parameters used. These parameters are identified and values found for the six cities that are part of the TRANSFORM project. A method to deal with excess electricity production from wind and solar power is constructed from literature, to ensure validity of the KPI calculations also at high shares of wind and solar power integrated in the electricity grid.

Numeric validity of the MOI-to-KPI impact model is largely ensured by the fact that all impact calculation methods come from literature and expert stakeholders. Validity in the sense of meeting its purpose was tested in a case study with two stakeholders from the municipality of Amsterdam. In combination with the Decision Support Tool, the method developed in the current study provides stakeholders with valuable quantitative insights. It enables evaluation of the influence of building owners' willingness to transform, on the impacts of an implementation plan. It provides clearer action-to-result logic in the impact estimations, and makes sure that no non-usable potentials are included in the calculations. This gives the stakeholders more clarity in how to effectively proceed in the urban energy transition towards a low carbon city.

1 Introduction

1.1 Cities' responsibility to transform

Climate change represents an urgent and potentially irreversible threat to human societies and the planet (UNFCCC, 2011). A lack of serious interventions will lead to more frequently occurring crises and natural disasters, and hazardous threats to public health (EC, 2007). If we continue to emit greenhouse gases at the current rate, human civilisation will not be possible on the current scale in the future. The effects of climate change are globally destructive on the long term. On shorter term, numerous economic sectors are dependent on climate conditions and are threatened to encounter direct effects of climate change on their activities and revenues: agriculture, forestry, fishery, tourism, health care, etcetera. Although society is becoming more and more aware of the urge to shift away from our dependency on fossil fuels, CO₂ emissions continue to be too high, as becomes evident from numerous reports, among which an alarming report of last year by the Intergovernmental Panel for Climate Change (Le Fevre, 2013).

Effective intervention is needed in order to reach the ambitious climate targets set by the EU for the year of 2020: 20% lower CO₂ emissions, 20% of energy from renewables and 20% increase in energy efficiency (these will be referred to as the 20-20-20 targets). To bring this even further, by 2050, the EU wants to have achieved a transition to a near-zero carbon energy system (EC, 2011).

Cities and citizens play a major role in realising the 20-20-20 targets, since urban areas currently consume about three-quarters of the global energy demand (Lazaroiu & Roscia, 2012). Most decisions on implementing energy innovations are made locally, by city stakeholders (Den Boer, 2011), often driven by city councils by using their influence over the community (McEvoy, Gibbs, & Longhurst, 1998). It is increasingly recognised that mitigation actions at city scale are needed to achieve CO₂ emission reductions (Shackley, Fleming, & Bulkeley, 2002).

While playing such an important role in reducing CO₂ emissions, city actors have difficulties at choosing cost-effective, low carbon, financially feasible actions over business-as-usual scenarios (Den Boer, 2011). Short term payback periods are often preferred over life cycle approaches. City governments have sustainable energy visions, but these are often oversimplified. A main cause of this is a non-integrated approach that does not connect waste, water, energy cycles, urban planning and budgets of city governments. Other key reasons for the lack of advance are “non-technical barriers, including attitude and behaviour” (Brownsword, Fleming, Powell, & Pearsall, 2005, p. 168). In addition, the different interest groups within a city make it complex and difficult to manage a city.

The transformation of a city into a low carbon city requires disruptive change in planning, development and decision making. Planning and energy visions need to be integrated, and decision making processes need to become more flexible. Cities would need to combine long term strategy and vision with practical, financially robust transformation plans for implementation in environments that are open to innovative ways of working (Den Boer, 2011). Moreover, it is very important to have an integrated social network of stakeholders, in order to pursue sustainable development in the city (Devine-Wright, Fleming, & Chadwick, 2001).

If the decision making processes of city stakeholders were better aligned and more effective, the transformation of cities into low carbon cities could be accelerated. As Nicholas Stern noted¹: “making the right decisions can lead to quick results”.

¹http://www.ted.com/talks/lord_nicholas_stern_the_state_of_the_climate_and_what_we_might_do_about_it

1.2 The role of quantitative tools

How can the decision making process within cities be made more effective? An essential part of the solution is the use of quantitative data and analytical tools (Hurst & Giles, 2014). In fact, "high quality analytical data and tools² are vital for predicting and understanding [...] the complex interactions between energy supply, distributors, and consumer demand, [...] in order to enable informed energy system design, implementation and operation decisions" (Bazilian et al., 2012, p. 1). Smart analysis of city data can lead to faster ways of receiving feedback in the development process of transformation plans (Den Boer, 2011). It could provide decision makers with realistic estimations of the impacts of different transformation plans, enabling them to adjust and optimise these plans before starting with implementation. While data analysis tools can be a powerful means to achieve informed decision making, it is a challenging task to develop tools that meet the conditions needed to provide effective energy analytics (from Bazilian et al., 2012):

1. validated models must be available and appropriate for the target environment;
2. suitable data must be available for input into the model and for verifying model-based results;
3. models must be operated by people trained in the use of the tools and in interpreting the outcomes for local conditions.

While quantitative tools can play a prime role in the transformation of cities into low carbon cities, the application of software and data in the energy domain is in its early stages. One problem is the fact that energy models must be continuously adapted and extended to new contexts, to deal with the complexity of energy generation and distribution systems coupled with technological advances. Keirstead and Calderon (2012) have done an elaborate literature review of 219 urban energy system models. The authors propose a theoretical definition of an urban energy system model and evaluate the state of the current practice. They show that there is a lack of model integration within the urban energy systems modelling community. Not many efforts have been focused on creating integrated modelling systems that are built for broader audiences and purposes, with the exception of two integrated assessment models, shortly summarised below.

The first one of these (Pataki et al., 2009) is an interdisciplinary study into the role of climate, urban expansion, urban form, transportation, and the urban forest on the net CO₂ emissions in the Salt Lake Valley, Utah. A system dynamics model was developed that highlights the feedback loop between urban land development, transportation investments, and CO₂ emissions. Likewise, transportation and land use policies that can dampen this feedback loop are brought forward as most effective in reducing CO₂ emissions. The model treats stocks and flows in the system as aggregated (top-down), and albeit the interdisciplinary approach of the study, it omits interferences in the system related to energy savings or renewable energy generation.

The second one, by Barker et al. (2010), is a study that couples a global energy-environment-economy model (E3MG) with an air pollution model. It uses global energy and economics data split up into 20 regions. The model estimates the future energy demands, emissions, macroeconomic effects and air pollution impacts of two low carbon scenarios compared to the reference case. The low carbon scenarios contain interventions such as a carbon-emissions trading scheme, carbon taxes and regulations that stimulate the use of EVs. It is a global top-down model with no detail about smaller-scale interventions and the exact impacts of sustainable technologies.

The authors of the urban energy model review (Keirstead & Calderon, 2012) conclude that there is significant potential for urban energy systems modelling that uses a sophisticated integrated perspective. Besides, most research so far has focused on national reduction strategies, which makes a great untouched potential for reduction of CO₂ emissions using a bottom-up approach (Gupta, 2008). The current study aims to accelerate the urban energy transition by providing decision makers with a bottom-up data analytics instrument.

²where tools refer to models, simulations and other analytical programs

1.3 Why bottom-up?

Cities and their stakeholders can make a big difference in becoming a future-ready, low carbon society. The question is not whether our society can run without fossil fuels, the only question is how. What are the most (cost-)effective ways for reducing carbon emissions in a city? How can stakeholders and decision makers (from municipalities to companies to citizens) most effectively focus their efforts to contribute to a future low carbon city?

The answers to these question are very much depending on local characteristics, and on the context of the decision making environment of a stakeholder. For every actor in an urban system, different instruments and intervention options are available, and different situational factors determine the attractiveness of certain choices. A system cannot be accurately described from a top-down perspective, assuming equal conditions for the city as a whole, as this omits local constraints and opportunities. As an actor from the municipality of Amsterdam notes: “Concerning energy policy, we always treated the city as being the same everywhere, but this is simply not true. We have to zoom in and look at the specifics of areas, or even buildings in the city.”

Zooming in on local situational factors will improve the ability to take informed decisions. However, when there are multiple policy options available, simply analysing these local characteristics will not suffice for stakeholders to have a clear insight as to which option is best. A method for comparison is essential. In order to compare, the effects of different interventions need to be measured on a generic score, or a set of indicators that express the impacts of different options in a generic way. Only then, good comparison between alternatives will be possible for all stakeholders involved, which will lead to informed decision making on urban energy planning.

1.4 Research context

The study is carried out within the context of a large European project, that aims to support city decision makers in transforming their cities into low carbon cities: the TRANSFORM project. Being part of this project has the advantage that findings can immediately be tested in the appropriate context, by relevant stakeholders. Moreover, since there are multiple knowledge institutes involved in the TRANSFORM project, and experts on urban energy systems, the project environment serves as a great source of knowledge.

In the TRANSFORM project, 19 partners in six European cities - Amsterdam, Hamburg, Copenhagen, Genoa, Lyon, and Vienna - are working together to overcome the barriers for transforming cities into low carbon cities, and realise the local and EU 20-20-20 targets (Le Fevre, 2013). A group of energy and grid companies, commercial partners and knowledge partners support the six cities with quantitative and qualitative input to improve and integrate their current energy strategies and help implement these strategies in the urban context. The project supports cities to turn their sustainability ambitions into realistic implementation plans and to achieve integrated planning (Den Boer, 2011). The decision making process of transforming into a low carbon city was analysed in the context of the TRANSFORM project, and can be seen in figure 1.

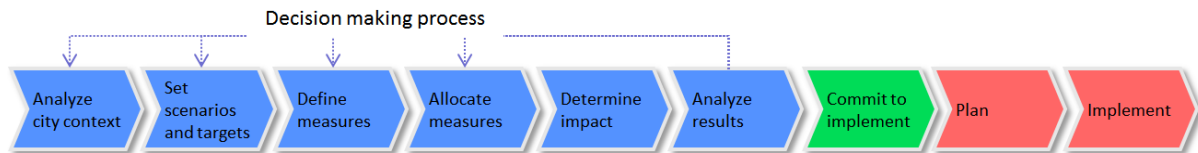


Figure 1: Stepwise process for the transformation of a city into a smart city, from Wenzler (2013).

To enable informed decision making in the transformation process, qualitative and quantitative support are needed. The TRANSFORM programme offers this decision making support in multiple forms; i.e. by defining

what a smart energy city should be, by organising sessions where stakeholders exchange knowledge and ideas, by drafting transformation agendas and implementation plans, and by developing a qualitative as well as quantitative decision support environment. All these activities of the European TRANSFORM project are split up into six work packages. An overview of these six work packages is shown in figure 2. Here, one can see that the current research is part of work package 3.

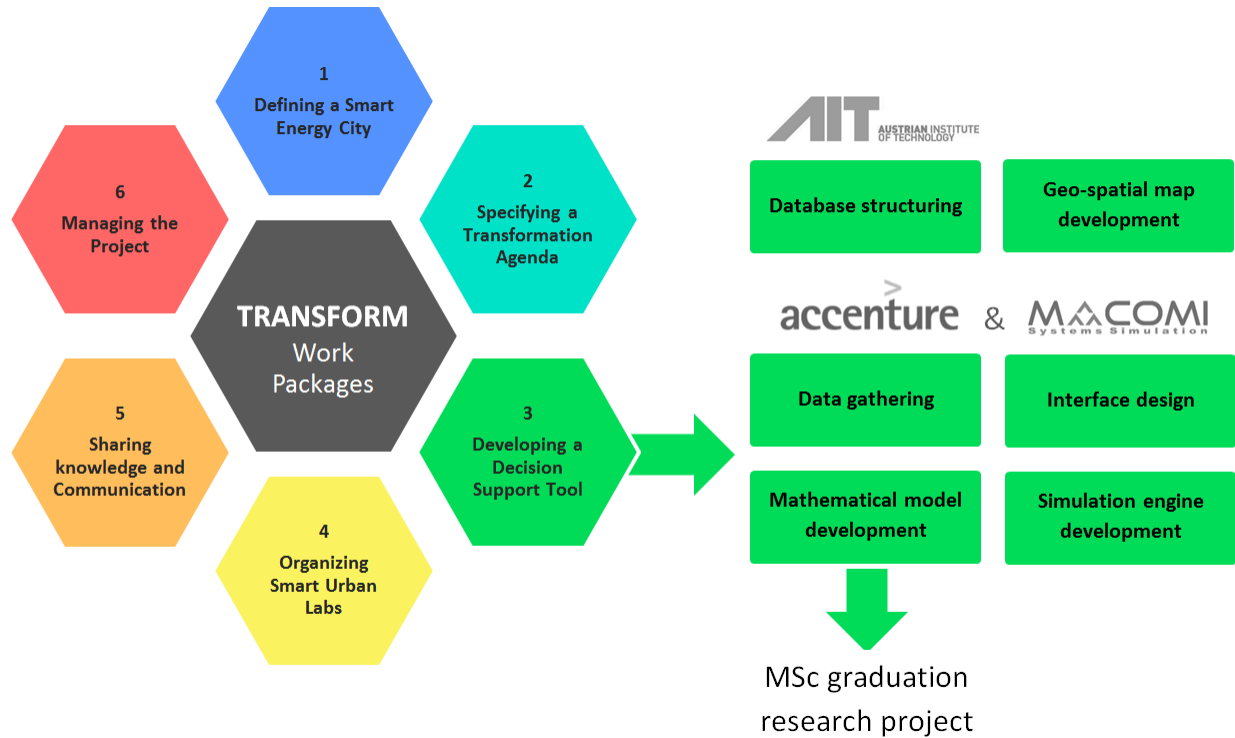


Figure 2: The role of the current research project in the greater TRANSFORM project.

TRANSFORM work package 3 is dedicated to the development of a quantitative Decision Support Tool that uses real city data and enables decision makers to evaluate the impacts of different transformation plans, under varying scenarios. The Decision Support Tool will allow for informed decision making by city leaders and involved stakeholders, thereby also providing an innovative open platform that has the flexibility to be disseminated for use in a wide range of cities with distinct contexts.

The development of the DST is done by three parties. As seen in figure 2, the Austrian Institute of Technology mainly focusses on the structuring of the database and on developing the functionalities that allow users to visualise data/results on geo-spatial city maps. Accenture and Macomi work together on designing the interface of the DST, developing the simulation engine and mathematical model behind it, and on gathering the necessary data from cities. Using this city data in a smart way, to estimate the impacts of a large set of sustainability measures and relate them to four key performance indicators (KPIs), is the challenge of the current research.

1.5 Description of the Decision Support Tool

What will follow now is a very practical description of the design of the TRANSFORM Decision Support Tool, to give an insight in the functionalities that it provides to decision makers. A user will be guided through four steps, as described below.

- 1. Analyse the city context** The current situation of the city can be analysed, in terms of energy consumption and other KPIs, and targets can be set for what one wants to reach in the future. Maps are available that show city data on building level, which allows for the identification of areas with high potential of improvement. The KPIs can be calculated as contributions of individual entities (buildings) or as a total value. The advantage of saving the contributions per building is that the impact of certain scenarios can be viewed in a geo-spatial map. An initial, pre-simulation map shows where the high-potential areas of a city are located and a post-simulation map shows what the effects of the measures are in specific areas of the city.

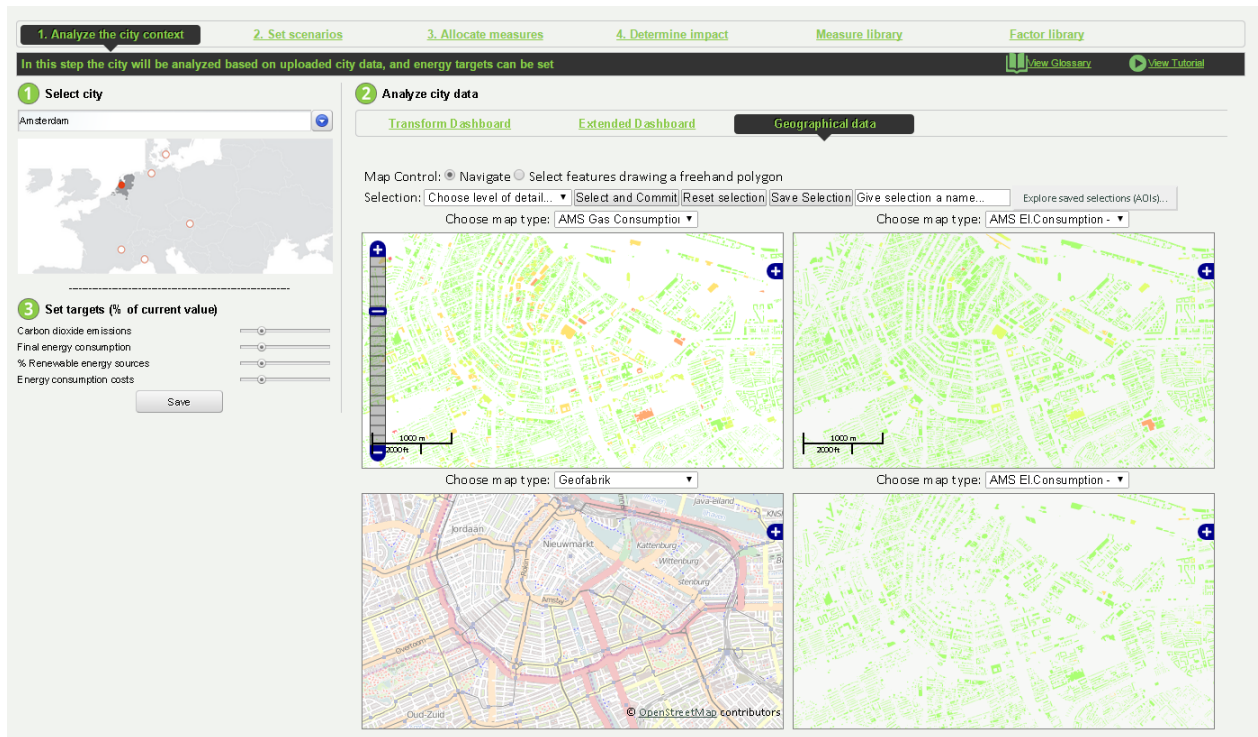


Figure 3: Tool screenshot of step 1: analyse the city context

- 2. Set scenarios** A scenario is the evolution of a number of uncertain factors (like oil price, gas price, population growth, etc.) that a city stakeholder cannot control. A user can create different evolutions of factors, and combine them within scenarios. The purpose of this scenario setting is that the user can compare the feasibility and impact of sustainability measures under different future assumptions.

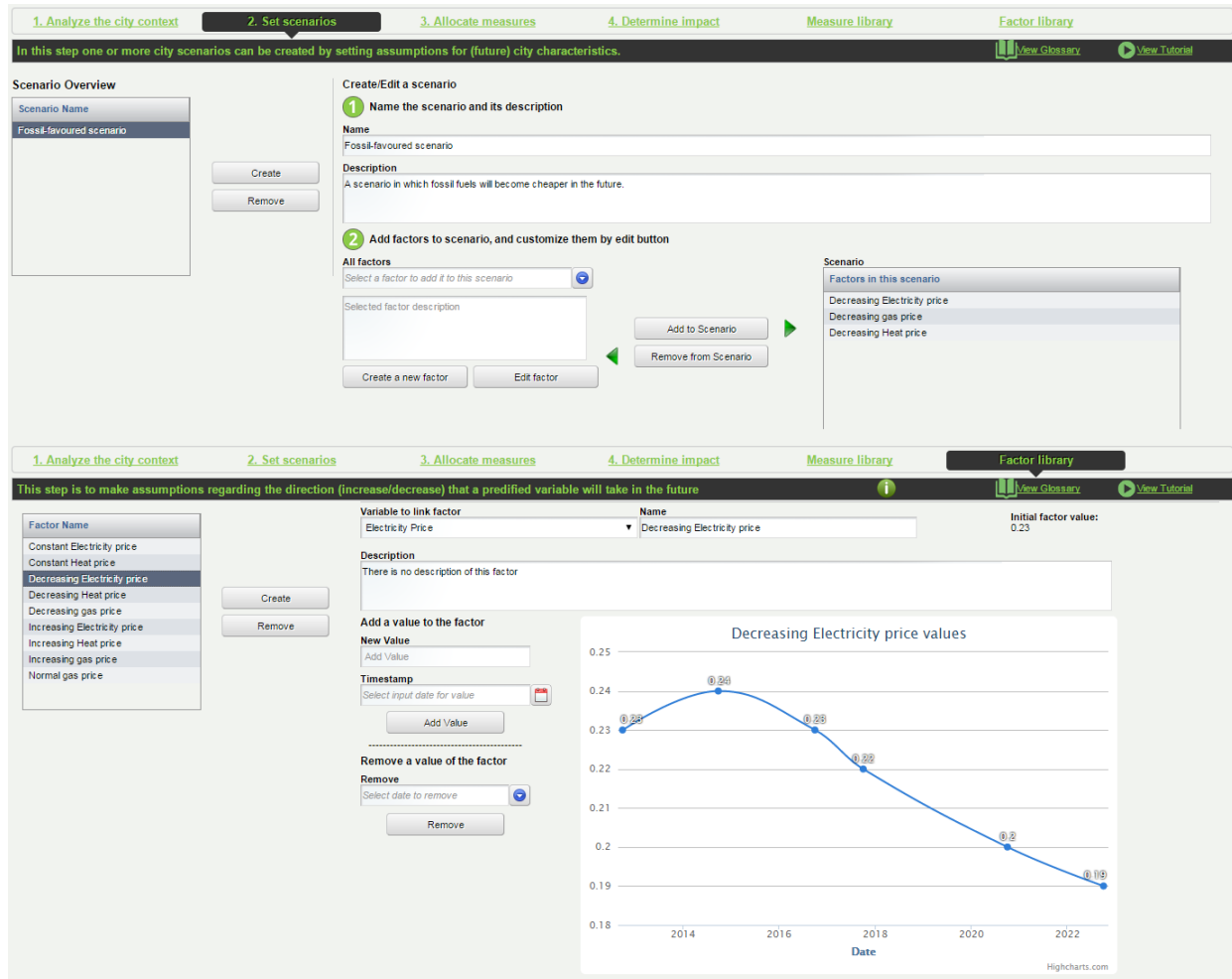


Figure 4: Tool screenshot of step 2: set scenarios

- 3. Allocate measures** In this step, the user can make different transformation plans for the city. These transformation plans are called measure portfolios. For every measure portfolio, a group of measures is defined that are allocated in areas and time frames. Also, a penetration rate is chosen for every measure, that refers to the percentage of buildings in which the measure is actually applied, i.e. uptake rate.

1. Analyze the city context **2. Set scenarios** **3. Allocate measures** **4. Determine impact** **Measure library** **Factor library**

In this step a measure portfolio can be created containing one or more measures that are allocated to a specific city area and implementation period

Measure Portfolio Overview

Measure Portfolio
Lokale warmtevoorziening

Create
Remove

Select a portfolio to view enablers

Create/Edit a measure portfolio

1 Name the new measure portfolio and its description

Name
Lokale warmtevoorziening

Description
Measure portfolio description

2 Add measures to the portfolio, and customize them by the edit buttons

All measures

- Shower Heat Exchanger
- Thermal Heat Grid
- Heat Pump
- Aquifer Thermal Storage open system
- Retrofit offices
- Warmte maken
- AMC waste heat
- Air Water Heat Pump

Add to portfolio
Delete from portfolio

3 Allocate measure to time

From
01/10/20

Penetration rate
100

Measure: Heat Pump

From	Penetration rate
10/01/2015	20.0
10/01/2020	100.0

Remove

4 Allocate measure to area

Measure: Heat Pump

Map Control: ☐ Navigate ☒ Select features drawing a freehand polygon **Help**

Selection: BLOCK use_of_building = domestic **Select** **Reset** **Save Selection** Give selection a name

Choose map type: Geofabrik

Map showing a selected area in Amsterdam (orange highlighted).

Figure 5: Tool screenshot of step 3: allocate measures

Measure Editor The impacts of measures can be defined in the “Measure Editor”, as shown in figure 6. The current values of building attributes (such as Electricity Consumption for Heating Building) are requested by the red nodes, which - together with the yellow nodes (representing constants) - can be used as inputs of a formula defined in the light green nodes (see figure 7). These light green nodes can then be assigned to the darker green nodes, which represent the values of the building attributes after implementation of a measure.

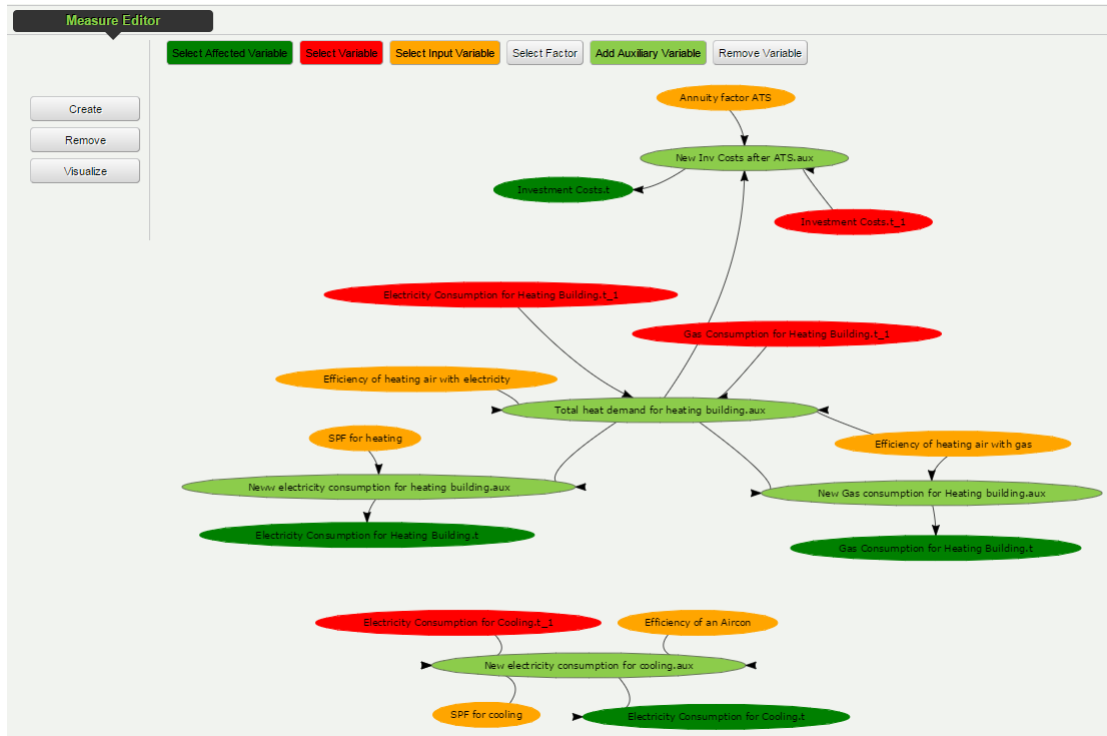


Figure 6: How a measure of interest can be modelled in the TRANSFORM decision support tool.

Figure 7: Editing a formula within a light green node.

4. **Determine impact** In the last step, the user can determine the impacts of a measure portfolio (defined in step 3), given a certain scenario (step 2). A combination of measure portfolio and scenario is called an experiment. One experiment basically represents a possible future for the city. The user can view and compare the outcomes of different experiments.

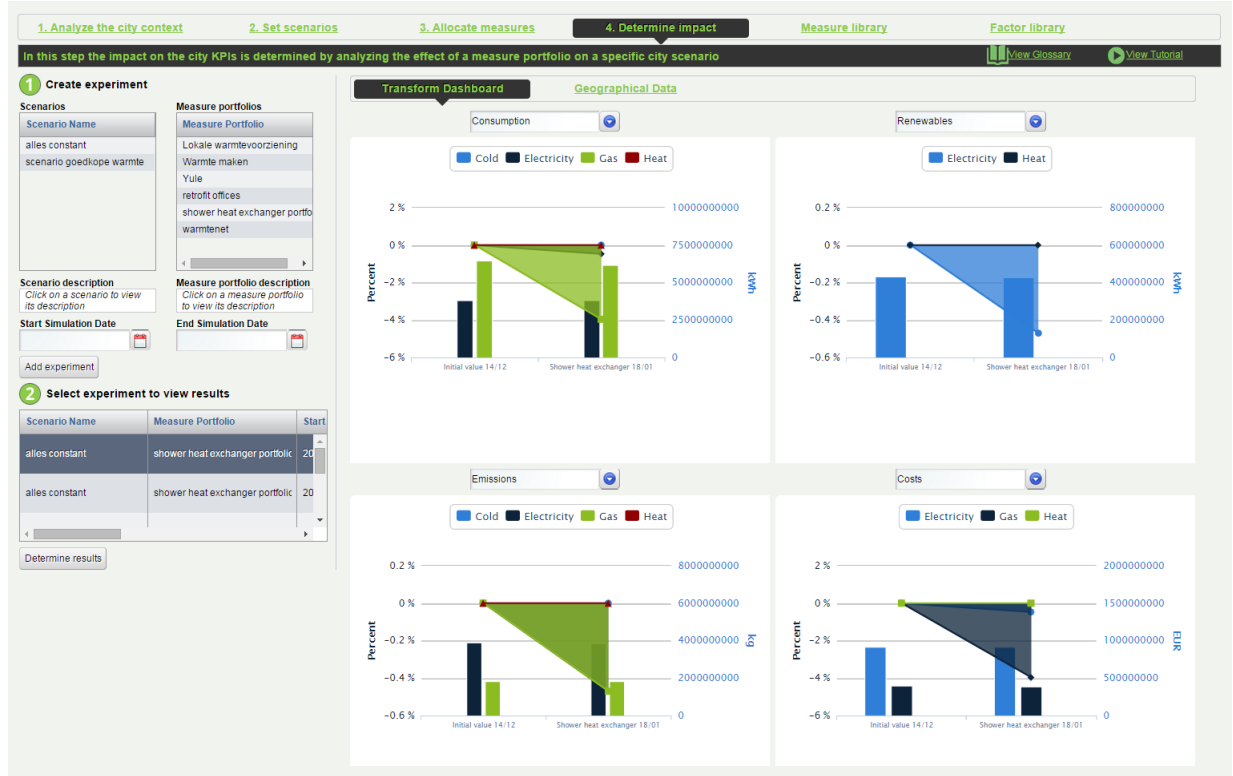


Figure 8: Tool screenshot of step 4: determine impact

1.6 Available city data

Large stakeholders such as municipalities and energy companies own data about the buildings within a city; data of which the resolution is commonly available on an address level. Municipalities for example have data about the floor space of every address in the city, as well as the construction year and purpose of use (office/domestic/shop/etcetera). Energy companies have billing data that refers to the energy consumption of their clients. Having these city data will allow for more accurate estimations of the impacts of interventions in the urban energy system. For example, knowing the ratio of gas consumption to floor space, provides an insight in the efficiency with which this building is heated, and therefore the possible gains by retrofitting the building. In this section, it will be analysed what data are commonly available within cities, focussing on data relevant for energy planning.

Within the TRANSFORM project, much effort has been put into data gathering, the findings of which are very useful for the current study. From the six TRANSFORM partner cities, Amsterdam turns out to have the richest data availability, as a result of the municipality's "Energy Atlas" project³ that aims to make all city data available as open data. The Energy Atlas contains numerous datasets about just any subject one can think of, from traffic light history to house value to breeding grounds of swifts, sparrows and starlings.

³<http://maps.amsterdam.nl>

What’s interesting for the current study, are the datasets in the category of Energy & Climate. These contain data about energy consumption and renewable energy generation potentials. Together with the basic municipal administration data, these readily available data contain the following relevant - building-related - data points:

Building properties		Energy data	
GIS Shapefile ⁴		Electricity consumption	kWh/year
Construction year		Gas consumption	m ³ /year
Building function		Heat consumption	kWh/year
Floor area	m ²	Energy label	
Number of storeys			
Ownership by housing corporation	yes/no		

Table 1: Available city data points within the TRANSFORM project.

This set of data points was found (partially) available for every city participating in the TRANSFORM project. Therefore, an assumption is made that this is the set of readily available data that can be obtained for any city, and it will serve as the main data input for the current study. The data points displayed in table 1 can be largely enriched into more meaningful data points, as will follow later in this report (see table 8 for a sneak preview).

1.7 Research questions

The objective of the current study is to provide city stakeholders on all levels with an instrument that gives them insight in the costs and impacts of intervention options, taking into account local situational factors. The main research question of this study can therefore be formulated as:

Within the city context, how can the impacts of carbon-reducing measures be accurately expressed in a generic set of performance indicators, exploiting fine-grained city data?

This question can be broken-down into a group of sub-questions:

1. How can the available city data be enriched into more meaningful data points about the energy performance of buildings?
2. What are the measures of interest for city stakeholders, and how can the impacts of the measures of interest be expressed as a function of the enriched city data?
3. How can these impacts be expressed by the four generic KPIs as defined within the TRANSFORM project?
4. What city parameters are used to calculate these KPIs, and how are their values determined?
5. Does the resulting MOI-to-KPI impact model in combination with the Decision Support Tool help city stakeholders in the decision making process, by enabling good comparison between interventions, while taking into account local characteristics?

⁴A geospatial vector data format for geographic information system (GIS) software, see <http://en.wikipedia.org/wiki/Shapefile>

1.8 Scope limitations

To narrow down the research scope, three scope limitations have been decided upon. Firstly, the focus of this study will be on the buildings sector of energy consumption in a city, omitting the industry, transportation and agriculture sectors. The reasons for this are data availability (see section 1.6) and the focus of the research questions on buildings' energy performance. Also, the contribution of buildings in global energy consumption is significantly increasing, reaching shares between 20% and 40% in developed countries, and is now larger than in the other major sectors of industry and transportation (Pérez-Lombard, Ortiz, & Pout, 2008). This implies that the most significant improvements can be achieved in the buildings sector.

A second scope limitation is related to the types of measures included in the mathematical model. A distinction can be made between measures with a *direct* impact on energy consumption and other KPIs, and *policy measures* (adapted from Stern, 2007) with an indirect impact such as advertisement campaigns or subsidies. The problem with the latter type of measures is that the impacts of these are hard to quantify. Since this study has a quantitative focus instead of a qualitative one, measures with an uncertain / hardly-quantifiable impact are excluded from the scope.

Lastly, variations in the CO₂ emissions per kWh produced electricity due to import and export of electricity will be omitted in this research. It is difficult to trace the production mix of imported electricity. The national average production mix values will be applied to imported electricity as well.

1.9 Outline of the report

In section 2, the research methods are briefly described, followed up by the stakeholder analysis in section 3. An extensive check of the currently available literature that aims to answer questions similar to the current research question is found in section 4. In section 5, the methodology is described for enriching available city data, from 10 data points to 34 data points. Section 6 follows up on this with a description of how these data points can be used to calculate the impact of 11 sustainability measures on a building level. How these impacts are then expressed in the four KPIs of CO₂ emissions, energy efficiency, share of renewables and costs is formulated in section 7. A set of city parameters is used in these KPI formulations, the values of which are found in section 8. The results are tested for a region in the South East of Amsterdam, along with city stakeholders, as described in the case study in section 9. Finally, conclusions and a discussion are found in section 10. In the appendices, the interviews scripts can be found, as well as a quantitative analysis on how to deal with excess electricity production at high shares of wind and solar power.

2 Methodology

This study consists of four parts: (1) mapping the current needs and wished of city stakeholders, (2) assessing the novelty of the current research / checking for similar studies, (3) defining the impacts of building-related sustainability measures and relating them to KPIs (4) testing the validity and added value of the study.

(1) Stakeholder analysis: unstructured interviews

First of all, the interests of different parties with a stake in the current research project and/or the greater TRANSFORM project and/or an urban energy transition generally are mapped in a stakeholder analysis. On the basis of this qualitative stakeholder analysis, lies a number of unstructured interviews with relevant parties. The reason for choosing unstructured interviews is the open character of this method, which matches the objective of exploration of potential wishes and needs of city stakeholders (in the decision making process on the transformation towards low carbon cities). Every stakeholder has a different perception and role within the decision making arena, and therefore a list of standard, structured questions would not suffice for analysing stakeholder objectives and interests.

Stakeholders are selected from three different cities participating in the TRANSFORM project, namely Amsterdam, Copenhagen and Lyon, to control for city-specific biases and to increase generalisability across different geographical locations. Within these cities, interviewees are selected that represent diverse organisations (municipalities, housing corporations, universities, energy companies, construction companies, consultancy companies, etcetera) to ensure that the analysis includes a broad range of stakeholders.

After gathering the stakeholders' interests, objectives and wishes, these are extracted into specific requirements for the decision support tool developed for TRANSFORM, which in part determine the requirements for the current research. Next to these requirements, the interviews bring to light which sustainability measures the stakeholders have on their agendas, or would be interested in. These are called the Measures of Interest (MOIs) of which the impacts on a building level will be formulated in this study. In some cases the interviewees provide expert information on the operation of certain measures.

(2) Similarity check: literature review

Many studies are conducted on urban energy modelling and sustainability measures, but the current study proclaims that an integrated study with an objective equal to the one stated in section 1.7 was not done before. To support this statement, i.e. to demonstrate the uniqueness of the current research, existing literature needs to be reviewed. An attempt is done to find all the articles with similar objectives to the current one, and compare their objectives with the current research's objectives. This can assure that the current research question was not answered by earlier studies. The scientific relevance of the current study can be demonstrated using this literature review.

(3) Model development: literature review

Literature research remains to shape a large foundation of this study while defining the impacts of the Measures of Interest and the expression of these in four KPIs. A large number of scientific articles and reports is consulted to find different options for calculating measure impacts, and the methods most suitable for the current research are used as input. Information from different sources is aggregated to shape a comprehensive energy model that represents a city's energy performance on building level.

(4) Validity check: case study

Lastly, a case study is carried out to test whether the current study helps city stakeholders in gaining insights in the cost-effectiveness of sustainability measures. A region of Amsterdam (Zuid Oost) was chosen as an area to perform the case study on, since several stakeholders from the municipality have shown interest in transforming this area and performing quantitative analyses on this area to improve the decision making process. Readily available data of Amsterdam is used, and measures of interest for the city stakeholders are incorporated in the Decision Support Tool. Several scenarios and implementation plans are constructed in collaboration with the city stakeholders, and the impacts of these were calculated by simulation in the Decision Support Tool. A method of comparison is essential in order to demonstrate the added value of the bottom-up analysis as compared to a more conventional top-down analysis. For that sake, a top-down study conducted by members of the municipality of Amsterdam was taken as a reference. A reflection on the bottom-up results in comparison with this top-down study can provide insights in the validity of the bottom-up method, and on the added value of it for decision makers.

3 Stakeholder analysis

A stakeholder analysis is done where stakeholders are considered people who (can) take part in the transformation of a city into a low carbon city. As the current study is aimed at providing these stakeholders with a method of informed decision making, the wishes of these stakeholders determine to great extent what the requirements for the current research are. These requirements were identified by holding interviews with stakeholders from three cities involved in the TRANSFORM program: Amsterdam, Lyon and Copenhagen (see Appendix for summaries of the interviews held).

From the interviews it becomes evident that there are different types of stakeholders, each type with different objectives, interests and incentives in the urban energy transition context. It follows that the stakeholders can be divided into three groups: municipal parties, commercial parties, and scientific parties. This categorisation of stakeholders is shown in figure 9, where their general motivations for using the TRANSFORM decision support tool are depicted in the outer shell.

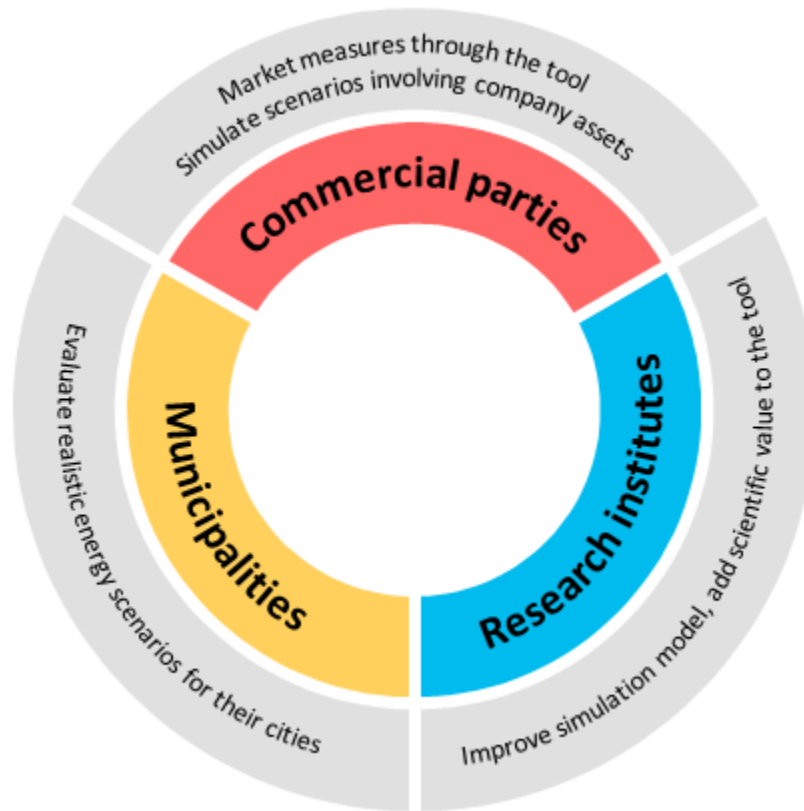


Figure 9: Stakeholder diagram. The inner shell represents the three stakeholder groups, the outer shell their main objectives for using the TRANSFORM decision support tool.

A more detailed analysis of the stakeholder interviews leads to precise requirements from each stakeholder group, for an instrument that helps in making better-informed decisions concerning energy strategy. Every group is treated separately in the following three subsections.

3.1 Municipalities

Municipalities and government-related parties' main objective is to improve the liveability of their cities; for them it is a duty to protect citizens from future harm of climate change. They have to comply with the 20-20-20 targets, and a decision support tool is of main interest for them to sharpen energy visions, and evaluate realistic future energy scenarios in which the targets will be met.

Municipalities would benefit greatly from a decision support environment that can convert their vague energy visions into concrete implementation plans, indicating *what* should happen, *where* and *when*. The impacts of different implementation plans are very much dependent on local characteristics. A holistic view on the city is no longer sufficient, impacts should be calculated by taking into account properties of buildings that come from city data; i.e. a bottom-up approach is required.

In order to test the effectiveness of different implementation plans, it would be necessary to show the impacts of these implementation plans on the indicators that determine the 20-20-20 targets: carbon emissions, energy efficiency and share of renewables. In addition, it is of high relevance to know whether, and under which conditions, different implementation plans are economically feasible. This makes for the need of calculating investment costs of plans, under different evolutions of uncertain factors such as gas and electricity price.

Requirement 1: Spatial allocation of measures In the *what* and *where* specifications in implementation plans, *what* refers to the measures that one can take and *where* refers to the location to which these measures are allocated.

Requirement 2: Temporal allocation of measures Likewise, *when* refers to the time frame in which measures are implemented, i.e. at what time will implementation of a measure be done, and will the measure start having its impact.

Requirement 3: Four KPIs The decision support tool of TRANSFORM needs to focus on four KPIs, three of which are the indicators that define the 20-20-20 climate targets, another which totals the costs of energy consumption and investment in measures. Once again, the three 20-20-20 indicators are: CO₂ emissions, Energy Efficiency, and Share of Renewables.

Requirement 4: Scenario setting How the performance of (a group of) measures behaves under changing external factors can be analysed by testing these under various uncertainty scenarios. A scenario includes a set of uncertainty factors, each with a certain future evolution. The decision support tool should enable users to sketch different evolutions of factors, and combine factors within a scenario. Different scenarios can be chosen under which the impacts of measures are calculated.

Requirement 5: Bottom-up approach There are two approaches of modelling an energy system. A top-down approach “works at an aggregated level, typically aimed at fitting a historical time series of national energy consumption or CO₂ data. Such models tend to be used to investigate the inter-relationships between the energy sector and the economy at large” (Kavgic et al., 2010, p. 1684). A bottom-up approach on the other hand, is built up from disaggregated data, and focuses on individual contributions of entities to the total energy consumption and/or CO₂ emissions of a larger system. Municipalities have indicated that especially the local characteristics are important to take into account, and therefore a bottom-up approach should be taken for the decision support tool.

3.2 Commercial parties

Commercial parties are often the actors that can actually implement sustainable technologies. Their main objectives are to analyse hotspots in the city that are suitable for implementation, and to promote their sustainability measures by having them modelled in a decision support tool. Commercial parties also view an integrated tool as a means of starting the conversation with competing parties, in order to prevent the implementation of conflicting measures that will harm both parties. For these parties it is very important to have the impacts of measures modelled in a practical way.

Commercial parties offer measures that are especially suitable for specific types of buildings, i.e. insulation is especially effective in older houses with a large energy consumption per square meter. They could use the Decision Support Tool to identify opportunities in the city, i.e. areas where measures can have a big impact. Commercial parties sketched the idea of being able to select buildings based on a set of criteria.

Requirement 6: Flexible spatial scale Some measures can be implemented on building level (e.g. solar panels), others only on district level (e.g. thermal heat grid). This implies the need for a flexible spatial scale on which measures can be allocated.

Requirement 7: Filter function To identify opportunities as in areas in the city where measures can have a big impact, the option to filter buildings based on user-defined criteria would be very helpful.

3.3 Research institutes

Lastly, there are research parties involved in the energy transition. These parties are very valuable for providing knowledge, and within the current project context they can help to validate the impact calculations used in the Decision Support Tool. For these parties, the scientific value is most important. There is no direct practical use of the tool for scientists, but the integration of narrowly-scoped modelling systems into one urban energy model and assuring the validity of it is a main objective for the scientific energy and modelling community. Two requirements that improve the accuracy of the impact calculations are identified from the interviews.

Requirement 8: Consumption split up per purpose Most of the energy conservation measures that can be implemented on a building scale, have influences on energy consumption for a specific purpose (insulation of a building for example only influences the energy consumption that is used for heating and cooling the building). For that matter, the decision support tool should split up the energy consumption variables in purposes for which the energy is consumed.

Requirement 9: Seasonal and daily fluctuations in energy demand and supply The integration of renewable electricity in the grid can lead to excess electricity production at times of low demand combined with high wind/solar availability. The Decision Support Tool should account for this overproduction when a scenario incorporates a high share of wind and/or solar power in the electricity production mix.

3.4 Measures of interest

Next to setting the requirements for the energy model and the functionalities of the tool, every stakeholder involved also has wishes as to which measures need to be simulated. From the stakeholder interviews it became apparent which measures are relevant. Some measures proposed by stakeholders were excluded from the scope, such as “energy education”, as the impacts are simply too subjective to model in a quantitatively accurate way. Other measures, such as retrofit/refurbishment, were specified with a different name and more narrowly to avoid misinterpretation (retrofit is a broad term that can include many different components, depending on interpretation; therefore, the term retrofit was replaced by insulation and window replacement). The measures of interest are:

MOI 1: Solar PV panels Generating electricity locally from roof-placed solar PV panels.

MOI 2: Façade PV panels Capturing solar energy by placing PV panels at a large angle on building façades.

MOI 3: Insulation Reducing a building’s heat leakage by thickening walls, roof and floor with insulation material.

MOI 4: Window replacement Reducing a building’s heat leakage by installing highly insulated glazing.

MOI 5: LED lighting Light emitting diode technology, providing the same illumination level with a much lower energy consumption.

MOI 6: Shower Heat Exchanger A heat exchanger system that extracts heat from waste water, used to preheat boiler water.

MOI 7: District Heating Grid A heat supply system that connects a centralised heat plant with residential and commercial consumers, where combined heat and power generation allows for a higher energy efficiency.

MOI 8: Air Source Heat pump An air source heat pump is basically a reversed refrigerator: a device that uses electricity to extract heat at a low temperature from the outside air, and converts it to a higher temperature (output heat). The output heat can be used to directly heat an inside space, or to heat water.

MOI 9: Aquifer Thermal Storage (open system) Inter-seasonal heat and cold storage underground, in order that captured waste heat during summer can be captured and harnessed during winter. Likewise, waste cold is stored in winter, to be pumped up during summer.

MOI 10: Micro CHP A combined heat and power plant on a household scale, using gas very efficiently for generating heat and electricity.

MOI 11: Wind turbines Large capacity wind mills that are placed within city boundaries, not to be confused with small urban wind turbines, which are never a feasible option.

3.5 Translating requirements into design

The requirements as extracted from the stakeholder analysis can be translated into a conceptual design of the decision support tool, and the position of the current study in this. In figure 10, requirements are depicted in the yellow boxes, with their number corresponding to the numbering earlier in this chapter. The green contours each represent a project component within work package 3 of TRANSFORM, in the same way as we have seen in figure 2. The four grey boxes represent the parts of the mathematical model development on which the current thesis is focussed: data enrichment (section 5), measures of interest impact formulas (section 6), mathematical KPI definitions (section 7), and city parameter restrictions (section 8).

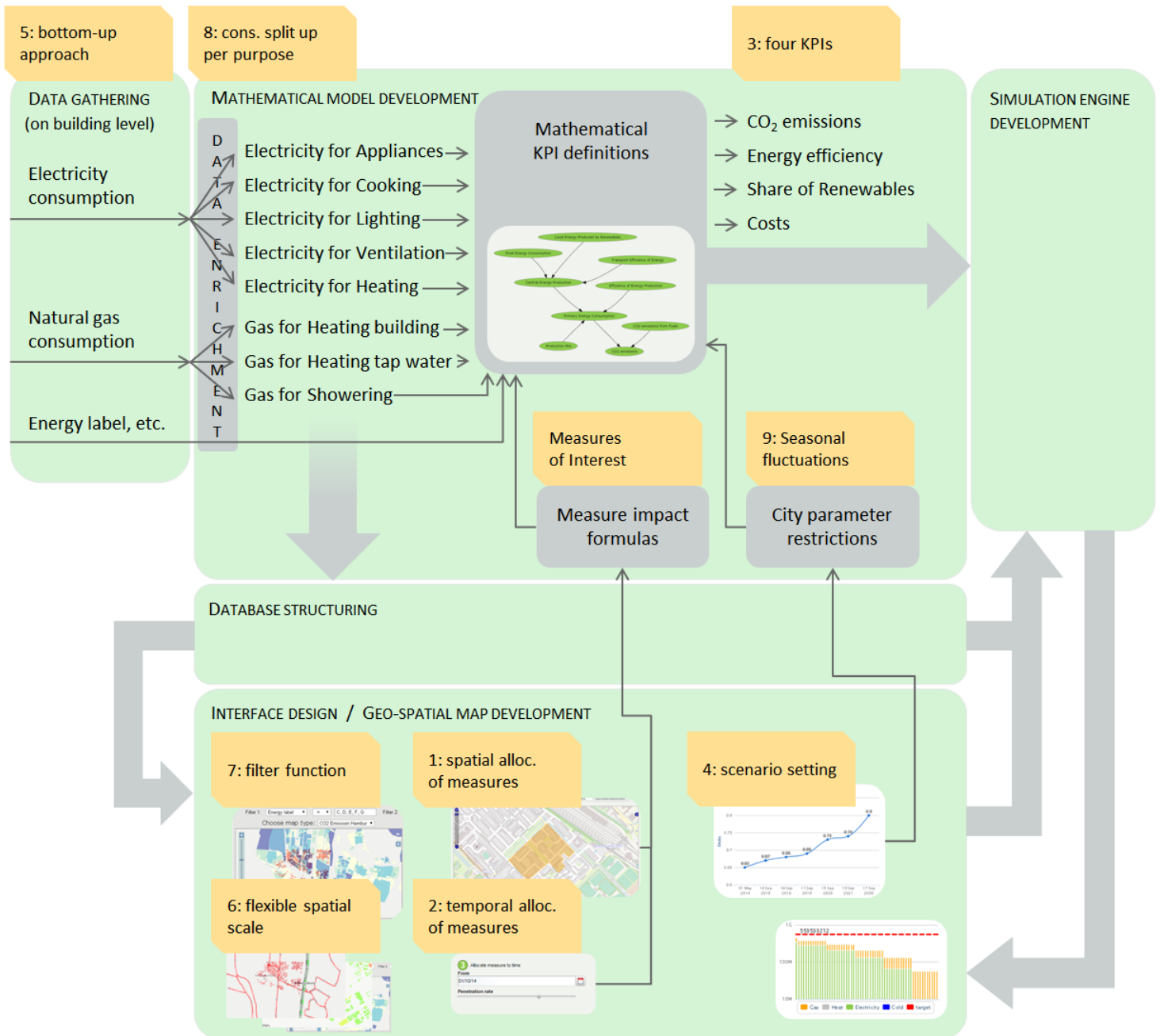


Figure 10: How stakeholder requirements (yellow boxes) determine design of the decision support tool, and the role of the current research in this (grey boxes).

4 Literature Review

An extensive review was done into existing literature with the purpose of identifying earlier research with objectives similar to the current research objective. As described in section 2, this is done to demonstrate the uniqueness of the study and to legitimise this research as being scientifically relevant. Therefore, a search query was formulated that aims to find all the articles that potentially have the same objective as the current study⁵:

```
TITLE-ABSTR-KEY((city OR cities OR urban) AND (impact OR effect OR influence) AND energy
AND (emissions OR efficiency OR renewable OR cost) AND (intervention OR measure OR
mitigation OR action OR policy) AND (comparison OR assessment OR examination) AND data
AND (local OR building OR area OR microscale))
```

Conference reviews and book reviews were excluded, as well as articles in the following irrelevant subject areas: Agricultural and Biological Sciences; Medicine; Business, Management and Accounting; Chemistry; Biochemistry, Genetics and Molecular Biology; Chemical Engineering; Nursing; Psychology. This leaves a remainder of 55 articles for analysis.

The 55 articles were compared on a number of criteria, so as to check the overlap of their research objectives with the current research objective. This analysis is summarised in table 2. The first three criteria were considered most important, as any article that does not meet all these three criteria has no chance to resemble the current study:

1. Focus on energy in buildings sector?
2. Quantitative?
3. Driven by data on building level?

A non-match with one of the first three criteria led to the exclusion of the respective article for further analysis. 35 out of the 55 articles did not focus on energy in the buildings sector, leaving 20 articles. 4 out of these 20 articles described a qualitative method instead of a quantitative, leaving 16. Out of these remaining 16 articles, only 10 were driven by data on a building level, and therefore these were analysed in more detail⁶. Three additional criteria were chosen that can check more precisely whether the studies reflect the same research objective. These criteria are:

4. Applying data enrichment?
5. Measures of Interest included
6. Relevant KPIs calculated

All 10 articles include some sort of data enrichment method, but not a single one with the same enrichment objective as in this study. The sustainability measures included in the 10 studies also differ largely from the Measures of Interest for the current study. 5 out of the 10 studies do not treat any single measure out of the 11 Measures of Interest. We will shortly describe the 5 other articles, which have some overlap with the Measures of Interest.

⁵Scopus was consulted with this search query

⁶these relevant studies are numbered 3, 5, 7, 11, 17, 26, 35, 36, 43 & 54

The article with reference number 3 (Bergamasco & Asinari, 2011) is purely focussed on solar PV panels, and more precisely on calculating the roof area of buildings that is available for PV panels. This is done by using satellite images from Google Maps, and applying a complex algorithm. This study could serve as a perfect input for the current research, for analysing the potential of solar PV panels in a city⁷. It can however not answer the research question of the current study.

Reference 5 (Caputo, Costa, & Ferrari, 2013) focusses for the largest part on the estimation of energy consumption within buildings, based on data related to dimensions and building use. This contrasts strongly with the current study, which treats these energy consumption data as an input. However, after having described the method for consumption data estimation, the study reflects on energy consumption reduction strategies and the fact that their impacts can be calculated using the estimated bottom-up data. The measures that overlap with the Measures of Interest for the current study are heat pumps, the district heating grid and solar PV panels. The results of this are discussed very briefly but details on how these impacts are calculated are not available in the article; it is treated as a small extension of the main research aim of estimating energy consumption. Clearly, this study is not answering the research question that we aim to answer.

Reference 11 resembles the current study the most closely. It describes the development of the integrated Geospatial Urban Energy Information & Support System (iGUESS) that aims to help five European cities reduce their CO₂ emissions. iGUESS is a web-based interface that uses city data sources, data analysis and modelling tools, to help urban planners decide where, on what technologies, and when to invest. The tool contains city datasets, and a Module catalog with a number of algorithms that can be run over these datasets, determining PV potential, wind potential, or more mathematical functions. The system does not include any of the other Measures of Interest, thereby making it unsuitable to answer the research question as stated for the current study.

References 35 and 36 (Millward-Hopkins et al., 2013, 2012) describe an analytical methodology that uses geometric data describing buildings and vegetation to calculate the aerodynamic characteristics of the urban surfaces. The authors then use this to make an evaluation of the viability of urban wind energy at the city scale. These studies obviously do not resemble the current research objective⁸.

The lack of a resembling study justifies the scientific relevance of the current research.

⁷this was omitted though, since the method of calculating the available roof area described in this study proved to be complex and time consuming, i.e. not within the boundaries of the scope of this study

⁸neither will they be used further in this study, since urban wind mills are omitted because of their generally low economic viability (see section 6.11)

#	Reference	Description	Focus on energy in buildings sector?	Quantitative?	Driven by data on building level?	Applying data enrichment?	MOIs	Relevant KPIs calculated	Comments
1.	Andre1995	Assessing the societal and environmental impact of improving the traffic regulation system	NO						
2.	Aunan et al. (1998)	Health and environmental benefits from air pollution reductions	NO						
3.	Bergamasco and Asinari (2011)	Algorithm that uses ortho-images to calculate the roof share availability for PV installations, pitch brightness, shadowing and azimuthal angle	YES	YES	YES	YES	solar pv	<i>none</i>	
4.	Calvin et al. (2012)	Comparison of 23 models that predict future energy use and emissions of Asia	NO						
5.	Caputo et al. (2013)	Characterizing the energy performance of the built environment and evaluating the effects of different energy strategies	YES	YES	YES	YES	heat pump, district heating grid, solar pv	RES	Energy consumption estimated con-data
6.	Chang et al. (2004)	Decision-making support system for establishing a recycling-oriented society	NO						
7.	Chrysoulakis et al. (2013)	Modelling urban metamolism: the energy and pollutant fluxes between buildings and the environment	YES	YES	YES	YES	<i>none</i>	CO2	
8.	M. et al. (2009)	Relationship between public opinion on wind power and public participation in turbine site planning and design	YES	NO					
9.	Dale and Bilec (2014)	Compare environmental impacts of energy and water scenarios, integrating both resources	YES	YES	NO				
10.	Dargay and Pekkarinen (1997)	Evaluation of public transport pricing policies	NO						
11.	De Sousa et al. (2012)	Decision support platform for urban energy planning	YES	YES	YES	YES	solar pv, wind turbines	CO2, CST	
12.	Dehghan et al. (2013)	Energy and exergy analysis of solar ponds	NO						
13.	Dodson and Sipe (2008)	Assessment of vulnerability to rising oil prices in Australian cities	NO						
14.	Duffy (2009)	Life cycle energy analysis of recent residential development in Dublin	YES	YES	NO				
15.	Fagan et al. (2010)	Assessment of integrated urban water systems	NO						
16.	Fiaschi et al. (2012)	Analysis of current energy consumption of public buildings and survey into possible improvements	YES	YES	NO				

Table 2: Similarity check of existing literature with the current study's aim, based on several criteria.

#	Reference	Description	Focus on energy in buildings sector?	Quantitative?	Driven by data on building level?	Applying data enrichment?	MOIs	Relevant KPIs calculated	Comments
17.	Ghalenoe (2011)	Assessing the sustainability performance of a residential apartment through a multi-criteria approach	YES	YES	YES	YES	<i>none</i>	CO2, CST	Focussed on one building only
18.	Ghose (2010)	Data mining in the Indian mineral industry	NO						
19.	Gidhagen et al. (2011)	Assessing the impact of emissions on future air quality	NO						
20.	Gurney et al. (2011)	Estimate fossil fuel CO ₂ emissions on 10 km x 10 km spatial scale	NO						
21.	Heinonen and Junnila (2011)	Analysis of current carbon consumption in two cities	NO						
22.	Hosier et al. (1993)	Analysis of future energy costs of urbanisation	YES	YES	NO				
23.	Huang and Wang (2013)	Regression model for the influence of socio-economic factors on carbon emissions	NO						
24.	Jancevska and Glamocanin (2013)	Detecting potential areas for investment in wind energy sources in Macedonia	NO						
25.	Jimenez and Flores (2014)	Reducing CO ₂ emissions in Madrid with electric vehicles and nuclear energy	NO						
26.	Jo et al. (2010)	Method for assessing the benefits of reflective roofs in an urban area	YES	YES	YES	YES	<i>none</i>	CO2, CST	
27.	Kissinger et al. (2013)	Ecological footprint analysis of materials in consumer goods on a city scale	NO						
28.	Kolosz and Grant-Muller (2015)	Cost-benefit analysis for Intelligent Transport Systems	NO						
29.	Leme et al. (2014)	Comparing alternatives for energy recovery from waste in Brazil	NO						
30.	Lombardi and Trossero (2013)	Pointing out the need for a radical shift in evaluation approaches in urban planning, using the “Jevons Paradox” and the “energy rebound effect”	YES	NO					
31.	Mansour et al. (2011)	Evaluating the impact of electric vehicles	NO						
32.	Mazzei and Prati (2009)	Measuring the changes in concentration of particulate matter before and after the closure of a steel smelter plant	NO						
33.	Mdluli and Vogel (2010)	Qualitative analysis of energy-use behaviour in poor communities	YES	NO					

Table 2: Similarity check of existing literature with the current study’s aim, based on several criteria.

#	Reference	Description	Focus on energy in buildings sector?	Quantitative?	Driven by data on building level?	Applying data enrichment?	MOIs	Relevant KPIs calculated	Comments
34.	Milenic and Vranjes (2014)	Assessment of geothermal energy potential in Belgrade	NO						
35.	Millward-Hopkins et al. (2013)	Assessing the potential of urban wind energy	YES	YES	YES	YES	wind turbines	<i>none</i>	
36.	Millward-Hopkins et al. (2012)	Mapping wind speeds as a function of height	YES	YES	YES	YES	wind turbines	<i>none</i>	
37.	Mohan and Sharma (2008)	Air quality assessment from thermal power plants	NO						
38.	Murin et al. (2010)	Impact of electric vehicles on the winter load peak	NO						
39.	Myer (2005)	Evaluating carbon sequestration options	NO						
40.	Ng et al. (2014)	Environmental life cycle assessment of different water conservation policies	NO						
41.	Norman et al. (2006)	Comparing high and low residential density on the related energy use and greenhouse gas emissions	YES	YES	NO				
42.	Oguntoke et al. (2013)	Assessment of the effects of wood waste burning on air quality and human health	NO						
43.	Roehr and Laurenz (2008)	Environmental benefits of green roofs and façades	YES	YES	YES	YES	<i>none</i>	CO2	Focussed on one building only
44.	Santillán Soto et al. (2013)	Measuring solar irradiation in two cities	NO						
45.	Sovacool and Brown (2010)	Comparison of the carbon footprints of 12 metropolitan areas	NO						
46.	Thanh and Matsui (2013)	Exploring alternative waste treatment practices in Vietnam	NO						
47.	Tonn et al. (2003)	Assessing the relationships between two programs that support low-income households	NO						
48.	Van Kamp et al. (2011)	The influence of climate change on urban noise	NO						
49.	Van Mierlo et al. (2005)	Comparison of the environmental damage from vehicles running on different fuels	NO						
50.	Wiesel et al. (2012)	Analysis of sustainable affordable housing projects	YES	NO					
51.	Xu et al. (2008)	Modelling urban heat flux	YES	YES	NO				

Table 2: Similarity check of existing literature with the current study's aim, based on several criteria.

#	Reference	Description	Focus on energy in buildings sector?	Quantitative?	Driven by data on building level?	Applying data enrichment?	MOIs	Relevant KPIs calculated	Comments
52.	Yao and Song (2013)	Environmental impact assessment of eco-route planning	NO						
53.	Zachary (2013)	Using statistical mechanics to understand land cover changes on a continental scale	NO						
54.	Zellner et al. (2008)	A framework, including an agent-based model, for urban sustainability assessment	YES	YES	YES	YES	<i>none</i>	CO2, CST	Focussing on broader policy decisions; based on a hypothetical urban system (dummy data)
55.	Zhang et al. (2007)	Health-based assessment of air pollution in urban areas of Beijing	NO						

Table 2: Similarity check of existing literature with the current study's aim, based on several criteria.

5 City data enrichment

5.1 Energy consumption per purpose

Cities have delivered input data on building block level, that contain several consumption variables, such as electricity consumption and gas consumption. For many carbon-reducing measures are directed towards certain energy end-use services, it is valuable to know how much energy is used for a certain purpose (Lighting, Heating building, etcetera.). It results in an ability to focus measures better on certain portions of total consumption, and to make a more realistic estimation of the impact of measures that only influence one or a few energy usage purposes. However, cities do not have data available on such level of detail. It would be necessary to have a procedure of enriching the city data in order that the consumption values are known per purpose up to an accurate level.

A method for enriching energy consumption data was developed that uses city statistics, referring to the city average distribution of energy consumption for different energy services. The procedure will be demonstrated by using the dataset of Amsterdam. The input data available on building level are electricity consumption, gas consumption and energy label. The input statistics are shown in table 3.

Function	Carrier	Appliances	Cooking	Lighting	Heating building	Heating tap water	Showering	Cooling	Ventilation systems
Domestic	Elec.	60.0%	5.0%	16.0%	12.0%	0.6%	2.4%	4.0%	0.0%
Domestic	Gas	0.0%	2.0%	0.0%	79.0%	3.8%	15.2%	0.0%	0.0%
Education	Elec.	43.2%	3.9%	46.4%	0.0%	2.2%	0.0%	0.6%	3.7%
Education	Gas	0.0%	0.0%	0.0%	99.6%	0.4%	0.0%	0.0%	0.0%
Hotel	Elec.	32.9%	0.0%	39.9%	0.0%	0.3%	1.0%	16.0%	10.0%
Hotel	Gas	0.0%	8.8%	0.0%	83.6%	1.5%	6.1%	0.0%	0.0%
Industry	Elec.	60.0%	0.0%	30.0%	0.0%	0.0%	0.0%	5.0%	5.0%
Industry	Gas	0.0%	0.0%	0.0%	90.0%	10.0%	0.0%	0.0%	0.0%
Medical	Elec.	27.3%	1.3%	53.2%	0.0%	0.2%	0.8%	5.9%	11.2%
Medical	Gas	0.0%	1.3%	0.0%	88.0%	2.1%	8.5%	0.0%	0.0%
Office	Elec.	46.8%	0.0%	37.3%	0.0%	0.7%	0.0%	9.4%	5.7%
Office	Gas	0.0%	0.0%	0.0%	99.9%	0.1%	0.0%	0.0%	0.0%
Shop	Elec.	19.7%	0.0%	67.9%	0.0%	1.0%	0.0%	8.1%	3.3%
Shop	Gas	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%
Sport	Elec.	29.6%	3.1%	44.2%	0.0%	0.1%	0.4%	0.0%	22.6%
Sport	Gas	0.0%	0.0%	0.0%	85.3%	2.9%	11.8%	0.0%	0.0%
Other	Elec.	37.1%	1.9%	43.6%	1.7%	0.7%	0.7%	6.3%	8.1%
Other	Gas	0.0%	1.7%	0.0%	90.8%	1.6%	5.9%	0.0%	0.0%

Table 3: Percentages of electricity and gas consumption for the defined purposes and building functions. From Ministerie van Economische Zaken (2012); Meijer and Verweij (2009).

For justifying the enrichment method that will be described in the remainder, two assumptions need to be made:

Assumption 1: The energy consumption for a purpose varies linearly with the floor area in m^2 .

This assumption follows from the Community Domestic Energy Model (CDEM) as described by Firth, Lomas, and Wright (2010), which is based on four housing stock models. The model has been thoroughly validated to give accurate estimations of the real energy consumption for a purpose by basing this on the floor area.

Assumption 2: For only a limited set of energy usage purposes, the average energy consumption per m^2 is dependent on the energy label. These energy label-dependent purposes are Heating building, Cooling and Ventilation systems.

This assumption follows from the fact that energy labels say something about the way a building is constructed. The construction method of a building in its turn is only affecting the building-related energy consumption, i.e. consumption for heating the building, cooling the building, and ventilating the building. The assumption implies that buildings with energy label G have a higher average consumption per m^2 for these purposes than buildings with energy label A, and that the remaining purposes (like Appliances, Cooking, etc.) have a fixed average energy consumption value per m^2 , independent of the energy label. In mathematical terms:

$$\begin{aligned}\bar{A}_f &= \bar{B}_f = \bar{C}_f = \dots = \bar{G}_f \\ \bar{A}_v &\neq \bar{B}_v \neq \bar{C}_v \neq \dots \neq \bar{G}_v\end{aligned}$$

where:

$\bar{X}_y$ = The average energy consumption per m^2 for a purpose y of all buildings with energy label X

$f = \{\text{Appliances, Cooking, Lighting, Heating tap water, Showering}\}$

$v = \{\text{Heating building, Cooling, Ventilation systems}\}$

Figure 11 illustrates the principle of increasing building-related energy consumption with increasing energy label, as stated in assumption 2.

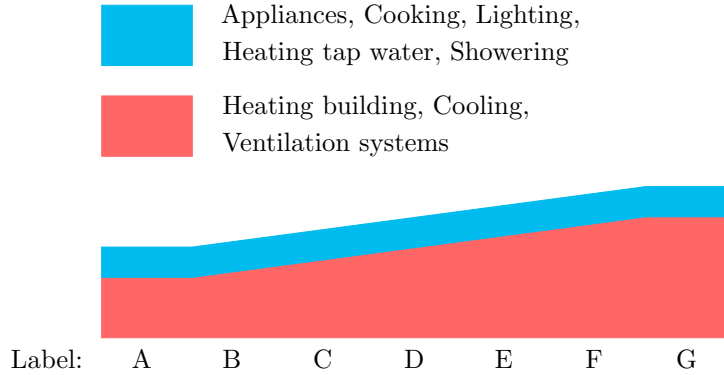


Figure 11: How energy label-dependent consumption averages vary over the different energy label groups, while energy label-independent averages stay constant.

By using the assumptions, city statistics and city data, a method can be derived that will calculate the shares of gas/electricity consumption for each purpose, depending on energy label. This needs to be done while

assuring that the weighted shares (weighted based on floor area) add up to the shares as given by the city statistics. The logic behind this method is modelled in Excel. The output this method gives for domestic buildings in the city of Amsterdam is shown in figures 12 and 13.

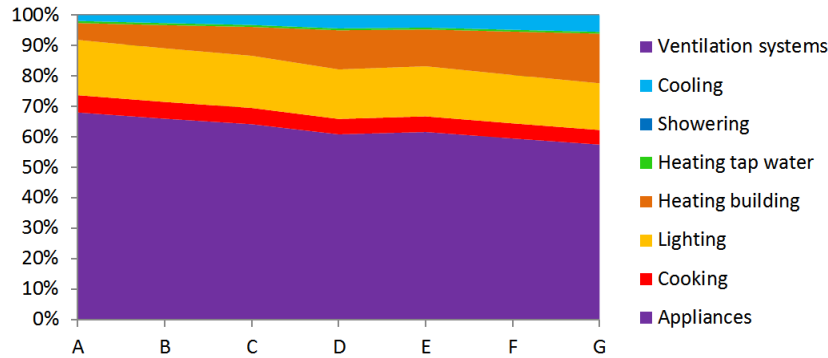


Figure 12: Shares of electricity consumption for different purposes (y-axis), as function of energy label (x-axis).

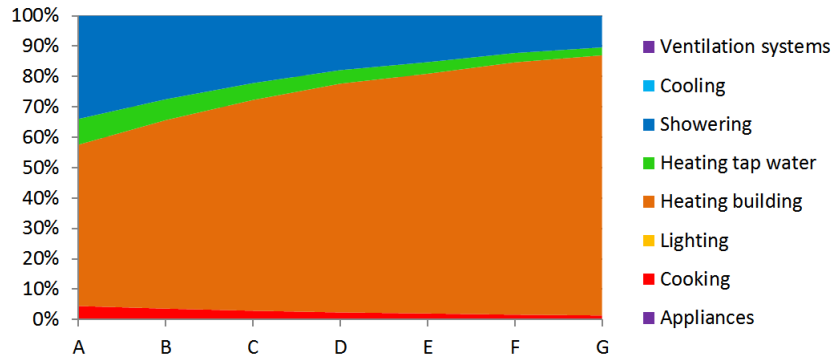


Figure 13: Shares of gas consumption for different purposes (y-axis), as function of energy label (x-axis).

These shares are calculated for every function (i.e. domestic, office, shop, etcetera) so we get a different distribution of consumption per purpose for every combination of function, carrier, and energy label. Taking function, carrier, energy label and the energy consumption values as input, one can calculate for each building in the city how much gas and electricity is consumed for each purpose, on an accurate level. In addition, to make it easier to compare gas consumption with electricity and heat consumption, the gas consumption values are converted from m^3/year to kWh/year , using the conversion coefficients as given in table 4.

Country	Gross calorific value of natural gas (kWh/m^3)
Austria	10.55
Denmark	11.57
France	11.21
Germany	10.33
Italy	10.58
The Netherlands	9.26

Table 4: Gross calorific value of natural gas, average values of the gas consumed in six countries participating in the TRANSFORM project. From IEA (2012), where values for any other country can be found as well.

5.2 U-values from region and construction year

To be able to calculate the gains from insulating a building, it is important to know the current insulation state of that building. U-values are an indication of the insulation grade of a building. Higher U-values represent poor insulation, lower U-values good insulation.

There are several ways to estimate the current U-values of a building's surfaces from the city data input as displayed in table 1, most notably from the energy label (which refers to building properties) or construction year. As it proved difficult to translate energy label into U-values for all surfaces - because of ambiguous definitions of energy labels - the choice was made to base the current U-value estimations on construction year. The assumption is made here that buildings comply with the insulation standards in force during the construction year of the buildings. ECOFYS (2005) summarised the insulation standards of European buildings over history, in three different climatic zones (see table 5). This table is used to enrich the city data, assigning four U-values to each building, respectively for floor, walls, roof and windows. This enables more accurate calculation of the costs and effects of insulation measures.

U-values (W/(m ² K))	Built before 1975	Built 1975-1990	Built 1991-2002	Built 2003-2006	Built after 2006
Cold climatic zone					
Roof	0.50	0.20	0.15	0.15	0.13
Façade	0.50	0.30	0.20	0.18	0.17
Floor	0.50	0.20	0.18	0.18	0.17
Windows	3.00	2.00	1.60	1.42	1.33
Moderate climatic zone					
Roof	1.50	0.50	0.40	0.25	0.23
Façade	1.50	1.00	0.50	0.41	0.38
Floor	1.20	0.80	0.50	0.44	0.41
Windows	3.50	3.50	2.00	1.84	1.68
Warm climatic zone					
Roof	3.40	0.80	0.50	0.50	0.43
Façade	2.60	1.20	0.60	0.60	0.48
Floor	3.40	0.80	0.55	0.55	0.48
Windows	4.20	4.20	3.50	3.04	2.71

Table 5: Translating construction year and climatic zone into U-values, from ECOFYS (2005). The cold climatic zone refers to the countries Finland and Sweden; the moderate climatic zone to Austria, Belgium, Denmark, France, Germany, Ireland, Luxembourg, The Netherlands and United Kingdom; and the warm climatic zone to Greece, Italy, Portugal and Spain.

5.3 Determining building dimensions

In addition to knowing the U-values of buildings' surfaces, it is important to know the dimensions of these surfaces, to be able to determine how insulation is done exactly and how much the costs and energy savings will be. Since no 3D city models were found available for the participating cities, these building dimensions need to be estimated. Knowing the floor area, shape, building function, and number of storeys of every building in a city can provide us with estimations about the façade area, windows area and roof area.

For the façade and windows surface area, the GIS shapefiles of every building can be used to run a query that calculates the length of the contour of that shapefile (i.e. the ground level wall length). Multiplying this by the number of storeys of the building and an average storey height of 3.5 meters⁹ returns the total wall area, including windows. The windows area then is calculated by multiplying the total wall area with the window-to-wall ratio (taken as average based on building function, see table 6), and the net façade area (without windows) can in turn be calculated by multiplying the total wall area by (1 - window-to-wall ratio).

In a similar fashion, the roof area can be determined by calculating the surface area of the GIS shapefiles. This assumes flat roofs, while small houses most often have pitched roofs. The lack of more detailed buildings data obliges us to make a few simplifying assumptions. Buildings with a domestic function and 3 storeys or less will be assumed to have a pitched roof. Taking an average roof pitch of 45° leads to a multiplier of $\sqrt{2}$, used to estimate the roof area of small houses.

The data operations as described here, can provide building attributes that are of interest for insulation measures, as well as for the roll-out of solar PV panels. For the latter, it is important to know whether the roof is pitched or not (where we assumed that domestic houses with 3 storeys or less have a pitched roof). Therefore, a new binary indicator is created called PR (pitched roof).

Building function	Window-to-wall ratio
Domestic	0.16
Education	0.22
Hotel	0.34
Industry	0.06
Medical	0.27
Office	0.35
Shop	0.11
Sport*	0.22
Other*	0.22

Table 6: Average window-to-wall ratios for different building functions, from CBPCA (1991); Winiarski et al. (2007). *Not available, so average values are assumed.

⁹<http://www.ctbuh.org/HighRiseInfo/TallestDatabase/Criteria/HeightCalculator/tabid/1007/language/en-GB/Default.aspx>

5.4 Determining heating efficiencies

Buildings can use many different technologies for heating its inside air and water. Common options are a gas boiler, an electric heater, a heat pump, or a connection to the district heating grid. μ stands for the efficiency of the heating system, which is an important value to know for every building, since it translates energy consumption into actual heat demand. The actual heat demand determines how large new heating installations/connections need to be, and what the energy consumption will be after installing a new heating system. Therefore, heating efficiencies need to be known or estimated at a building level.

The heating efficiency can vary largely between buildings, depending on the heating system it uses. It is not given by the input data what heating system every building uses exactly, so again, for determining these heating efficiencies and therewith actual heat demands, simplifying assumption need to be made. The only distinction in heating efficiencies that can be made is between different carriers used (electricity, natural gas, heat) and different mediums heated (air/water).

Logically, a building connected to the heat grid has a 100% heating efficiency as there is no conversion process inside the building. Heating space by an electric system, other than a heat pump, will always have 100% efficiency (Otter Tail, 2009) for heating air, while the efficiency for heating water is quite low (around 25%). The efficiency of a heating system that runs on gas can vary from 70% to more than 100%. Average heating efficiencies per carrier and per medium will be used, as stated in table 7.

Heating efficiency $\mu_{m, c}$	m = air	m = water
c = electricity	100%	25%
c = natural gas	90%	90%
c = heat	100%	100%

Table 7: Assumed values of heating efficiencies of heating systems using different carriers.

5.5 Summary

In summary, the 10 data points that make up readily available city data as depicted in table 1 can be enriched in four ways, leading to the building variables that are used for the remainder of this study (34 data points) as shown in table 8. Each data point is given an mathematical abbreviation (first column) and the units are displayed in the third column.

Building properties		
Y_{con}	GIS Shapefile	wkb format
	Construction year	
	Building function	
A_{floor}	Floor area	m^2
OHC	Ownership by housing corporation	1 / 0
PR	Pitched roof	1 / 0
U_{roof}	U-value roof	$W/(m^2K)$
U_{facade}	U-value façade	$W/(m^2K)$
U_{floor}	U-value floor	$W/(m^2K)$
$U_{windows}$	U-value windows	$W/(m^2K)$
A_{roof}	Roof area	m^2
A_{facade}	Façade area	m^2
$A_{windows}$	Windows area	m^2
Energy data		
$FC_{elec, appliances}$	Electricity consumption for Appliances	kWh/year
$FC_{elec, cooking}$	Electricity consumption for Cooking	kWh/year
$FC_{elec, lighting}$	Electricity consumption for Lighting	kWh/year
$FC_{elec, heating building}$	Electricity consumption for Heating building	kWh/year
$FC_{elec, tap water}$	Electricity consumption for Heating tap water	kWh/year
$FC_{elec, showering}$	Electricity consumption for Showering	kWh/year
$FC_{elec, cooling}$	Electricity consumption for Cooling	kWh/year
$FC_{elec, ventilation systems}$	Electricity consumption for Ventilation systems	kWh/year
$FC_{gas, cooking}$	Gas consumption for Cooking	kWh/year
$FC_{gas, heating building}$	Gas consumption for Heating building	kWh/year
$FC_{gas, tap water}$	Gas consumption for Heating tap water	kWh/year
$FC_{gas, showering}$	Gas consumption for Showering	kWh/year
$FC_{heat, heating building}$	Heat consumption for Heating building	kWh/year
$FC_{heat, tap water}$	Heat consumption for Heating tap water	kWh/year
$FC_{heat, showering}$	Heat consumption for Showering	kWh/year
$\mu_{air, elec}$	Efficiency of heating air with electricity	%
$\mu_{air, gas}$	Efficiency of heating air with gas	%
$\mu_{air, heat}$	Efficiency of heating air with electricity	%
$\mu_{water, elec}$	Efficiency of heating water with electricity	%
$\mu_{water, gas}$	Efficiency of heating water with gas	%
$\mu_{water, heat}$	Efficiency of heating water with heat	%

Table 8: Nomenclature of city data variables used.

6 Measures of Interest

The measures of interest that were identified in the stakeholder interviews are described here in more detail. The impacts of the measures on a building level are extracted from literature and expressed in a generic fashion, so as to make the impacts comparable. The investment costs of measures are converted into annual costs of capital to be able to compare investments with annual running costs (consumption). This is done by multiplying the investment costs by an annuity factor a :

$$a = \frac{(1+i)^n * i}{(1+i)^n - 1}$$

where i is the interest rate and n the service lifetime. The interest rate is set at 4%, which is a reasonable assumption for long term loans in Europe¹⁰. The service lifetime is different for each measure, and can be found in the subsections below. Different service lifetimes of 15, 20, 25, 30 and 40 years lead to the five different annuity factors used in this report:

	Service lifetime	Annuity factor
a_{15}	15 years	0.0899
a_{20}	20 years	0.0736
a_{25}	25 years	0.0640
a_{30}	30 years	0.0578
a_{40}	40 years	0.0505

Table 9: Annuity factors for service lifetimes of 15, 20, 25, 30 and 40 years, assuming an interest rate of 4%.

6.1 Solar PV panels

Solar photovoltaic (PV) panels generate electricity from solar energy by using semiconducting materials that exhibit the photo-voltaic effect. In urban environments, PV panels can be placed on roofs of buildings (as described in this section), or even on building façades (see section 6.2). For rooftop solar panels, crystalline silicon (c-Si) panels are chosen for the calculations in this measure, since it is the most widely applied technology. The amount of electricity that can be produced on the roof of one building is dependent on the size and shape of the roof, and on the geographical location.



The share of solar panel area per m² of roof area is dependent on whether the roof is flat or pitched. A pitched roof can be filled more efficiently with PV panels than a flat roof. From the assumptions in the city data enrichment method (section 5.3), it is estimated which roofs are pitched and which are flat. The orientation of the pitched roofs is unknown and therefore we have to make a simplifying assumption that all pitched roofs have a part directed southwards, and this part is assumed to be half of the total roof area. A flat roof can be covered with a certain ratio of panel area to roof area, dependent on what the minimum angle of the sun is on the specific geographic location. Meck (2014) describes a method for calculating the

¹⁰https://www.ecb.europa.eu/stats/shared/download/stats/download/mir_pr_t04/mir_pr_t04/mir_pr_t04.pdf

distance between arrays of solar panels (see figure 14) on which the following formula was based for the ratio of panel area to roof area R:

$$R = \frac{1}{\cos(\theta) + \frac{\sin(\theta)}{\tan(\alpha)}}$$

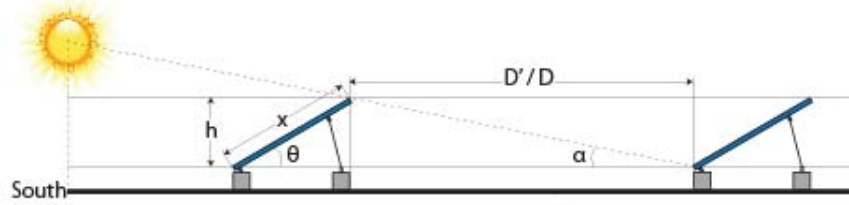


Figure 14: Side view of a tilted array of solar panels, showing the minimum angle of the sun α . From Meck (2014).

Now, the PV planner of SolarGIS (2014) was used to find the optimal inclination angle of solar panels θ for six geographical locations and together with the lowest solar angle α this gives the ratio of panel area to roof area R for every location, as shown in table 10. Table 10 also provides the global irradiation and effective output from solar panels placed southwards (azimuth 180°). A performance ratio $\eta_{pv} = 81.3\%$ was taken from SolarGIS (2014) as a common value for the whole PV system, considering losses from angular reflectivity (3.21%), conversion to DC in the modules (6.54%), other DC losses (5.51%), inverters (2.47%), transformer and AC cabling losses (1.52%) and availability (1.00%).

		Vienna	Copenhagen	Lyon	Hamburg	Genoa	Amsterdam
		Solar PV parameters					
θ	Optimal inclination angle	37°	39°	38°	38°	38°	37°
α	Minimum solar azimuth	18.4°	10.9°	20.8°	13.3°	22.2°	14.2°
R	Ratio of panel area to flat roof area	0.38	0.25	0.42	0.29	0.44	0.31
G_i	Global irradiation (kWh/kWp)	1378	1201	1513	1155	1659	1187
η_{pv}	Performance ratio	81.3%	81.3%	81.3%	81.3%	81.3%	81.3%
	Effective output (kWh/kWp)	1120	976	1230	939	1349	965

Table 10: Global irradiation and effective output per kWp of installed capacity under the optimal inclination angle, assuming a performance ratio of 81.3%, for the six TRANSFORM cities. From SolarGIS (2014). The minimum solar azimuth is the angle of the sun during solar noon on 21 December (the day at which the sun is at its lowest on the Northern hemisphere), this determines the spacing between arrays of PV panels. From Meck (2014).

Assuming the currently common capacity of $\beta = 0.160$ kWp per m^2 , the amount of “Local Production by solar power” $LP_{elec, solar}^t$ can be calculated by adding the new PV output to the latest value of the variable “Local Production by solar power” $LP_{elec, solar}^{t-1}$:

$$LP_{\text{elec, solar}}^t = LP_{\text{elec, solar}}^{t-1} + G_i * \eta_{\text{pv}} * P_{\text{solar pv}}$$

where

$$P_{\text{solar pv}} = \left(PR * \frac{1}{2} + (1 - PR) * R \right) * A_{\text{roof}} * \beta$$

The investment costs for solar PV panels could vary slightly for different regions in Europe. These costs values can be set by users of the Decision Support Tool, where also price developments over time can be modelled. Merely to give an indication, investment costs have been determined from stakeholder interviews and supplier websites, to be around 1.35 € per kWp plus a fixed cost of around € 1400 per installation. The lifetime of solar panels lies around 25 years. This gives the investment costs formula:

$$IC_{\text{solar pv}} = a_{25} * (1400 + 1.35 * P_{\text{solar pv}})$$

6.2 Façade PV panels

Installing solar PV panels on façades can be a good sustainable option for high-rise buildings, such as office buildings, in the urban environment (Yun & Steemers, 2009). Thin film solar panels are a good choice for this, since these also capture radiation from reflections onto the back side and perform better in shading. From all materials, copper indium selenide (CIS) is most chosen for thin film façade panels and according to experts also the most viable option (see appendix A). An example project are the façade panels installed on an office building in Amstelveen, the Netherlands (figure 15). SolarGIS (2014) gives us good estimations of the gains from panels placed on the south-oriented façade of a building, as depicted in table 11. Inspired by the example project, an angle of 70° is taken.



Figure 15: Thin film façade panels on an office building in Amstelveen, the Netherlands.

		Vienna	Copenhagen	Lyon	Hamburg	Genoa	Amsterdam
		Façade solar PV parameters					
θ	Inclination angle	70°	70°	70°	70°	70°	70°
G_i	Global irradiation (kWh/kWp)	1195	1068	1296	1014	1422	1036
η_{pv}	Performance ratio	82.0%	82.0%	82.0%	82.0%	82.0%	82.0%
	Effective output (kWh/kWp)	980	876	1063	830	1166	850

Table 11: Global irradiation and effective output per kWp of installed CIS thin film capacity under a 70° inclination angle, assuming a performance ratio of 82.0%, for the six TRANSFORM cities. From SolarGIS (2014).

Like in the previous subsection (6.1), we take a solar cell capacity of $\beta = 0.160$ kWp per m^2 . On the Northern hemisphere, typically only the south-oriented façade will be filled with panels since the gains are highest there. The lack of a 3D-model of all the buildings in a city requires us to make an assumption with regards to the south façade area. The best we can do is use a factor $\frac{1}{4}$ of the total façade area to be filled with PV panels. The “Local Production by solar power” $\text{LP}_{\text{elec, solar}}^t$ can be calculated by adding the new PV output to the latest value of “Local Production by solar power” $\text{LP}_{\text{elec, solar}}^{t-1}$:

$$\text{LP}_{\text{elec, solar}}^t = \text{LP}_{\text{elec, solar}}^{t-1} + G_i * \eta_{\text{pv}} * P_{\text{façade pv}}$$

where

$$P_{\text{façade pv}} = \frac{1}{4} * A_{\text{façade}} * \beta$$

The investment costs for thin film panels could vary slightly for different regions in Europe. These costs values can be set by users of the Decision Support Tool, where also price developments over time can be modelled. Merely to give an indication, investment costs have been determined from stakeholder interviews and supplier websites, to be around 1.70 € per kWp, including installation and inverters. These projects typically only take place on a larger scale, so that there is no initial fixed investment costs. The lifetime of thin film panels lies around 25 years. This gives the investment costs formula:

$$\text{IC}_{\text{façade pv}} = a_{25} * 1.70 * P_{\text{façade pv}}$$

6.3 Insulation

Insulation is often part of a “Retrofit” package to reduce the energy consumption for heating in existing buildings. It can include all parts of the building envelope, i.e. wall insulation, floor insulation and roof insulation. Two factors play a role for the decision on insulating or not. First, the current insulation degree of buildings, and second, the desired insulation degree. While every house owner has its own preferences when it comes desired insulation degree, the assumption is made here that if a house owner is insulating, he/she does so up to the optimal level. This assumes rational behaviour, i.e. maximising benefits and minimising costs.

ECOFYS (2007) did a study on the economically optimal insulation degree (U-values) of buildings in numerous locations in Europe, depending on the local climate and economic conditions. The optima are found at points where energy savings are largest compared to investment costs (see figure 16).

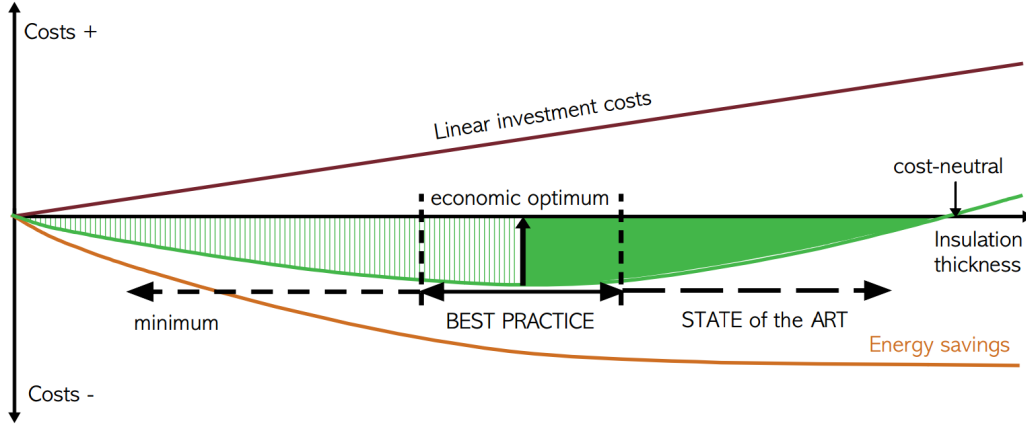


Figure 16: Typical investment and energy saving curves for building insulation, determining a rather wide economic optimum zone. From ECOFYS (2007).

It turns out that the optimal insulation levels are not dependent on the fixed costs of insulation measures or the current U-values, but only on variable investment costs, energy prices and climate conditions. This leads to optimal U-values for every region.

The authors did extensive data investigation to determine the values of these optimal U-values for a large number of cities in Europe. The optimal U-values for nine European cities are depicted in table 12, together with the Heating Degree Days (displayed as thousands of Heating Degree Hours), a measurement that reflects the outside temperature in terms of energy needed to heat a building. A complete list of optimal U-values and Heating Degree Days can be found in the original document by ECOFYS (2007).

The measure of insulation as described here includes insulation of roof, wall and floor up to the optimal economic level. As described in section 5.3, the wall area and roof area can be estimated quite precisely using available city data. Savings in heat demand are calculated taking the Heating Degree Hours (HDH) and optimal U-values (Π_s) of every surface s from table 12, the current U-values (U_s) of every surface s from the enriched city data (see section 5.2), as well as the wall-, floor- and roof area (A_s), and filling these in in the following formula (ECOFYS, 2007):

$$\Delta E = \text{HDH} * \sum_s (U_s - \Pi_s) * A_s$$

Cold climatic zone				
		Oslo	Stockholm	Helsinki
Π_{roof}	Optimal U -value roof	0.15	0.16	0.15
Π_{facade}	Optimal U -value façade	0.19	0.20	0.18
Π_{floor}	Optimal U -value floor	0.22	0.24	0.22
HDH	Thousands of Heating Degree Hours	113	101	118
Moderate climatic zone				
		Amsterdam	Copenhagen	Lyon
Π_{roof}	Optimal U -value roof	0.17	0.16	0.18
Π_{facade}	Optimal U -value façade	0.21	0.19	0.21
Π_{floor}	Optimal U -value floor	0.28	0.24	0.28
HDH	Thousands of Heating Degree Hours	73	89	70
Warm climatic zone				
		Barcelona	Rome	Athens
Π_{roof}	Optimal U -value roof	0.27	0.25	0.29
Π_{facade}	Optimal U -value façade	0.35	0.32	0.39
Π_{floor}	Optimal U -value floor	0.69	0.84	1.44
HDH	Thousands of Heating Degree Hours	28	30	21

Table 12: Optimal U -values and Thousands of Heating Degree Hours for nine European cities in three climatic zones, from ECOFYS (2007). HDH = HDD*24/1000

Since a building can use more than carrier for heating (e.g. one household uses electricity and the others gas to heat their homes), the total savings need to be divided over the different carriers used, in the right proportions. Also, different heating efficiencies $\mu_{\text{air}, c}$ for heating air (see table 7) need to be taken into account. The impact on a building level, of insulation towards the optimal U -values, can be formulated as:

$$\text{FC}_{c, \text{ heating building}}^t = \text{FC}_{c, \text{ heating building}}^{t-1} - \frac{\text{FC}_{c, \text{ heating building}}^{t-1}}{\sum_c \text{FC}_{c, \text{ heating building}}^{t-1}} * \frac{\Delta E}{\mu_{\text{air}, c}}$$

The investment costs for insulation are a sum of the fixed installation costs and the variable material costs, where the latter are determined by the thickness of the insulation material d . This thickness d is derived from the difference in U values and the average thermal resistance per cm of insulation material $R = 0.25 \text{ m}^2\text{K}/(\text{W}*\text{cm})$:

$$d_s = \frac{\frac{1}{\Pi_s} - \frac{1}{U_s}}{0.25}$$

Average fixed and variable costs for the moderate climatic zone can be derived from ECOFYS (2007):

		Roof	Façade	Floor
cst _{s, fixed}	Fixed costs (€ / m ²)	13.00	24.20	15.40
cst _{s, variable}	Variable costs (€ / (cm * m ²))	0.80	1.25	1.00

Table 13: Fixed and variable costs of insulation in the moderate climatic zone of Europe, including the countries Austria, Belgium, Denmark, France, Germany, Ireland, Luxembourg, The Netherlands and United Kingdom.

With this information, we can provide a rough estimation of the investment costs of insulation, which is equal to:

$$IC_{\text{insulation}} = a_{30} * \sum_s (cst_{s, \text{fixed}} + cst_{s, \text{fixed}} * d_s) * A_s$$

6.4 Window replacement

Similarly to the insulation measure, window replacement leads to a reduction in U-values, in this case for the window surfaces. The same method is used as the one for the insulation measure (see section 6.3 for details). The optimal U-values for three climatic zones and related investment costs are depicted in table 14.

		Cold zone	Moderate zone	Warm zone
Π_{window}	Optimal U-value (W/(m ² K))	1.33	1.68	2.71
cst _{window replacement}	Investment costs (€/m ²)	433	316	142

Table 14: Optimal U-values and investment costs for the replacement of windows, for three climatic zones in Europe, from ECOFYS (2005). The cold climatic zone refers to the countries Finland and Sweden; the moderate climatic zone to Austria, Belgium, Denmark, France, Germany, Ireland, Luxembourg, The Netherlands and United Kingdom; and the warm climatic zone to Greece, Italy, Portugal and Spain.

The impact of replacing the windows, on a building level, can be formulated in a similar fashion as was done for insulation:

$$FC_{c, \text{heating building}}^t = FC_{c, \text{heating building}}^{t-1} - \frac{FC_{c, \text{heating building}}^{t-1}}{\sum_c FC_{c, \text{heating building}}^{t-1}} * \frac{HDH * (U_w - \Pi_w) * A_w}{\mu_{\text{air}, c}}$$

The investment costs are equal to:

$$IC_{\text{window replacement}} = a_{30} * cst_{\text{window replacement}} * A_w$$

6.5 LED lighting

Lighting in office buildings currently consumes about 37% of the total electricity demand (see table 3). With LED technology just having reached the point of cost-competitiveness with traditional lighting technology, LED is considered a key way of saving energy, especially in offices. Table 15 gives an overview of the current state of LED technology and how it is expected to improve until 2030.

		2013	2015	2020	2030
cst_{LED}	LED Lamp price (€/klm)	13.60	8.00	4.00	1.60
η_{LED}	LED Efficacy (lm/W)	96	130	200	230

Table 15: LED lamp price and efficacy projections. From Navigant Consulting (2014). Prices in euros based on an exchange rate of EUR/USD = 0.80.

In table 15, the price of LED lighting is given in € per kilo-lumen, where lumen refers to an “amount of visible light”. In offices, a lighting demand E_{lx} of 0.5 klm per m^2 and a switch-on time t_{light} of 2750 hours/year is regarded standard (Dubois & Blomsterberg, 2011). The standard lighting demand is taken for every office building, since more detailed information about this is not available from city data. This makes the current measure calculations applicable to average office buildings (for other types of buildings, different lighting demand values should be regarded). Regardless of the values of E_{lx} and t_{light} , the new electricity consumption for lighting $\text{FC}_{\text{elec, lighting}}^t$ and the investment costs for LED lighting are calculated by:

$$\begin{aligned}\text{FC}_{\text{elec, lighting}}^t &= A_{\text{floor}} * \frac{E_{\text{lx}}}{\eta_{\text{LED}}} * t_{\text{light}} \\ \text{IC}_{\text{LED}} &= a_{15} * A_{\text{floor}} * E_{\text{lx}} * \text{cst}_{\text{LED}}\end{aligned}$$

With the standard office values, this gives an energy intensity of around 10 kWh/ m^2 yr for the year of 2015, which is considered a realistic target for office lighting in future low energy office buildings by Dubois and Blomsterberg (2011).

Motion Sensor lighting control

Occupancy sensors can reduce the switch-on time of office lights by 25% (Jennings, Rubinstein, DiBartolomeo, & Blanc, 2000), at a cost of € 1.44 per m^2 (Leviton, 2014). With this option added to the installation of LED lights, the impact and costs formulas become:

$$\begin{aligned}\text{FC}_{\text{elec, lighting}}^t &= A_{\text{floor}} * 0.75 * \frac{E_{\text{lx}}}{\eta_{\text{LED}}} * t_{\text{light}} \\ \text{IC}_{\text{LED}} &= a_{15} * A_{\text{floor}} * (E_{\text{lx}} * \text{cst}_{\text{LED}} + 1.44)\end{aligned}$$

6.6 Shower Heat Exchanger

A shower heat exchanger is especially developed for households, to recover heat from waste water. Water used for showering still has a temperature of around 37 degrees Celcius, the moment it is disposed of. A shower heat exchanger recovers the energy in waste water that is otherwise dispersed down the drain. This recovered energy is transferred to the incoming water. In this way, the temperature of the water that flows into the boiler is higher than in a reference situation, and the boiler needs less energy to heat up the water to the desired temperature (see figure 17). A shower heat exchanger is said to save about $\sigma_{\text{shower heat exchanger}} = 60\%$ of energy used for the purpose of showering (Moerman, 2012), irrespective of the energy carrier used to provide this energy, so this means:

$$FC_{c, \text{ showering}}^t = FC_{c, \text{ showering}}^{t-1} * (1 - \sigma_{\text{shower heat exchanger}})$$

The price of it is dependent on the amount of construction costs, which in turn depends on the scale on which installation takes place. A distinction will be made between shower heat exchanger implementation in a single house/apartment and implementation in a building block. The latter can in practice be done in houses owned by a housing corporation, since these corporations oftentimes own whole building blocks and can decide on renovation activities in their property. Different prices follow from this distinction, for two different cases:

Price of shower heat exchanger & installation costs	
Heat exchanger	€ 400
Installation in private house	€ 600
Installation in house owned by housing corporation	€ 300

Table 16: Investment costs for a shower heat exchanger, with a distinction between privately owned houses and houses owned by housing corporations.

The investment costs of the shower heat exchanger can therefore be formulated as a function of the binary variable OHC (Ownership by Housing Corporation):

$$IC_{\text{shower heat exchanger}} = a_{30} * (1000 - \text{OHC} * 300)$$

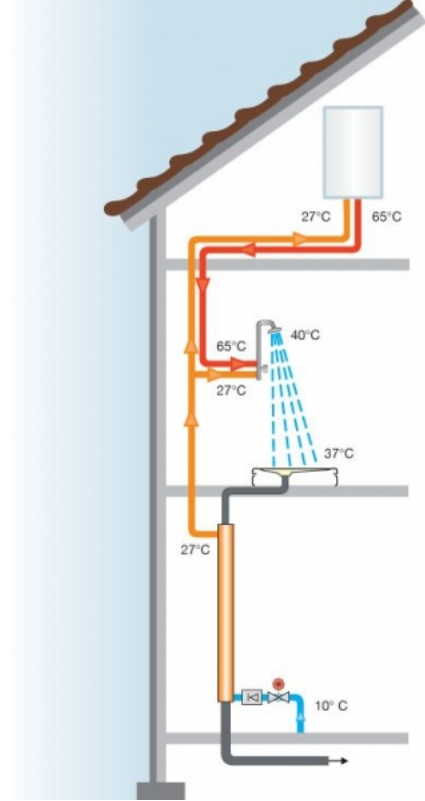


Figure 17: The principle of a shower heat exchanger. From Moerman (2012)

6.7 District Heating Grid

A district heating grid is a heat supply system for urban environments, that connects a centralised heat production unit to residential and commercial consumers, which consume the heat from the grid for the purposes of space heating and water heating. It is a more energy efficient system than having separate gas boilers in every building, due to the simultaneous production of heat and electricity in Combined Heat and Power (CHP) plants, as explained by figure 18. CHP plants are also suitable for the incineration of biomass, which leads to a higher share of renewables in the heat provision. Next to benefiting from the advantages of CHP plants, district heating grids can also capture and distribute waste heat that otherwise would be

dispersed into the environment, for example from industries or data centres. In summary, district heating systems use less fuel and “greener” fuel to meet the heat demand of residential and commercial consumers, which has a positive impact on the CO₂ emissions, energy efficiency, and share of renewables of a city.

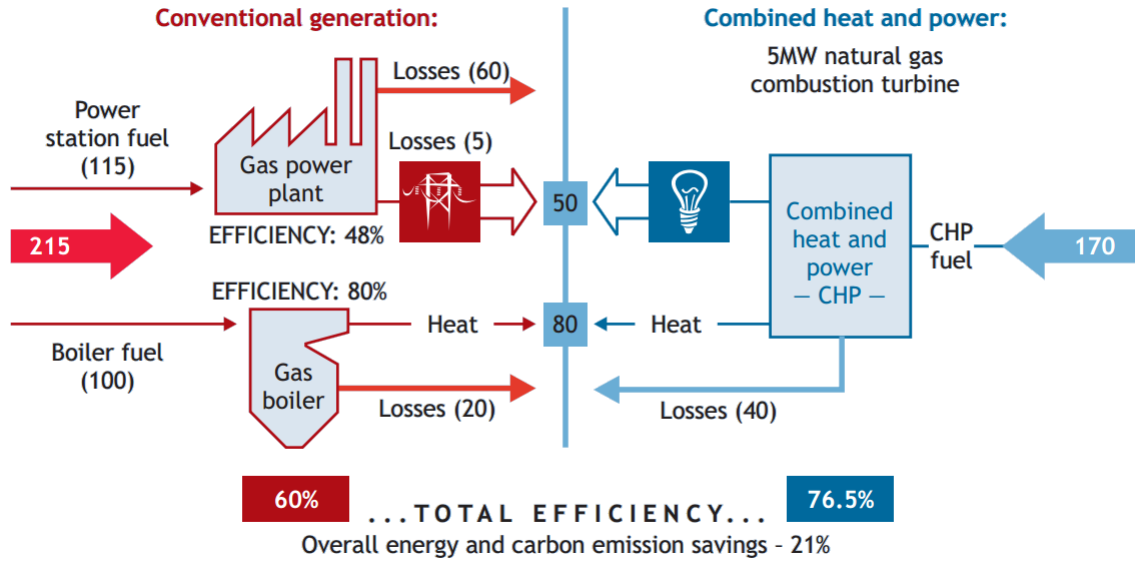


Figure 18: How a CHP plant is more efficient than separate heat and power plants. From IEA (2008a).

When a building gets connected to the District Heating Grid, the simple thing that happens is a change of carrier (from gas/electricity to heat) for the purposes of heating building, heating tap water and showering. The new carrier “heat” will cover the full energy demand for these three purposes. The total energy demand for these three purposes is calculated, and then attributed to the carrier of heat:

$$\begin{aligned}
 FC_{\text{heat, heating building}}^t &= \sum_{c = \text{carrier}} \mu_{\text{air, } c} * FC_{c, \text{heating building}}^{t-1} \\
 FC_{\text{heat, tap water}}^t &= \sum_{c = \text{carrier}} \mu_{\text{water, } c} * FC_{c, \text{tap water}}^{t-1} \\
 FC_{\text{heat, showering}}^t &= \sum_{c = \text{carrier}} \mu_{\text{water, } c} * FC_{c, \text{showering}}^{t-1}
 \end{aligned}$$

Please note that the FC values of other carriers need to be set to zero for these three purposes:

$$\begin{aligned}
 FC_{\text{elec, heating building}}^t &= FC_{\text{elec, tap water}}^t = FC_{\text{elec, showering}}^t = 0 \\
 FC_{\text{gas, heating building}}^t &= FC_{\text{gas, tap water}}^t = FC_{\text{gas, showering}}^t = 0
 \end{aligned}$$

Alongside the connection to a district heating grid, comes often the switch from cooking with gas to cooking with electricity:

$$\begin{aligned}
 FC_{\text{elec, cooking}}^t &= FC_{\text{elec, cooking}}^{t-1} + FC_{\text{gas, cooking}}^{t-1} \\
 FC_{\text{gas, cooking}}^t &= 0
 \end{aligned}$$

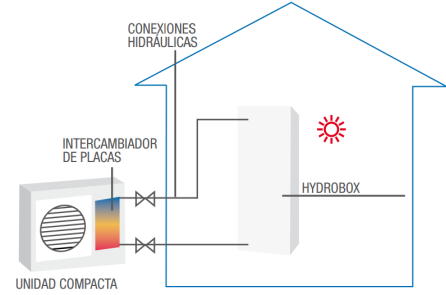
Investment costs are very much dependent on the location of the building in respect to the existing heating grid. The network properties should be incorporated, to make a good estimation of the required investments for a grid extension. The lack of data on this leaves us only the option to make a rough estimation. As stated by the existing district heating grid operator in The Netherlands (Nuon/AEB, 2012), the average costs per connection are € 5000. Since heating grids last for at least 40 years, the estimated cost of capital per connection are:

$$IC_{\text{district heating grid}} = a_{40} * 5000$$

6.8 Air Source Heat pump

An air source heat pump is a device designed to extract heat from the air by way of a loop and concentrate it for use to heat a space or heat water. It consists of a compressor, a blower motor and a circulation pump.

An air source heat pump is usually not suitable for large (office) buildings since these have a large heat demand (De Groene Menukaart, 2014). The heat pump is best applied in domestic buildings or small shops.



The heat pumps considered for this measure are from the Mitsubishi Ecodan series, which can be used for space heating and water heating (to 60°C), and operate remarkably well at low temperatures (no loss of performance until -15°C; working at temperatures down to -25°C) (Mitsubishi Electric, 2014). The efficiency of a heat pump is measured by the Coefficient of Performance (COP). Basically, the COP is the amount of heat inserted into the building divided by the amount of electricity consumed to transport this heat. A Mitsubishi Ecodan series heat pump has an average COP for space heating of 4.0 and a COP for heating water of 2.0, values that are common also among other heat pump series. The electricity consumption for heating after installing a heat pump, is based on the current energy demand and these COP values:

$$FC_{\text{elec, heating building}}^t = \sum_{c = \text{carrier}} \frac{\mu_{\text{air, c}} * FC_{c, \text{heating building}}^{t-1}}{4.0}$$

$$FC_{\text{elec, tap water}}^t = \sum_{c = \text{carrier}} \frac{\mu_{\text{water, c}} * FC_{c, \text{tap water}}^{t-1}}{2.0}$$

$$FC_{\text{elec, showering}}^t = \sum_{c = \text{carrier}} \frac{\mu_{\text{water, c}} * FC_{c, \text{showering}}^{t-1}}{2.0}$$

Note that the FC values for heating space and water with the other carriers needs to be set to zero. To overcome miscalculations with other measures that interact with this measures, the building will be given new efficiency values for heating with electricity:

$$\mu_{\text{air, elec}} = 4.0$$

$$\mu_{\text{water, elec}} = 2.0$$

Heat pumps have a service lifetime of about $n = 20$ years. Per 100 m² of floor area, about 10 kW of output capacity is required (Comfort Klimaat, 2014). The prices for different sizes and models of Mitsubishi heat pumps are difficult to find; only a Spanish catalogue included all required pricing information (Almagrup, 2014) so these prices will be used here. The prices increase more or less linearly with heat pump output capacity, giving a price of about € 400 per kW of output capacity of the heat pump (or € 40 per m²), and an additional investment of € 2100 for the “hydrobox” that enables domestic hot water preparation. The total investment costs are calculated by:

$$IC_{\text{heat pump}} = a_{20} * (2100 + 40 * A_{\text{floor}})$$

6.9 Aquifer Thermal Storage (open system)

An aquifer thermal storage system uses inter-seasonal heat- and cold-storage, located underground, and connected with the inside building through a pipeline system and heat pump(s). During summer, cold from the cold storage is pumped into the building, and heat from inside the building is pumped into the heat storage. During this process, the underground heat storage is heated by 4 to 8 degrees Celcius (Klokman, Olsthoorn, & Beemster, 2013). Once it gets winter, the heat pump switches direction; heat is now pumped from the underground heat source into the building, cooled down by the heat pump, and injected into the cold storage. In this way, the excess heat in buildings during summer is not wasted, but used again during winter, and vice versa, which leads to a lower primary energy consumption (Van der Maas, 2013).

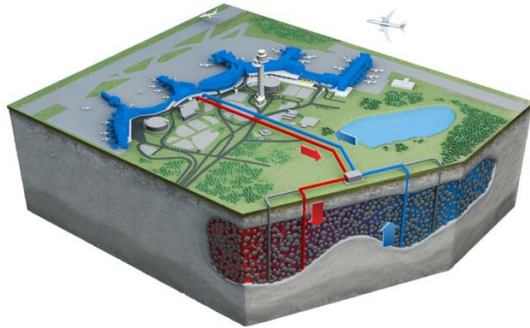


Figure 19: ATS Summer operation - cooling. From Underground Energy (2014).

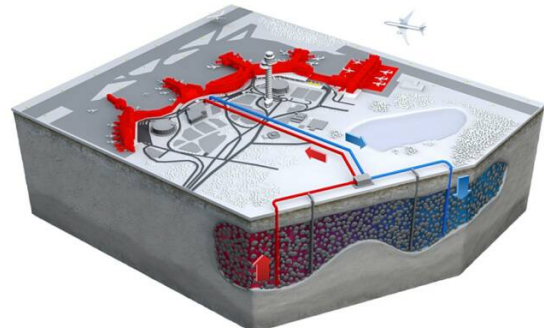


Figure 20: ATS Winter operation - heating. From Underground Energy (2014).

In order for such an energy storage system to be sustainable, it is important that the heat demand and cold demand be equal. E.g. a heat demand that is double the cold demand, will cause the cold well to cool down at a higher rate than it would heat up, leading to a net decrease in temperature every year. Needless to say, this is not sustainable on the long term. Luckily, in case there is no perfect balance between heat and cold demand, efficient heat/cold regeneration can compensate for this to reach an energy balance. Still, the system is most efficient in climates where winters are cold and summers warm.

The underground heat and cold storages are located next to each other on equal depth, and exist of soil that holds some groundwater. The underground layer that contains these storages is called the aquifer. Suitable layers of soil for the aquifer are found at different depths, depending on the geographical location. It was difficult to find data on the depths of suitable layers in all of the participating cities within TRANSFORM. For Amsterdam, it is known that suitable layers are located between 70 and 180 meters below sea level (Klokman et al., 2013). These depths will be assumed for the investment costs calculations, making these valid for Amsterdam.

The efficiency of an aquifer thermal storage system is measured by the Seasonal Performance Factors (SPFs) of the heat pump, one for heating and one for cooling. Basically, the SPF is the amount of energy (heat/cold) inserted into the building divided by the amount of electricity consumed to transport this heat or cold. In table 17, practical values for these SPFs are noted.

Practical SPFs	
Heating	3.9
Cooling	6.3
Regeneration	22

Table 17: SPF values of an aquifer thermal storage system, for heating, cooling, and regeneration, based on measured data. From Nam et al. (2010) and Van der Maas (2013).

It follows from stakeholder interviews that typically about 90% of the heat demand will be covered by the aquifer thermal storage system, and the remaining 10% of the heat demand will still be provided by a gas boiler. We will start with calculating the total effective heat and cold demand of a building:

$$E_{\text{heating building}} = \sum_{c = \text{carrier}} \mu_{\text{air, c}} * FC_{c, \text{heating building}}^{t-1}$$

$$E_{\text{cooling}} = \mu_{\text{aircon}} * FC_{\text{elec, cooling}}^{t-1}$$

where a current cooling efficiency of $\mu_{\text{aircon}} = 3.6$ will be assumed and the heating efficiencies are as stated in table 7. An imbalance in heat and cold demand needs to be compensated by regeneration:

$$FC_{\text{elec, regeneration}}^t = \frac{|E_{\text{heating building}} - E_{\text{cooling}}|}{\text{SPF}_{\text{regeneration}}}$$

The new energy consumption values for heating and cooling the building are:

$$FC_{\text{elec, heating building}}^t = 0.9 * \frac{E_{\text{heating building}}}{\text{SPF}_{\text{heating}}}$$

$$FC_{\text{gas, heating building}}^t = 0.1 * \frac{E_{\text{heating building}}}{\mu_{\text{air, gas}}}$$

$$FC_{\text{elec, cooling}}^t = \frac{E_{\text{cooling}}}{\text{SPF}_{\text{cooling}}}$$

Note that the FC values for heating space and water with the other carriers needs to be set to zero (like was done in section 6.7 and 6.8). To overcome miscalculations with other measures that interact with this measure, the building will be given a new efficiency for heating its building with electricity:

$$\mu_{\text{air, elec}} = \text{SPF}_{\text{heating}}$$

Note that the energy required for heating water is omitted as being provided by the aquifer thermal storage system. This energy demand is typically still provided with a conventional gas boiler (the one that also fulfils the peak demand for heating the building) because this is generally still more efficient. Besides, an aquifer thermal storage system is most suitable for large (office) buildings and will in practice never be installed in small domestic buildings. Large buildings like offices have a low energy demand for heating water, which makes the investment in a water-heating system connected to the aquifers non-feasible. Thirdly, using the aquifer thermal storage for heating water will certainly cause an imbalance in heating and cooling demand, which is unfavourable.

Now, it is important to know what the required size of the installation is, to be able to calculate the investment costs. A calculation sheet for investment costs was provided by Martin Bloemendal, expert on Aquifer Thermal Storage systems from Delft University of Technology. This sheet was used to make a good estimation of the investment costs, as a function of the heat and cold demand. The assumption was made that the aquifer layer starts at 70 meters depth, and can be maximum 90 meters high. A heat or cold demand (whichever is larger) of 2.6 GWh/year or lower can be fulfilled by a system with one doublet (a set of 1 heat and 1 cold storage well). A higher heat or cold demand requires two doublets. These two cases make a different investment costs function. In figures 21 and 22, the investment costs for both situations are plotted against maximum energy demand, and the linear trendline formulas are displayed in the graphs. This leads to the general investment function of:

$$E_{\max} = \max(E_{\text{heating building}}, E_{\text{cooling}})$$

$$IC_{\text{aquifer thermal storage}} = a_{40} * \left\{ \min(\max(2600000 - E_{\max}, 0), 1) * (81603 + 0.0297 * E_{\max}) \right. \\ \left. + \min(\max(E_{\max} - 2600000, 0), 1) * (125707 + 0.0462 * E_{\max}) \right\}$$

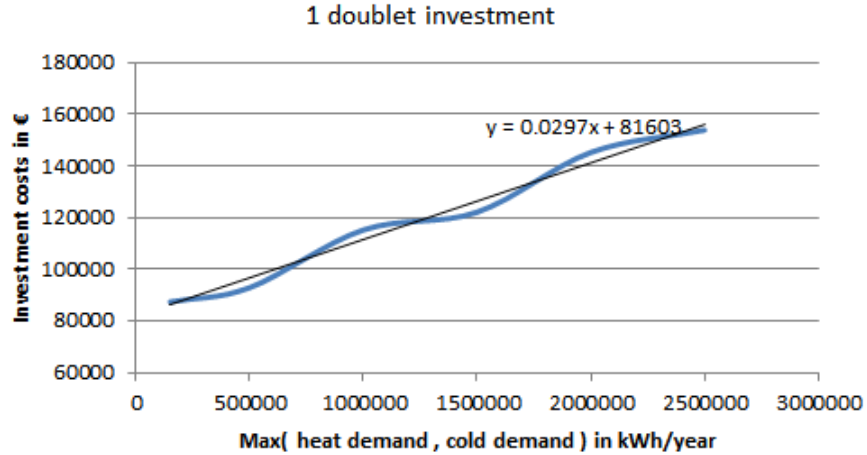


Figure 21: Investment costs of a system with one doublet, as function of the maximum energy demand (heat or cold).

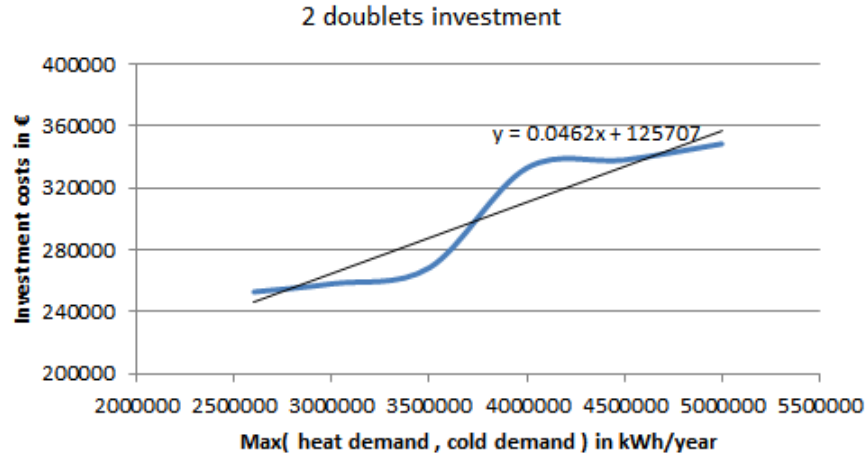


Figure 22: Investment costs of a system with two doublets, as function of the maximum energy demand (heat or cold).

6.10 Micro CHP

The principle of a combined heat and power (CHP) plant was already explained in section 6.7. A micro CHP unit follows the same principle, but then on a small scale (see figure 23). It can be used within households, or small offices, but a larger number of generators in parallel can also satisfy the energy demand of larger buildings. As figure 23 shows, a micro CHP generator consumes natural gas, of which 25% of the energy content is converted into heat (for heating the building and heating tap water / showering) and 60% into electricity. This combined generation is - like in large-scale CHP plants - more efficient than separate electricity production and heat generation. In this way, a micro CHP generator will increase energy efficiency and lower CO₂ emissions.

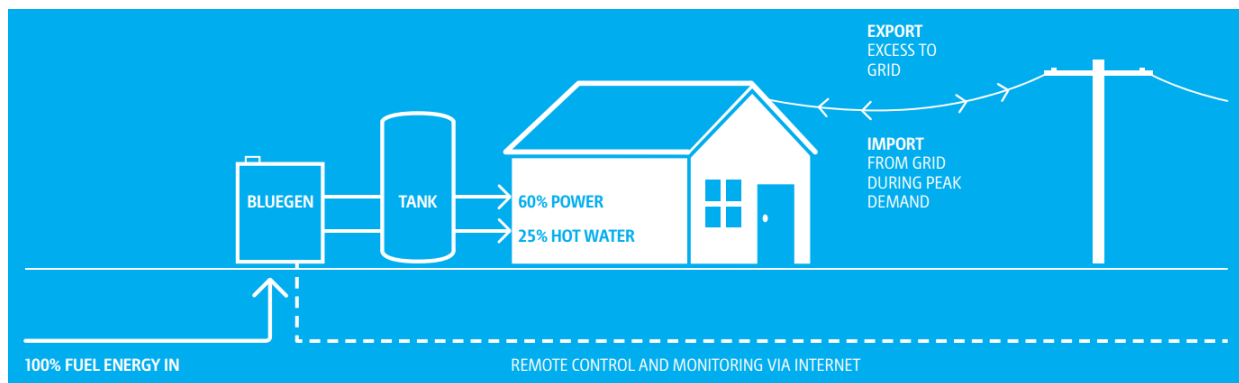


Figure 23: The principle of a BlueGen Micro CHP generator. From BlueGen (2014).

Typically, a Micro CHP serves as replacement of the existing heating system. Therefore, it is assumed that a micro CHP plant runs at a capacity level that fulfils the total heat demand of a building (for heating building, heating tap water and showering).

$$\begin{aligned}
FC_{\text{gas, heating building}}^t &= \sum_{c = \text{carrier}} \frac{FC_{c, \text{heating building}}^{t-1} * \mu_{\text{air}, c}}{0.25} \\
FC_{\text{gas, tap water}}^t &= \sum_{c = \text{carrier}} \frac{FC_{c, \text{tap water}}^{t-1} * \mu_{\text{water}, c}}{0.25} \\
FC_{\text{gas, showering}}^t &= \sum_{c = \text{carrier}} \frac{FC_{c, \text{showering}}^{t-1} * \mu_{\text{water}, c}}{0.25}
\end{aligned}$$

The produced electricity is then fed into the grid:

$$LP_{\text{elec, chp}}^t = (FC_{\text{gas, heating building}}^t + FC_{\text{gas, tap water}}^t + FC_{\text{gas, showering}}^t) * 0.60$$

The price of a BlueGen generator is about € 30,000 (RE New Economy, 2012) and it will last for about 15 years (Ceramic Fuel Cells Limited, 2009), resulting in a yearly cost of capital of:

$$IC_{\text{micro chp}} = a_{15} * 30000$$

6.11 Wind turbines

Urban wind mills are an extremely uneconomic option for generating electricity (MacKay, 2008) and will therefore not be considered as a serious option in this study. Large-scale wind turbines however, are a very feasible option for generating renewable energy. The downside of this option is that space is limited in urban environments, especially when it comes to installing 160 meter high wind turbines. It is nonetheless worth it to explore the potential of installing wind turbines within city boundaries. Amsterdam has provided data on areas that can potentially serve as wind parks, along with the maximum capacity CAP_{wind} and the maximum potential of electricity generation $LP_{\text{wind, max}}$ in every area. This makes it very easy to estimate the annual power produced when a part $SHARE_{\text{selected}}$ of such an area will be covered with wind turbines.

The impact of installing wind turbines within the city boundaries will have a small impact on the national production mix of electricity. The impact of extra installed wind power capacity will therefore not be calculated through in the production mix, but the before-mentioned areas with wind turbines will be treated as separate entities that produce electricity locally (which is then consumed within the city). The investment costs for onshore wind turbines are taken from IPCC (2014) at € 1680 per MW of installed capacity, along with a lifetime of 25 years. This information creates the rather simple impact formulas:

$$\begin{aligned}
LP_{\text{wind}}^t &= LP_{\text{wind, max}} * SHARE_{\text{selected}} \\
IC_{\text{wind turbines}} &= a_{25} * 1680 * SHARE_{\text{selected}} * CAP_{\text{wind}}
\end{aligned}$$

7 Definition of KPIs

As follows from the context and requirements set by the TRANSFORM project, the KPIs that reflect the energy performance of a city are the three indicators referring to the 20-20-20 climate targets, plus a costs indicator: CO₂ emissions, energy efficiency, share of renewables, and costs. The indicators will be calculated from the available city data and can be impacted by the implementation of measures. We have seen in section 6 that all these measures have an impact on either Final Consumption (FC) or Local Production (LP). These city variables are combined with a set of city parameters, to calculate the KPIs. Exact definitions of these KPIs are not given within the TRANSFORM project, and therefore, the KPIs are interpreted by the author using common definitions from renowned sources, in as far as the available data conditions allow these definitions to be applied. In this section, the four KPIs will first shortly be defined, and then it will be described how the city data variables of Final Consumption and Local Production, together with a set of parameters, relate (mathematically) to the KPIs.

CO₂ emissions Nowadays, the majority of emissions are energy-related emissions, which are the most significant driver of observed climate change since the mid-20th century (EPA, 2014). Therefore, with the term CO₂ emissions we will refer to these energy-related emissions. Next to CO₂, there are other greenhouse gases being emitted from burning fossil fuels, which are included in the climate targets. These targets are usually measured in CO₂ equivalent, a way to add up the effects of different greenhouse gases. One kilogram of CO₂-equivalent in emissions is equal to the impact that one kilogram of CO₂ has on the atmosphere (CBS, 2014). For example, the emission of 1 kg of nitrous oxide (N₂O) is equal to the emission of 310 kg of CO₂, and thus equals 310 kg CO₂-equivalent. The KPI CO₂ emissions therefore refers to energy-related greenhouse gas emissions, measured in CO₂ equivalent.

Energy efficiency is intuitively a simple concept, but writing a clear definition can be extremely complex (IEA, 2014a). According to the Lawrence Berkeley National Laboratory (2014), energy efficiency is “using less energy to provide the same service”. This makes the distinction clear between switching off a light (less energy but no service, i.e. energy conservation) and replacing an incandescent lamp with a LED lamp (less energy but same service, i.e. energy efficiency). Energy efficiency can be defined as the “amount of service” divided by the primary energy consumption. In that way, reductions in energy efficiency come from the conversion process of final energy to service, from transmission and distribution, and from energy generation. However, the “amount of service” has no generic units and cannot be measured easily. Especially within the context of the current study, it is impossible to quantify the total amount of services provided to buildings, based on the available city data. It is not known what type of refrigerator a household is using and how energy efficient the toaster is. For that matter, the definition of energy efficiency needs to be simplified and a more mechanical definition will be used: energy efficiency is final energy consumption divided by primary energy consumption. It is once again very important to note that energy efficiency within this report merely relates to the energy production and distribution efficiencies, and not to the conversion efficiency of energy into an energy service¹¹.

Share of renewables The UN (2014) gives a definition of the share of renewable energy sources in total energy use. This is the total energy demand produced by renewable sources, divided by the total energy consumption. Renewable sources can in this case be combustibles like biofuels, biomass and waste, or non-combustibles such as solar, wind, hydro, and geothermal.

Costs The costs KPI has two components: costs from energy consumption and costs from investment in sustainability measures. The latter are transformed into yearly costs of capital as described in section 6. The former are simply the energy bills that consumers pay. Adding these up will give a good indication of the total economic viability of certain groups of measures, or implementation plans.

¹¹The efficiencies of heating air and water could be the exception, and included in the overall energy efficiency calculation. However, since these values are not exactly known from available city data (see table 7), just like efficiencies of other energy conversion applications, they are omitted in the KPI energy efficiency within this study

Next to the city data variables:

$FC_{c,p}$	= Final consumption of carrier c for purpose p	kWh/year
$LP_{elec, s}$	= Local electricity production from source s	kWh/year
$\mu_{m,c}$	= Efficiency of heating medium m with carrier c	%

and the investment costs IC_m for every measure m, as described in section 6, we use the following city parameters to calculate the KPIs:

$MX_{f,c}$	= Production Mix (share of carrier c produced by fuel f)	%
$\eta_{f,c}$	= Production efficiency of energy carrier c from fuel f	%
ε_f	= CO ₂ emissions from fuel f	gCO ₂ -eq/kWh
τ_c	= Transmission and distribution efficiency of energy carrier c	%
p_c	= Retail price of energy carrier c	€/kWh

The production mix parameters refer to the amount of electricity that is produced, not the amount that is consumed. At high shares of wind and solar power, an amount of excess electricity $P_{elec, excess}$ is produced (at times when supply is higher than demand). A share of wind power of 40% refers in this case to 40% of the total electricity production (i.e. consumed electricity plus excess electricity). In Appendix B, one can view how the amount of excess electricity is calculated as a function of the shares of wind and solar power. There are different ways to deal with excess electricity (see Appendix B), but the dynamics of these different options and their economic feasibilities are outside the scope of the current study. Therefore, it is assumed that excess electricity is simply not consumed or stored, i.e. curtailed from the grid.

7.1 CO2 Emissions

The total CO₂-equivalent of emissions is calculated as follows:

$$CO2e = \sum_c \sum_f \frac{MX_{f,c} * \left(\sum_p FC_{c,p} - \sum_s LP_{c,s} + \tau_c * P_{elec, excess} \right)}{\eta_{f,c} * \tau_c} * \varepsilon_f$$

7.2 Energy Efficiency

The energy efficiency is defined as the total final consumption (by households, offices, etcetera) divided by the primary energy that is needed to produce this energy. It is calculated as follows:

$$EEF = \frac{\sum_c \sum_p FC_{c,p}}{\sum_c \sum_f \frac{MX_{f,c} * \left(\sum_p FC_{c,p} - \sum_s LP_{c,s} + \tau_c * P_{elec, excess} \right)}{\eta_{f,c} * \tau_c}}$$

where $n = \{ \text{appliances, cooking, lighting, cooling, ventilation systems} \}$ and $w = \{ \text{heating tap water, showering} \}$

7.3 Share of Renewables

The Share of Renewables is the percentage of energy demand (i.e. energy consumption) that is produced by a renewable energy source:

$$\text{RES} = \frac{\text{MX}_{\text{renewables, heat}} * \sum_p \text{FC}_{\text{heat, p}} + \sum_r \text{MX}_{r, \text{elec}} * \left(\sum_p \text{FC}_{\text{elec, p}} - \sum_s \text{LP}_{\text{elec, s}} + \text{P}_{\text{elec, excess}} \right) + \sum_s \text{LP}_{\text{elec, s}} - \text{P}_{\text{elec, excess}}}{\sum_c \sum_p \text{FC}_{c, p}}$$

where $r = \{ \text{hydro, wind, biomass, solar, geothermal} \}$

7.4 Costs

Costs have three components: consumption costs, investment costs and maintenance costs. Maintenance costs are omitted from the model since these vary too much and there is no data on current maintenance costs of existing energy systems in buildings. Assumed here is that a consumer who produces electricity locally, only pays for the net usage of electricity. This simplification was made because feed-in tariff policies differ strongly per country¹² and change over time, i.e. the dynamics of these are considered outside of the scope of the current research.

In the current study, the costs for storing excess electricity are not considered, as it is assumed that excess electricity is always curtailed, i.e. wasted. Appendix B gives more background information on the costs of storing electricity, an option that can be added in a continuation of the current study.

$$\text{CST} = \left(\sum_p \text{FC}_{c, p} - \sum_s \text{LP}_{c, s} \right) * p_c + \sum_m \text{IC}_m$$

where $m = \{ \text{solar pv, facade pv, insulation, window replacement, LED, shower heat exchanger, district heating grid, heat pump, aquifer thermal storage, micro chp, wind turbines} \}$

¹²http://en.wikipedia.org/wiki/Feed-in_tariff

8 City parameters

The following parameters are not building-related. They say something about the properties of the energy supply system of a city. In this section, the current values of these parameters are given, as they were found in reports from international / European energy institutions. Most parameters will be subject to changes in the future. Therefore, the city parameters will be treated as factors (see figure 4), that can have different future evolutions under different scenarios.

$MX_{f,c}$ = Production Mix (share of carrier c produced by fuel f)	%
$\eta_{f,c}$ = Production efficiency of energy carrier c from fuel f	%
ε_f = CO ₂ emissions from fuel f	gCO ₂ -eq/kWh
τ_c = Transmission and distribution efficiency of energy carrier c	%
p_c = Retail price of energy carrier c	€/kWh

The emissions in CO₂-equivalent per unit of fuel are considered fixed, as they are constant by laws of physics, assuming that the average composition of a fuel is constant over time and region. The IPCC (2014) provides a thorough analysis of the emissions from electricity generation by different power plants, and gives global averages for efficiencies of these plants and emissions per kWh output. More specific data on emissions per type of plant, and the composition of plant types in every country would give more accurate estimations of the total CO₂ emissions. However, these data were not found readily available and therefore, the global averages of emissions per fuel type are used as input for this study¹³, see table 18.

ε_f	CO ₂ emissions from fuels (gCO ₂ -eq/kWh*)
Coal	320
Oil	288
Natural gas	270
Biomass	230
Solar	41
Geothermal	38
Hydro	24
Nuclear	12
Wind	11

Table 18: Lifecycle CO₂ emissions, including the albedo effect, from different fuels. Calculated from IPCC (2014). *For coal, oil, and natural gas, 1 kWh refers to the gross calorific value, or energy content of a fuel. In all other cases it refers to 1 kWh of produced electricity.

Production mixes and production efficiencies are subject to the same limitations as CO₂ emissions per unit of fuel, as described above. The lack of data on these parameters for all power plants in every country obliges us to use national averages, from several sources, as depicted in table 19. The production efficiencies of heat are not directly found in these sources, since a large share of heat comes from CHP plants, and for these it is hard to quantify which part of the primary energy is used for electricity generation and which part for

¹³e.g.: emissions from 1 kWh gross calorific value of coal = emissions from 1 kWh electricity from a coal plant * efficiency of a coal plant

	Austria	Denmark	France	Germany	Italy	Netherlands
MX _{f,elec}	Production mix of electricity ^a					
f = natural gas	22.0%	16.9%	5.2%	15.5%	50.1%	64.6%
f = coal	8.3%	40.6%	2.7%	43.8%	14.9%	19.3%
f = oil	1.6%	1.3%	0.6%	1.1%	6.6%	1.3%
f = nuclear	0.0%	0.0%	79.0%	18.0%	0.0%	3.7%
f = hydro	58.0%	0.1%	9.0%	3.9%	15.9%	0.1%
f = wind	3.0%	28.4%	2.2%	8.2%	3.3%	4.6%
f = biomass	7.0%	12.7%	0.9%	6.3%	3.6%	6.4%
f = solar	0.3%	0.1%	0.4%	3.2%	3.6%	0.1%
f = geothermal	0.0%	0.0%	0.0%	0.0%	1.9%	0.0%
$\eta_{f,elec}$	Production efficiency of electricity ^b					
f = natural gas	46%	45%	48%	43%	51%	47%
f = coal	41%	43%	39%	38%	38%	39%
f = oil	36%	40%	31%	34%	41%	43%
MX _{f,heat}	Production mix of heat ^c					
f = natural gas	38.2%	26.3%	62.1%	47.5%	58.0%	73.9%
f = coal	3.4%	23.4%	7.1%	32.8%	0.7%	11.2%
f = oil	6.6%	1.8%	15.5%	1.1%	26.5%	4.8%
f = others	5.5%	10.4%	7.6%	8.9%	1.6%	3.9%
f = renewables	46.2%	38.0%	7.6%	9.7%	13.2%	6.2%
$\eta_{f,heat}$	Production efficiency of heat ^d					
f = natural gas, coal, oil	85%	110%	98%	113%	87%	95%
f = renewables, others	100%	100%	100%	100%	100%	100%
Share of heat in District Heat Grid produced by CHP plants ^e						
All fuels	55%	82%	53%	58%	48%	55%
Net production efficiency of CHP plants						
Overall ^f	65.5%	72.7%	78.7%	75.6%	64.5%	68.8%
Electricity generation ^g	44.2%	43.5%	43.9%	39.2%	47.4%	45.1%
Heat generation ^h	80.4%	114.3%	106.0%	129.5%	83.0%	99.6%
Production efficiency of heat produced by back-up plants (non-CHP) ⁱ						
All fuels	90%	90%	90%	90%	90%	90%

Table 19: Electricity and heat production parameters.

^aFrom EU (2013)

^bFrom IEA (2008b). The production efficiencies of nuclear and renewable electricity are assumed to be 100%.

^cFrom EU (2013)

^dAs calculated from values in the remainder of this table. For the renewable fuels and other fuels, a production efficiency of 100% is assumed.

^eCalculated from EU (2013), or from <http://www.iea.org/media/files/chp/profiles/Denmark.pdf> and <http://www.iea.org/media/files/chp/profiles/Netherlands.pdf>

^fFrom Eurostat (2003)

^gWeighted average of electricity production efficiencies from fossil fuels

^hCalculated from overall efficiency, electricity generation efficiency, and electricity-to-heat ratio of CHP plants, where the latter was found in EU (2013). For details on this calculation method, please contact the author.

ⁱProduction efficiencies of non-CHP plants are assumed to be equal to standard boiler efficiency (see table 7).

heat generation. However, the overall efficiency of CHP plants is known, so efficiencies for heat generation by CHP plants can be calculated by weighing these with the average efficiencies of power plants. Subsequently, average production efficiencies for heat (from CHP plants and back-up plants) can be calculated using an average production efficiency of 90% by back-up plants and weighing both averages according to the division in CHP/non-CHP plants.

The initial transmission and distribution efficiencies and energy consumption prices are depicted in table 20. A simplifying assumption was made for the natural gas networks, taking into account no losses in transmission and distribution. In practise there could be losses due to leaks in the grid, but these were not accounted for since no reliable numbers about these losses were found. The reported transmission and distribution efficiency of heat differs greatly between sources, and was not available in reports from major institutes. A percentage of 60% was taken, as this followed from an interview with a heat grid operator in Amsterdam.

	Austria	Denmark	France	Germany	Italy	Netherlands
τ_c	Transmission & distribution efficiency (%)					
Electricity	95.1%	93.4%	93.7%	96.1%	93.1%	96.2%
Natural gas	100%	100%	100%	100%	100%	100%
Heat	60%	60%	60%	60%	60%	60%
p_c	Retail price (€/kWh)					
Electricity	0.218	0.315	0.155	0.310	0.245	0.206
Natural gas	0.0743	0.1040	0.0717	0.0757	-	0.0830
Heat	-	0.080	0.066	-	-	0.090

Table 20: Energy retail prices from IEA (2014b). Heat consumption costs and transmission/distribution efficiencies from stakeholder interviews. Electricity transmission & distribution efficiencies from Index Mundi (2010). No losses in the transmission and distribution of natural gas are assumed.

9 Case study: Amsterdam Zuid Oost

Amsterdam Zuid Oost is an area (in the South East of Amsterdam) that was selected as an interesting area to perform a case study on (see figure 24). Multiple stakeholders within the region and from municipality have shown an interest in transforming the area into a more sustainable neighbourhood. Group discussions between these stakeholders have led to energy visions and project plans, but they indicated that a quantitative backing is missing. The stakeholders would like to get an insight in how these projects would have an impact on the important indicators (like CO₂ emissions), and how much each plan would contribute to reaching the sustainability targets. The urban energy model is meant to do exactly this, so this was identified as a good opportunity to test the model in a real-life case. Within the case study, several meetings with the stakeholders were set up to test whether the developed model/tool can enable informed decision-making for the stakeholders. Before diving into the details of these sessions, a background on the region's context will be described.

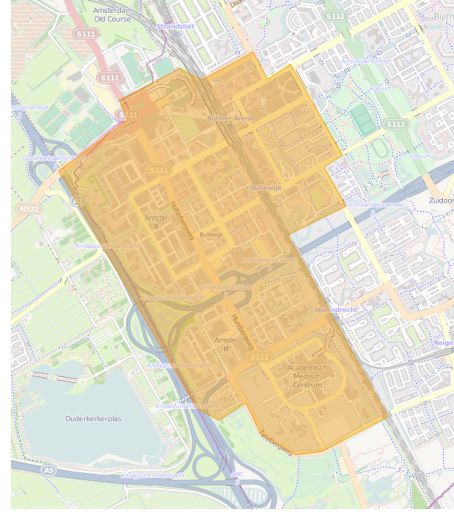


Figure 24: Map of Zuid Oost

9.1 The Zuid Oost region context

Amsterdam Zuid Oost is a mixed-use area of about 300 hectares, including the Ajax soccer stadium, offices, enterprises, leisure and entertainment industry, shopping malls, academic hospital, data centres, residential areas and an energy plant. The business activities are key contributors to the high energy consumption in the area. It is a relatively low-income area (€ 16,722 per household per year in comparison to the Amsterdam average of € 29,708), with a high unemployment rate (19%). 23% of the inhabitants live on a minimum income, and the perceived safety is relatively low. The area attracts a high number of visitors (nine million per year) due to its shopping and leisure facilities. It contains a number of head offices, although 25% of the office space is vacant. Many communities are organised within local churches and sports clubs, and efforts have been taken to improve the image of the area, with success in recent years. It is desirable to increase the number of middle class income households and the office occupancy in the region. The municipality of Amsterdam's medium-long term vision for Zuid Oost is to integrate housing into the office area to make it a more lively, socially safe and attractive environment. Retrofitting and the creation of new parks are already planned on the medium-long term. The combination of low prices and little restrictions (monumental, etc.) makes the region very suitable for urban innovation and experiments. The area is perfectly suitable for smart grid developments, for both thermal- and electricity grid.

In 2012, the Amsterdam Energy and Climate Office was founded, and started an initiative with local stakeholders in the Zuid Oost area (companies, NGOs, public parties) to start up sustainability projects in Zuid Oost. Sessions were organised where renters, owners, service providers, housing corporations, and other stakeholders came together to connect and brainstorm. The sessions resulted in seven projects targeted at CO₂ reduction. Even more project ideas popped up during the Intensive Lab Sessions of the TRANSFORM consortium in Amsterdam. Stakeholders are enthusiastic about these project, but the exact impact on CO₂ emissions and energy consumption are not known yet.

9.2 Sustainability performance and targets

The city of Amsterdam has set ambitious CO₂ reduction targets of 40% by 2025 and 75% by 2040, compared to 1990 levels. Since emissions have been steadily increasing by a total of 33% between 1990 and 2012, these reduction targets translate to 55% by 2025 and 81% by 2040 compared to 2012 levels. These numbers serve as a basis for the local reduction targets of the Zuid Oost region. The Measures of Interests for reaching these targets follow from stakeholder interviews, to be: insulation, window replacement, LED lighting, solar PV panels, wind turbines, and aquifer thermal storage systems. Figure 25 represents a top down study by the municipality of Amsterdam, that shows the estimated impact of different measures, and how these reductions compare to the target levels of consumption/emission. Important to note here is that the term consumption and emission were treated as equivalent indicators with the term consumption referring to energy consumption that causes CO₂ emissions (e.g. solar PV panels can lead to a reduction in consumption).

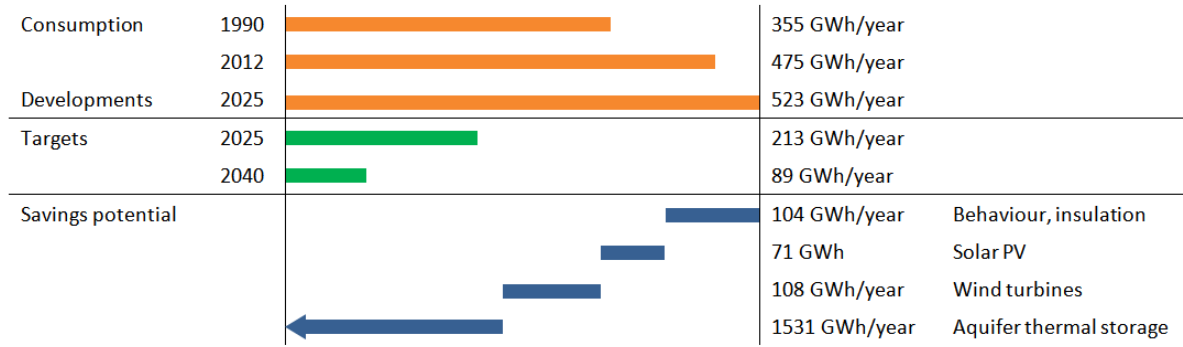


Figure 25: Top down potential study of Zuid Oost, by the municipality of Amsterdam.

9.3 Goal of the case study

A case study is done in collaboration with two stakeholders from the municipality of Amsterdam, using the results of the current research in combination with the decision support tool, in order to estimate the impact that can be achieved by implementing the above-mentioned measures in the Zuid Oost region. The benefits of this case study are two-sided. On one hand, it provides the city stakeholders with their desired impact estimations on the four relevant KPIs, after implementing a large number of sustainability measures. On the other hand, this case study will answer the last research question: Does the resulting MOI-to-KPI impact model in combination with the Decision Support Tool help city stakeholders in the decision making process, by enabling good comparison between interventions, while taking into account local characteristics? It serves as a validation method for the current study.

9.4 Case study set up

A session was set up with the two stakeholders from the municipality of Amsterdam, that have no prior experience with the Decision Support Tool. They selected a set of five Measures of Interest for the Zuid Oost area, with the types of buildings that these measures can be applied to, and realistic completion dates for every measure (see table 21).

Measure	Completion date	Applied to building types
Insulation + window replacement	01-01-2016	all
LED lighting + sensors	01-01-2017	education, hotel, office
Solar PV panels	01-01-2018	all
Aquifer thermal storage	01-01-2019	office
Wind turbines	01-01-2020	-

Table 21: Implementation plan for the Zuid Oost case study.

A key problem for decision makers is the inability to predict the willingness of building owners to implement sustainability measures in their buildings. The decision support tool can be used to test the impacts of measures given that only certain types of building owners will implement them, and only certain percentages of these building owners. In collaboration with the two city stakeholders, we have designed several implementation plans, where measures are allocated in different building types and at different uptake rates¹⁴.

First of all, it would be interesting to know what the result would be if all building owners were willing to contribute to the energy transition, by implementing one or more suitable sustainability measures in their building, i.e. exploring the maximum potential of the area. Secondly, a more realistic scenario would be interesting to explore, in which serious effort is needed to convince stakeholders in the area, but not up to the level of “persuading” every single actor to cooperate. As the city stakeholders indicate, it is often easier to align a smaller group of large, powerful stakeholders than a large group of “small” stakeholders, like households. Therefore, a distinction is made between the uptake among larger buildings and the uptake among small buildings, while both uptake rates are still chosen very optimistically (in order to set a sort of maximum to a feasibility range that is called realistic by the expert city stakeholders). Thirdly, a very pessimistic scenario would be interesting for setting the lower boundary to the feasibility range. With advice from the city stakeholders, minimum uptake rates were set that were deemed achievable under any circumstances. In summary, the following three implementation plans were chosen: (A) Maximum potential, (B) Large players align, high uptake, and (C) Minimum uptake.

A: Maximum potential Implementation plan A simply explores what can theoretically be done in the Zuid Oost area by only implementing the five selected Measures of Interest.

Measure	Date of implementation	Uptake	Applied to building types
Insulation + window replacement	01-01-2016	100%	all
LED lighting + sensors	01-01-2017	100%	education, hotel, office
Solar PV panels	01-01-2018	100%	all
Aquifer thermal storage	01-01-2019	100%	office
Wind turbines	01-01-2020	100%	-

Table 22: Implementation plan A for the Zuid Oost case study.

¹⁴where uptake rate refers to the percentage of selected buildings in which a measure will be actually implemented.

B: Large players aligned, high uptake Implementation plan B explores the option of having the large players aligned through a joint initiative, while also smaller actors have a relatively high willingness to transform their buildings.

Measure	Date of implementation	Uptake	Applied to building types
Insulation + window replacement	01-01-2016	90%	education, hotel, medical, office
Insulation + window replacement	01-01-2016	50%	domestic, shop
LED lighting + sensors	01-01-2017	90%	education, hotel, office
Solar PV panels	01-01-2018	90%	education, hotel, medical, office
Solar PV panels	01-01-2018	50%	domestic, shop
Aquifer thermal storage	01-01-2019	90%	office
Wind turbines	01-01-2020	100%	-

Table 23: Implementation plan B for the Zuid Oost case study.

C: Minimum uptake Implementation plan C explores the very pessimistic case in which only a few building owners are willing to contribute to the Zuid Oost energy transition.

Measure	Date of implementation	Uptake	Applied to building types
Insulation + window replacement	01-01-2016	20%	education, hotel, medical, office
Insulation + window replacement	01-01-2016	10%	domestic, shop
LED lighting + sensors	01-01-2017	20%	education, hotel, office
Solar PV panels	01-01-2018	20%	education, hotel, medical, office
Solar PV panels	01-01-2018	10%	domestic, shop
Aquifer thermal storage	01-01-2019	20%	office
Wind turbines	01-01-2020	10%	-

Table 24: Implementation plan C for the Zuid Oost case study.

9.5 Results

In figures 26-28, the impacts of the Zuid Oost implementation plans A to C are shown. Next to giving accurate estimations of the impacts of different sustainability measures, these results provide insights in the influence of consumers' willingness to transform on the ability to reach the climate targets. In the following pages, the results of every implementation plan are shortly discussed and compared with the top down result as given in figure 25.

Implementation plan A: maximum potential

Figure 26 represents the evolution of the KPIs under implementation plan A: maximum potential (see table 22), where the targets for 2025 are displayed with red dashed lines. It follows that there is enough potential in the Zuid Oost area to reduce emissions below the 2025 targets by aid of insulation, LED lighting, solar PV panels, aquifer thermal storage, and wind turbines. The reductions in consumption costs outweigh the investment costs largely¹⁵.

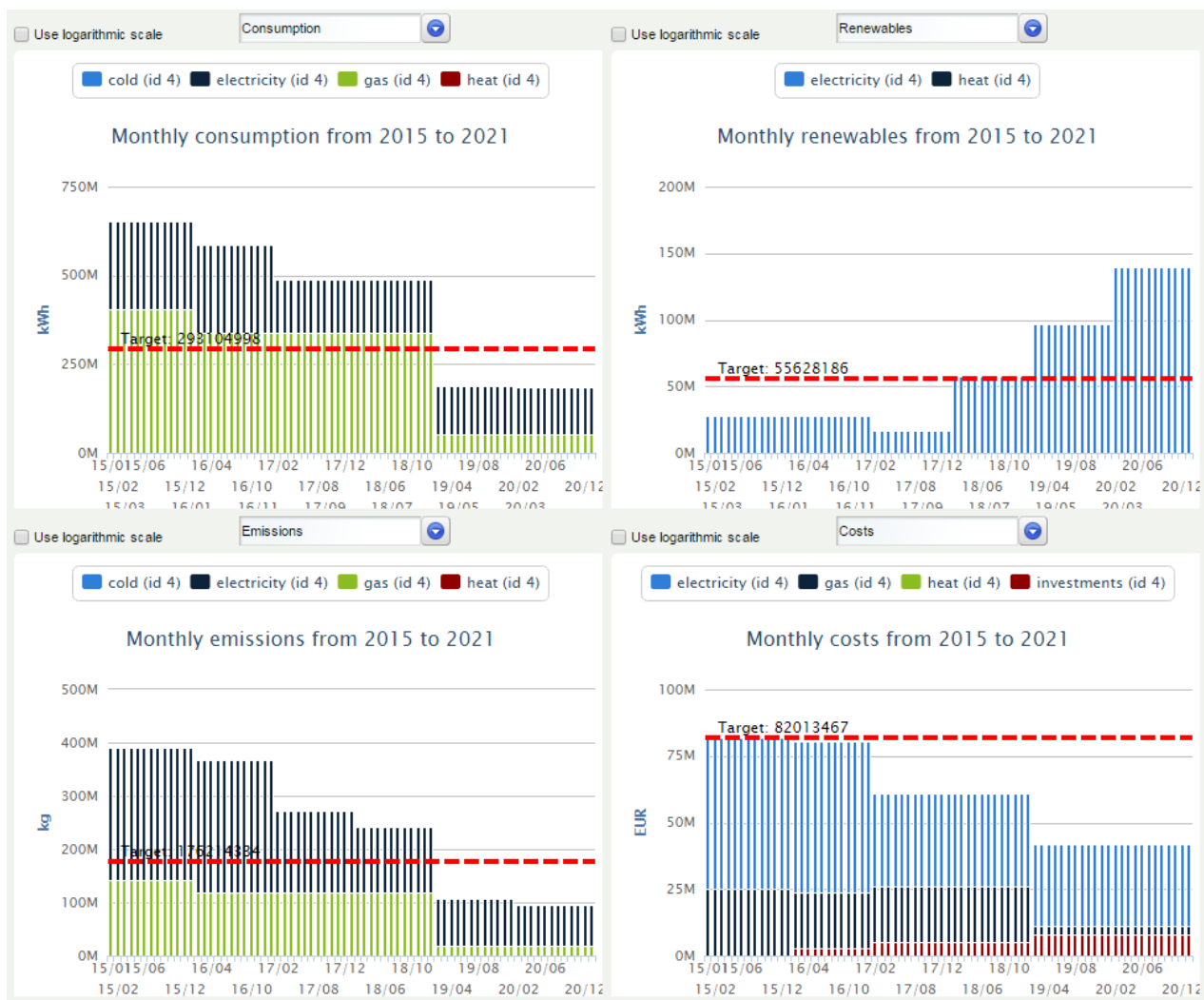


Figure 26: Impact of implementation plan A on the consumption, renewables, emissions and costs of Amsterdam Zuid Oost.

¹⁵note again that investment costs are converted into costs of capital (see section 6)

Figure 27 shows the implementation plan where large players (schools, hospital, offices, hotels) are aligned and form a joint initiative to transform the area, while the municipality pushes for a high uptake rate (50%) among the smaller players (see table 23). This result is assumed to be very optimistic, but realistically feasible. Also under this assumptions, the climate targets will easily be reached. In fact, the results differ only marginally from the maximum potential results.

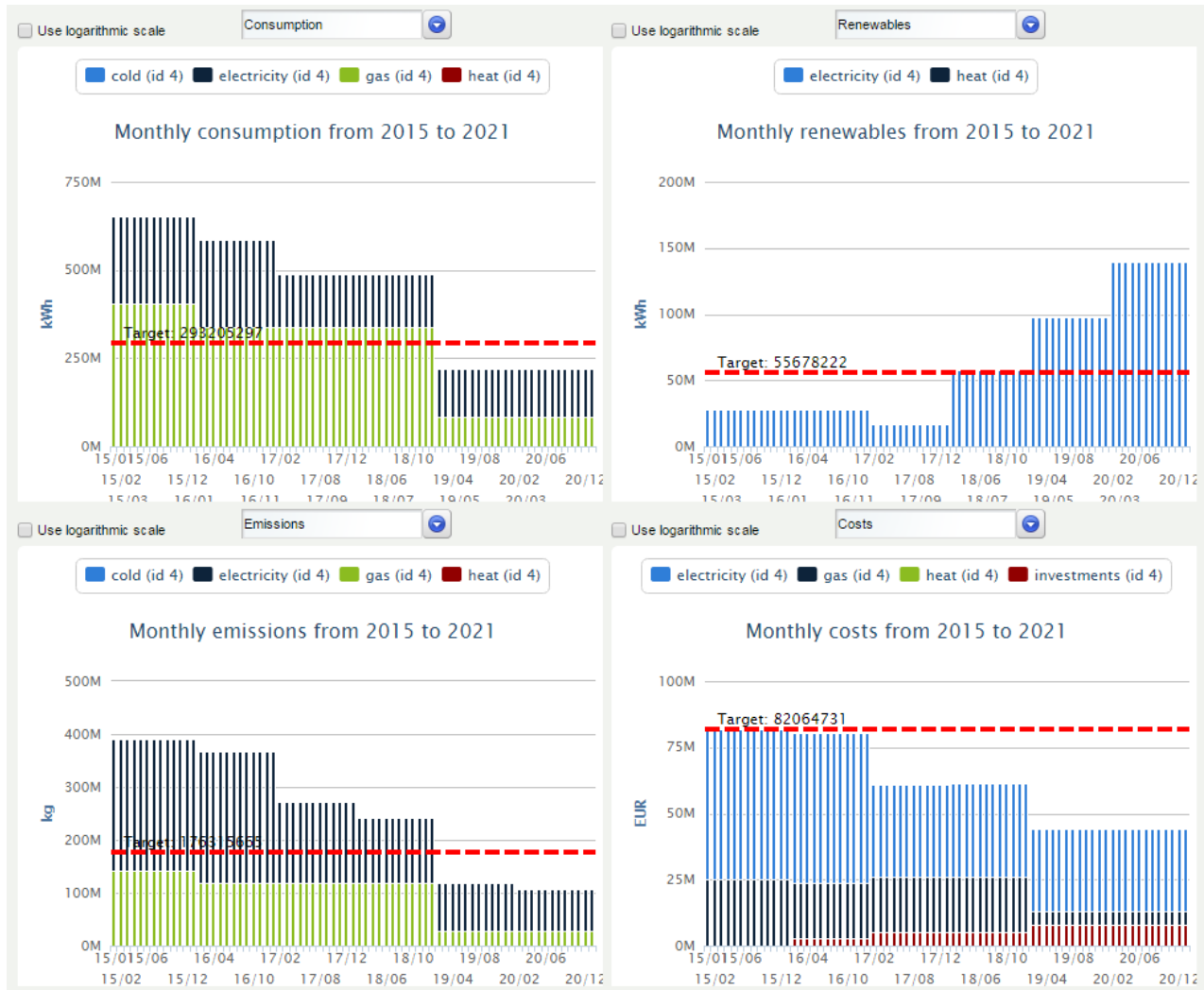


Figure 27: Impact of implementation plan B on the consumption, renewables, emissions and costs of Amsterdam Zuid Oost.

Implementation plan C: minimum uptake

Figure 28 shows that in a pessimistic, minimum uptake scenario (see table 24), targets will not be reached and energy costs will remain to be high in the future. However, according to the results, still a 36% reduction in CO₂ emissions is achievable at low rates of uptake for each measure (between 10% and 20% per measure).

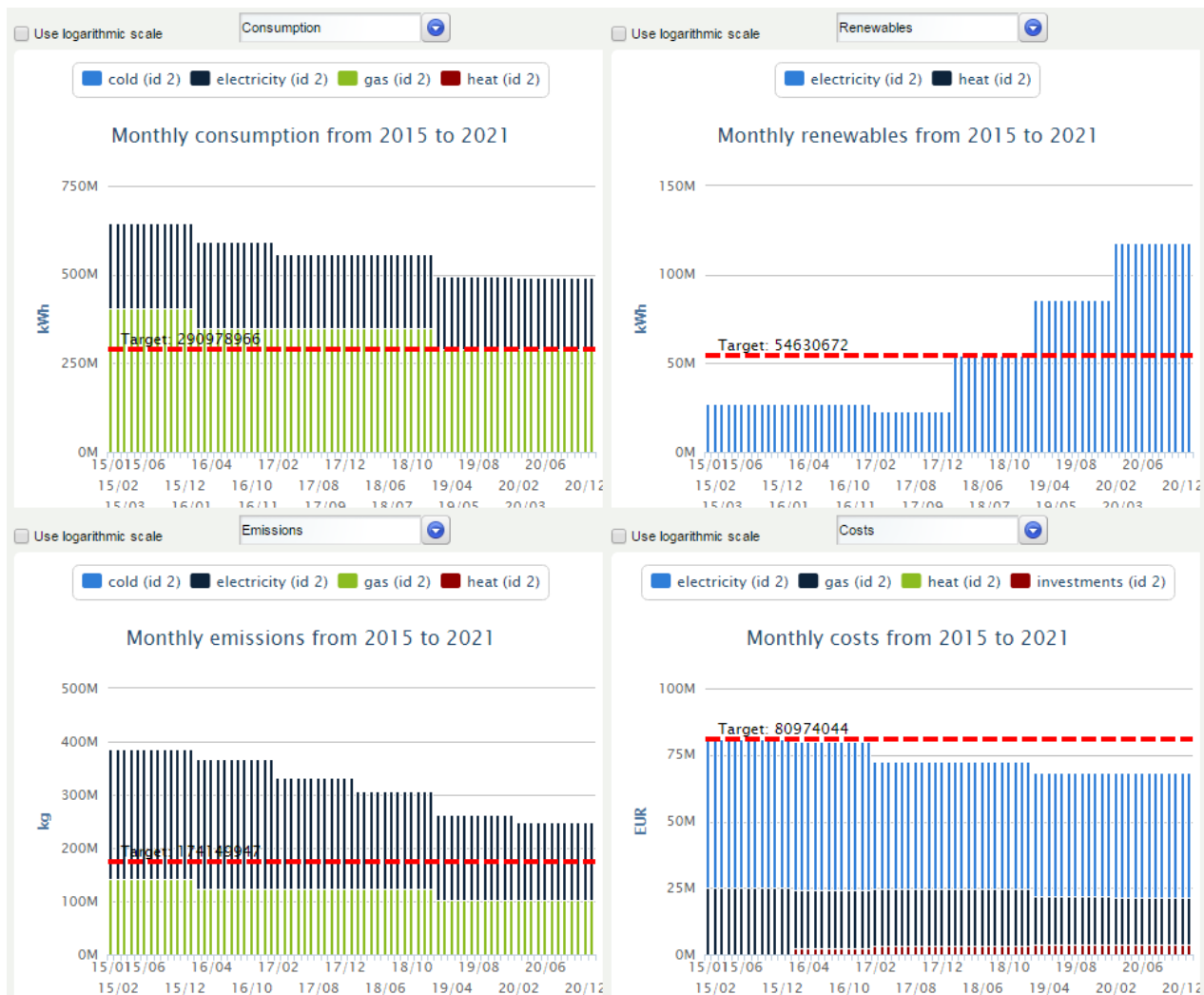


Figure 28: Impact of implementation plan C on the consumption, renewables, emissions and costs of Amsterdam Zuid Oost.

9.6 Reflection

The city stakeholders can get a number of insights from this case study results, that were not yet obtainable from the top down study. First of all, the case study provides a clearer action-to-result logic. The top down study assumed a reduction in emissions due to behaviour and insulation measures of 20% (a round estimate). The case study result shows that insulation and window replacement can reduce emissions in the area by maximum 6.2%, by taking into account actual building dimensions and insulating walls, floors, roofs and windows to the optimal level. By including LED lighting and motion sensors in larger buildings (which could be included in the definition of behaviour/insulation), a total reduction of 30.6% can be reached. This indicates that actual reductions from behaviour/insulation are very much dependent on the set of measures included in the definition of these terms. The case study, being more specific as to what the measures exactly entail, provides a clearer insight in what actions to take and to what effects these will lead. The effects are furthermore clearer in a sense that consumption and emissions are not intertwined like in the top down study (see section 9.2) and that the effects are shown in four KPIs instead of one.

Secondly, the case study provides the *useful* potential instead of the maximum potential, thereby not overestimating the impacts of measures. Where the top down study included a maximum reduction potential of 293% due to aquifer thermal storage systems, the case study has shown a maximum reduction potential of 34.2%¹⁶. Moreover, it is possible that the top down study overestimates results in general (e.g. also the solar PV potential is almost double) but this is not possible to state with certainty.

Thirdly, the case study has provided an insight into the role of building owners' willingness to transform. Two maxima of a range were given that represent a pessimistic and an optimistic scenario, with respectively low and high uptake rates of sustainability measures by building owners. Under the optimistic scenario, targets are easily reached (see figure 27), while under the pessimistic scenario, none of the targets are reached (see figure 28) but the impact is still very significant (e.g. emissions are reduced by 36%). This gives city stakeholders the useful insight that even with a low uptake rate, a diverse set of measures can still lead to serious improvements in the sustainability performance of a city's area.

¹⁶all percentages are taken relative to initial values

10 Conclusion and Discussion

10.1 Conclusions

The current study demonstrated the role of city data in gaining insights into the opportunities for sustainable development in the built environment. The goal of this research was to accurately express the impacts of sustainability measures in a generic set of performance indicators, using fine-grained city data. The hypothesis was that proper comparison between intervention alternatives, on four generic KPIs, enables city stakeholders to focus their efforts more effectively for becoming a low carbon city. With this, the study aims to be a contribution to the urban energy transition.

The study demonstrated that statistics and generally available city data can be used to give accurate estimations of building dimensions, insulation degrees of walls, roof, floor and windows, and of the division of energy consumption into eight different purposes depending on energy label. An initial dataset containing 10 data points per building can be extended into a dataset with 34 data points per building, by using the enrichment method as described in section 5.

The 34 data points that represent reported and approximated building properties can be used to determine the potential impact that sustainability measures have on the energy performance of buildings. From stakeholder interviews, 11 measures of interest were identified that city stakeholders deem important building-related measures for becoming a low carbon city. It turns out that within the larger energy-supply system, these measures have an impact on either final energy consumption or local production of electricity. On a building-level, energy efficiencies can be improved. The magnitude of impact of each measure is dependent on building-related properties such as roof area, façade area, geographical location, current U-values, and current energy consumption for certain purposes. Investment costs are converted into yearly costs of capital, which enables a direct and simple comparison between the costs and benefits (in terms of cost savings) of measures, i.e. the economic feasibility. This provides insights into the cost-effectiveness of sustainability measures on building level, based on real city data.

For actually comparing all costs and benefits, also in light of the 20-20-20 climate targets, a set of four KPIs was defined within the TRANSFORM project to assess the overall sustainability performance of a city. These KPIs are CO₂ emissions, energy efficiency, share of renewables and costs. The current status of a city relates to certain baseline values of these KPIs. While affecting the city's performance by implementing sustainability measures, changes in energy consumption and production break-down determine the evolution of these KPIs in the future. Comprehensive formulas of the KPIs were defined that relate the building-related data, in combination with city parameters, to the four KPIs.

The accuracy of the KPI calculations depends for a large part on the city parameters used. These parameters have been identified and values have been found for the six cities that are part of the TRANSFORM project. A method to deal with excess electricity production from wind and solar power was constructed from literature, to ensure validity of the KPI calculations also at high shares of wind and solar power integrated in the electricity grid.

Numeric validity of the MOI-to-KPI impact model is largely ensured by the fact that all impact calculation methods come from literature and expert stakeholders. Validity in the sense of meeting its purpose was tested in a case study with two stakeholders from the municipality of Amsterdam. In combination with the Decision Support Tool, the method developed in the current study provided stakeholders with valuable quantitative insights. It enabled evaluation of the influence of building owners' willingness to transform, on the impacts of an implementation plan. It provided clearer action-to-result logic in the impact estimations, and made sure that no non-usable potentials are included in the calculations. This has given the stakeholders more clarity in how to effectively proceed in the urban energy transition towards a low carbon city.

10.2 Limitations

Energy efficiency measures have a large uncertainty in their impact estimations. As showed in a sensitivity analysis by Firth et al. (2010), underperformance of energy efficiency measures can have a large accumulated influence on the CO₂ emissions estimations of a whole system. Failure to acknowledge this uncertainty can lead to a false sense of the reliability of energy efficiency measures. Although the current status and consumption split of buildings have been approximated by an enrichment technique using real city data, significant deviation from these approximations is still possible. Buildings are made from various materials, from solid brick walls to highly-insulated cavity walls, and can use a great variation of energy provision systems, all of which cannot be known with certainty from the city data. Next to these physical properties, the behaviour of a building's occupants determines to a large extent the patterns of energy use behaviour.

In this study, many assumptions and simplifications have been made, which can lead to large differences in the estimated impact of measures and the real impact that measures would have on a building. Examples of these imperfections are:

1. The estimated roof areas and façade areas are subject to simple assumptions, along with the orientation of buildings ($\frac{1}{2}$ or $\frac{1}{4}$ of area assumed to be oriented at 180° azimuth). Total wall areas for example also contain walls connected to neighbouring buildings, which will not be insulated. A more advanced GIS analysis should allow for detailed information about the orientation of buildings and the roof and façade area suitable for solar PV panels / insulation.
2. Shading effects are not incorporated in the solar capacity calculations.
3. Investment costs are largely dependent on region, quality of installation, specific building properties, and time. These dependencies were not incorporated in this study, as at many times a single number was used. Sophisticated price dynamics are lacking now, while they could improve the validity of the cost-effectiveness insights greatly.
4. The current heating efficiencies are estimated in a rather simple way. Discrepancies in gas boiler efficiency can for example be up to about 25%. Heating with electricity is now assumed to have 100% efficiency while an already installed heat pump would have 400% efficiency. It is not realistic to expect city data about the heating system is used in each building, but more advanced data enrichment techniques could be thought of that give more accurate estimations of this aspect.

10.3 Suggestions for future work

Having discussed the limitations of the current study, room for improvement becomes evident. However, beyond overcoming the imperfections of the current study, there are numerous other opportunities to raise the value of data analytics for the urban energy transition to a higher level.

Social aspects

First of all, more research should be done in how social aspects can block the energy transition, and more specifically how data can be gathered on the willingness of people to implement a certain measure in the building they live or work in. A possibility would for example be to extract big data from websites on which citizens can do energy scans for their homes. These websites have a database that gives good indications for the measures that citizens are looking into, and thus also more likely to be willing to implement these measures.

Network properties

Currently, the capacity and peak load of the electricity grid and district heating grid are not considered in the MOI-to-KPI model. However, these are very important to include in the calculations, especially for grid operators. The Decision Support Tool could be made of more value when network properties are included.

Stochastic scenario analysis

The integration of the current research results with the TRANSFORM decision support tool provides the functionality of testing the cost-effectiveness of measures under a number of scenarios. Insights in the development of uncertain future factors are however very limited. A user can simply define a few scenarios after which a deterministic analysis is done for each scenario, without having a clue about the likeliness that such a scenario will actually happen. A stochastic approach will incorporate a large number of scenarios while also calculating the probabilities for each scenario to happen. It provides stakeholders with more valuable insights, e.g. by outputting the probability that a certain measure will be feasible.

Optimisation algorithms

The 11 sustainability measures defined in this study can be tested in separately within the decision support tool, enabling a stakeholder to compare each of these 11 sustainability measures and picking the most effective. To come to an optimal solution that minimises costs, maximises impact, or represents an equilibrium, a stakeholder still has to do an quite extensive analysis. An optimisation process could be automated in a smarter model, that incorporates algorithms to find optimal solutions for every building in a city. In this case, a user of the decision support tool can for example set its desired future targets, and the simulation engine calculates the lowest-cost solution.

Merit order

As was stated by stakeholders from the municipality of Amsterdam, the model would be more accurate if it included the effects of locally installed renewable generation technologies (i.e. solar panels, wind turbines) on the average production mix of electricity from central sources. I.e. a lower demand from central sources would lead the utility companies to phase out the most expensive electricity plants. What is proposed for further research is a merit order calculation that takes into account the production costs of electricity from all different fuels and prioritises electricity production based on these costs. This will in turn determine the production mix of electricity, making the calculation more dynamic and realistic.

10.4 Concluding remark

The current study aimed at contributing to the urban energy transition by providing decision makers with the right instruments to focus their efforts effectively and speed up the decision making process. A clearer view on the costs and benefits of certain sustainability measures gives city stakeholders the possibility to act in an impactful way on a shorter term. As was noted by Nicholas Stern in his latest TED talk about tackling climate change: “making the right decisions can lead to quick results”. By emphasising the role of data analytics in making the right decisions, this study hopes to play a part in accelerating the transition towards clean, fossil-free cities.

11 Literature

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Appendix A: Interviews

Interviews were held with potential users of the tool from different backgrounds and different kind of organisations (municipalities, housing corporations, universities, energy companies, consultancy companies, etcetera). All interviews were done with an open character, i.e. no standard list of questions. The aim of every interview was to determine the interests and/or objectives of the actors, and the potential requirements that the actors would set to a Decision Support Tool.

29-04-2014 Geert den Boogert and Laura Hakvoort (DRO Amsterdam)

Geert and Laura indicate that a Decision Support Tool would be very useful for quantifying the impacts of sustainability development plans. First of all, the municipality focusses on development areas, and works with time frames for urban development. The Decision Support Tool should be able to simulate plans in space and time. Geert and Laura also talk about the 20-20-20 climate targets that are relevant for municipalities by sketching energy visions. They imply that the performance of a city should be measured on these climate targets, which are CO₂ emissions, energy efficiency, and share of renewables. Moreover, naturally, the municipality is interested in investment costs needed for different sustainable development plans.

21-05-2014 Bob Mantel (DRO Amsterdam)

Bob Mantel states that for making a good energy vision, a top-down approach - assuming equal conditions for the city as a whole - is not sufficient, as this omits local constraints and opportunities. He notes: “Concerning energy policy, we always treated the city as being the same everywhere, but this is simply not true. We have to zoom in and look at the specifics of areas, or even buildings in the city.”

26-05-2014 Stefan Mol (Waternet, NL)

Stefan Mol is a researcher at Waternet, and provided information on sustainability measures that could be implemented in the Decision Support Tool in order that it becomes useful for Waternet. He indicated that these would be the shower heat exchanger (MOI 6) and the aquifer thermal storage system (MOI 9). Stefan Mol provided expert information on the impact and costs of these measures on a household level. He noted that these measures have an impact on certain purposes of energy consumption only, e.g. the shower heat exchanger only on the energy consumed for showering. This requires the Decision Support Tool to know or estimate how much energy is initially consumed for each purpose.

03-06-2014 Ola Solér (Technical University of Denmark) and Kai Kanafani (City of Copenhagen)

Ola Solér and Kai Kanafani stress the usefulness of a functionality that allows to select a group of buildings where to implement measures, based on a property of those buildings. This was perceived as a request for a “filter function” while allocating measures in an area. Ola and Kai mention that their interest goes to examining the impacts of roof-mounted solar PV panels (MOI 1). The filter functionality came to light because monumental buildings cannot have any solar panels installed on their roof, therefore these monumental buildings should be filtered out during the allocation process. Ola and Kai would also be interested in how the economic feasibility of solar PV panels would change in the future, e.g. when the panels become cheaper or when electricity from the grid becomes more expensive. This could be done by setting different future scenarios for these prices.

16-06-2014 Sylvain Kock-Mathian (Hespul Lyon)

Sylvain explains what the measures of interest are for the municipality of Lyon (GrandLyon), and how these can be modelled. The measures are insulation (MOI 3), window replacement (MOI 4), LED lighting (MOI 5), and the extension of the district heating grid (MOI 7).

27-06-2014 Cardo Nerden (de Alliantie, NL)

“De Alliantie” is a housing corporation that owns a large part of the housing stock in Amsterdam. Cardo Nerden thinks the tool can be very useful for long-term projects and/or so-called “energy visions” for the housing corporation. “de Alliantie” and Cardo himself really want to steer towards the building of more sustainable houses. Cardo indicates an interest in modelling air source heat pumps (MOI 8) in the Decision Support Tool.

09-07-2014 Ivo Opstelten (Stroomversnelling, NL)

Stroomversnelling is an initiative of four construction companies and six housing corporations that aims to renovate 111,000 houses into ‘zero-on-the-meter’ houses, i.e. houses that consume no net energy. Ivo is critical about the Decision Support Tool and its use. In order to be of use for construction companies, it should be possible to filter buildings based on properties. That is to say, filter buildings with a certain function, number of inhabitants, construction year, energy consumption range, etcetera (like said earlier by Ola Solér and Kai Kanafani). As the construction companies offer renovation packages that are only suitable for certain types of buildings, the filter functionality can give them insights in what regions of a city they can best offer their services. These renovation packages of construction companies can then also be added to the tool as measures. The measures of interest for Ivo would be insulation (MOI 3), window replacement (MOI 4), solar PV panels (MOI 1), and air source heat pump (MOI 8).

18-07-2014 Sebastian Möller (AIT Vienna)

Sebastian stressed the advantage of incorporating seasonal fluctuations of energy demand and generation by renewables. In that way, the KPI calculations would be much more accurate, as it can then take into account the overproduction by renewable energy sources at times when demand is low.

23-07-2014 Geert den Boogert and Bob Mantel (DRO Amsterdam)

For the district in Amsterdam Zuid-Oost where Amsterdam wants to do some “experiments” with measures, Geert and Bob have multiple ideas. One that was not mentioned before by other interviewees is the Micro CHP generator (MOI 10).

24-07-2014 Béatrice Couturier, Flavia Barone and Sylvain Koch-Mathian (GrandLyon)

The people in Lyon are interested in secondary effects of measures. They name the example of insulation. This reduces energy consumption as a primary effect, but it also leads to more unused capacity of the existing district heating grid, which will then be available for new users. Modelling the network properties and performance was considered a possible future research objective, not included in the current study.

27-08-2014 Geert den Boogert and Laura Hakvoort (DRO Amsterdam)

Laura and Geert bring up the concept of a merit order production mix calculation: when the electricity demand from a central generation source is lowered by more installed solar panels on roofs, the production mix will change, since the production options with the cheapest marginal cost will always be chosen first. An increased capacity of solar panels in the city will thus lead to a decreased electricity generation by the most expensive source. This is identified as a topic for further research. Geert and Laura also indicate to be interested in the potential electricity that can be generated by large-scale wind turbines, installed within the urban boundaries (MOI 11).

03-09-2014 Sjoerd Klijn Velderman (BAM)

Sjoerd requested a filter function, and possibility to simulate the measures insulation (MOI 3), window replacement (MOI 4), solar PV panels (MOI 1), and air source heat pump (MOI 8). He confirms that the Decision Support Tool would be of great value for stakeholders in the decision making process, also for better alignment between competing parties with conflicting interests.

03-09-2014 Steven Kerstel (Nuon) and Jannis van Zanten (AEB)

Steven and Jannis also mention the “filter functionality” as being a key wanted feature of the Decision Support Tool. Besides, they bring up an idea for future research: the incorporation of social aspects into the tool by gathering more data on consumer preferences.

04-09-2014 Martin Bloemendal (TU Delft)

Martin is an expert on Aquifer Thermal Storage technology. He has provided data on how this technology works and what the investment costs are. This enables putting the measure (MOI 9) in the model.

17-09-2014 Jannis van Zanten (AEB) and Joris de Jong (Nuon)

Jannis and Joris provided a document with detailed information about the district heating grid (MOI 7), how it works and how much is accounted for as investment costs for additional connections. They also stress the fact that a district heating grid will never be connected to one building only, i.e. that this measure will be implemented on a district scale, what makes it necessary to make a distinction between this measure and other measures such as solar panels that can be implemented in one single building only.

21-11-2014 Gideon Goudsmit

Gideon Goudsmit is an independent sustainability consultant and a staunch advocate of façade solar PV panels (MOI 2). He provided information related to the investment costs of these panels, based on a sample project that he did on his office building in Amstelveen (see figure 15).

Appendix B: Excess electricity from wind and solar power

While conventional power plants can usually switch on and off their electricity generation activities in accordance with the electricity demand, wind mills and solar panels don't listen to consumer demand. Both renewable energy sources are non-dispatchable from production, and at the same time they are highly volatile, i.e. their power production varies strongly with time (Quintel, 2014). This brings along some complications for large scale roll-out of wind and solar power. A high share of wind and solar power in the production mix, will at times lead to a supply of electricity higher than the demand. A moment where supply surpasses demand is called an excess event. Although excess electricity is not visible on an annual average, it does occur during certain hours of the year.

Electricity production from wind energy is dependent on environmental conditions and random meteorological processes (Moura & de Almeida, 2010). Wind-generated electricity cannot be reliably forecast. The wind output varies seasonally between summer and winter, but also strongly on an hourly basis. Timely fluctuations can be very extreme during storms, having led for example to wind output differences of 12 MW within a minute and 2000 MW within 6 hours (compared to a total capacity of 2500 MW), on a stormy day in Denmark. Solar radiation deviates less strongly from its regular pattern than wind speed, which makes electricity production by solar power more predictable (Moura & de Almeida, 2010). Where wind power production reaches its peaks during winter, solar power is mostly available in summer. Solar radiation varies almost inversely relative to wind velocity, with a correlation between the two seasonal curves of about -0.7 in West Europe. This means that solar power can be used to compensate for the seasonal variations of wind power; the two electricity sources are complementary.

Heide et al. (2010) have determined the optimal mix between wind and solar power penetration in the electricity grid in Europe (see figure 29). For a 100% renewable Europe the seasonal optimal mix is 55% wind and 45% solar power generation, which additionally requires a storage capacity of about 1.4 times the monthly electricity consumption. For less than 100% renewable scenarios the optimal share of wind power increases in relation to the share of solar power.

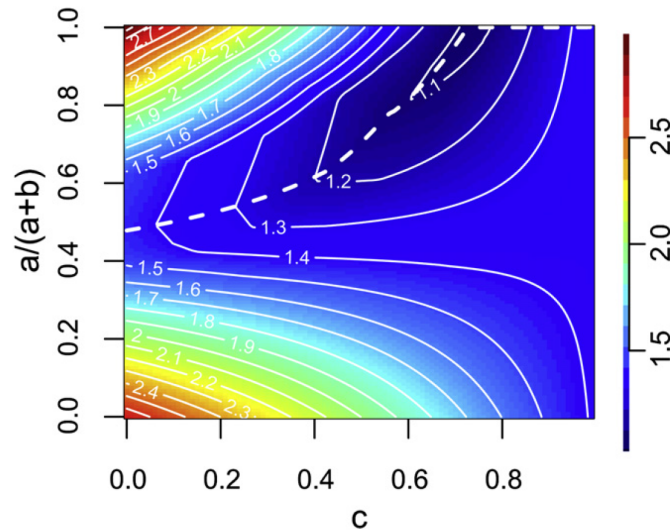


Figure 29: Maximum required electricity storage capacity (in average monthly demand) for all of Europe, as a function of coefficients a , b and c , which represent the shares of electricity from respectively wind power, solar power, and fossil fuels. The dashed curve represents the seasonal optimal mix between wind and solar power generation, as a function of the remaining conventional power generation. From Heide et al. (2010).

Denholm and Hand (2011) report a maximum share of electricity from wind and solar of 40%, without causing significant excess electricity ($\pm 1\%$). It was calculated for Denmark that up to a share of 30% wind energy, the energy system can absorb all wind-generated electricity without any wasted production (Pedersen & Eriksen, 2005). This threshold of 30% wind energy was also found by Bove, Bucher, and Ferretti (2012) for the countries Germany, Denmark, Netherlands, United Kingdom and Spain. Deuchler (2013) plotted the amount of excess electricity against the share of volatile electricity integrated in the electricity grid (see figure 30) for The Netherlands, which also leads to the conclusion that from 40% and above, significant amounts of excess electricity are produced ($>2\%$). At points of excess electricity production, wind turbines and solar panels need to be (partly) disconnected from the electricity grid, or “curtailed”.

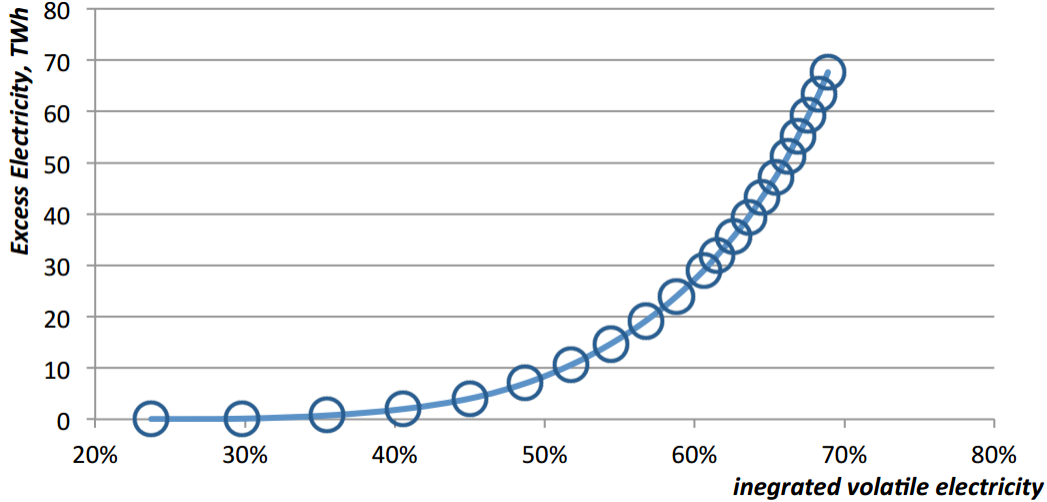


Figure 30: Excess electricity as a function of integrated volatile electricity¹⁷, based on a simulation study for The Netherlands. To put the excess electricity scale into perspective: the yearly electricity demand in the reference study was set at 116 TWh. A ratio of wind to solar capacity of 3.1 was taken. From Deuchler (2013).

The curve as shown in figure 30 is based on a ratio of wind to solar power of 3.1, and this curve would be slightly different when taking another ratio. To tackle this complexity is not the aim of the current research, so for sake of simplicity, the relation as showed in figure 30 will be assumed valid for any ratio of wind to solar power. The exponential function of the graph was approximated and used to calculate the amount of excess electricity, based on the total final electricity consumption and the share of wind and solar power in the electricity production mix¹⁸:

$$P_{elec,excess} = FC_{elec} * 0.0008 * e^{8.29 * RES_{elec, wind + solar}}$$

where

$$RES_{elec, wind + solar} = \frac{(MX_{elec, wind} + MX_{elec, solar}) * (FC_{elec} - LP_{elec, wind} - LP_{elec, solar}) + LP_{elec, wind} + LP_{elec, solar}}{FC_{elec}}$$

¹⁷where integrated volatile electricity = (production from wind and solar - excess production)/total demand for electricity

¹⁸where these shares refer to the total electricity production instead of grid-integrated electricity production, like explained in section 7.

Next to “wasting electricity” by curtailing wind and solar installations at times of a surplus, there are several options to reduce or deal with excess electricity (from Deuchler, 2013):

1. Export to neighbouring countries
2. Demand side management of domestic electricity consumers (electricity consumption is time-shifted to periods of high volatile generation)
3. Increased flexibility of combined heat and power plants
4. Electricity storage
5. Convert electricity into other useful energy carriers

Exporting is not a solid solution as neighbouring countries will possibly also have an excess of electricity at times of high volatile electricity generation. Demand side management can shift peak loads by a few percent at a low cost, e.g. an estimated 8.3% change in peak load at a cost of 0.023 €/kWh in the Portuguese context (Moura & de Almeida, 2010). The effectiveness of demand side management is nonetheless hard to predict and will not be considered within the scope of this research. Increased flexibility of CHP plants will also be omitted from the research scope, as it requires technological advancement. The two remaining options are electricity storage and electricity conversion (e.g. into gas or heat). Both are a way of storing electricity. A detailed analysis on the most economic way of storing electricity, considering also the conversion into other energy carriers, was done by Deuchler (2013), see figure 31.

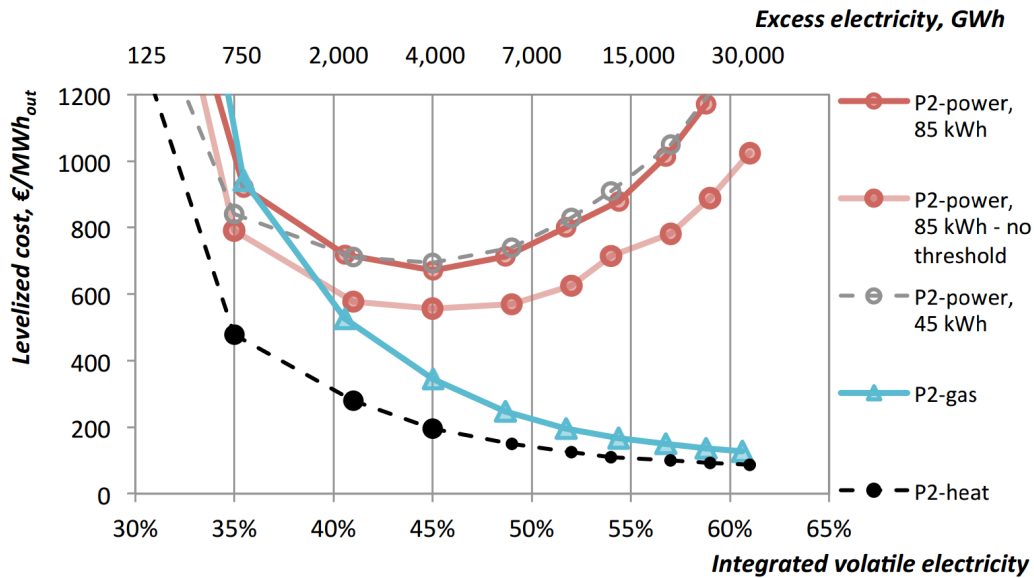


Figure 31: Levelised cost of five different electricity storage and conversion technologies, as a function of the amount of excess electricity, which is in turn a function of the share of wind and solar power integrated in the electricity mix. Numbers are valid for The Netherlands (to put the excess electricity scale into perspective: the yearly electricity demand in the reference study was set at 116,000 GWh). A curtailment reduction of 66% is used, and a ratio of wind to solar capacity of 3.1. The curve representing power-to-heat conversion is displayed with large and small markers. The small markers represent data points that actually exceed the potential for power-to-heat conversion in hot-water preparation. From Deuchler (2013).

It turns out that the cheapest option for storing electricity, according to Deuchler, is converting it into heat. This was based on a € 750 investment per household in a 100 liter electric boiler that heats up water in times of excess electricity. This option is only possible for storage of up to 4000 GWh of excess electricity. Above this, other technologies need to be used to curtail the electricity surplus. The second most economically viable option is electrolysis of water into hydrogen, which can then be blended with natural gas in the gas grid. In other words, the production of “green gas” from excess electricity. These two options are viable for electricity storage, as the levelised cost are lower than electricity costs when deployed at a reasonably large scale. Electric batteries are not yet economically viable for electricity storage. It is not the aim of the current study to go into detail about electricity storage options. These findings give merely a good indication of the additional costs of a well-balanced electricity grid, with high shares of wind- and solar power, and electricity storage facilities.