Integrating energy systems at the regional level:
A model based assessment of the Dutch energy system

ECN report for the EDGaR D1 project
Jeroen de Joode
Francesco Dalla Longa
Koen Smekens
Bert Daniels

ECN--E-16-007
March 2016

Acknowledgement

This research is part of the EDGaR D1 project: “Integrating local and regional energy systems for enhancing sustainability project”.

The authors would like to thank the partners in the project (Delft University of Technology, TNO, KIWA) for the cooperation and the feedback we received on earlier project documents and results that have led to this report. In addition, we thank the representatives of Alliander, Enexis and Stedin that have provided input to the project.

Financial support from the Energy Delta Gas Research (EDGaR) program is gratefully acknowledged. EDGaR is financed by the Northern Netherlands Provinces, the European Fund for Regional Development, the Ministry of Economic Affairs and the Province of Groningen.

Contact information

Contact person for this study at ECN is Jeroen de Joode (tel. 088 515 8250, dejoode@ecn.nl). The ECN internal project number for this project is 5.1965.
The overall project leader of this project is Daniël Scholten at Delft University of Technology (D.J.Scholten@tudelft.nl).

Abstract

An integral energy system model representing the Dutch energy system is used to explore the added value of distinguishing regional energy systems in analysing energy transition. Based on a model-based analyses we conclude that: (1) distinguishing regional energy systems in complex energy system models is not necessary when the focus is on analysing national energy transition issues, but is recommended when the focus is on analysing regional and local energy transition issues or analysing particular technologies, (2) differentiation into separate regions in an integral energy system model uncovers important differences between regions concerning the cost-optimal mix of technologies, their deployment throughout the year, and their deployment from hour to hour, and (3) further research may concern the role of energy infrastructure in energy transition and the modelling of smaller-sized regions (i.e. communities, neighbourhoods).

Contents

	Summary	**4**
1	**Introduction**	**7**
1.1	Background	7
1.2	Research goal and research question	8
1.3	Structure of the report	8
2	**Methodology**	**9**
2.1	OPERA model description	9
2.2	Hypotheses for analysis	18
2.3	Model simulations performed	19
3	**Model results**	**21**
3.1	Overall future energy system observations	21
3.2	Impact of modelling regions on national system results	23
3.3	Regional energy system results	25
4	**Conclusions and recommendations**	**34**
	References	**37**

Appendices

A.	Time slice approach adopted in OPERA	38

Summary

Contributing to successful Dutch energy transition via energy system modelling

Subject & goal
The Netherlands has set ambitious decarbonisation goals for the long term (2050). In achieving sustainability goals energy transition policy ideally makes a balance between the different public goals, which include an affordable energy system and a secure energy system. Optimisation models of the Dutch energy system can contribute to public and private policy-making by demonstrating the cost-optimal technology routes towards single or multiple energy policy goals. In order to do so, energy system models need to be fit-for-purpose. The goal set for the research described in this report was to analyse optimal energy transition path in the face of increasing energy system integration (i.e. the integration of electricity, gas and heat systems) and in particular evaluate the added value of separately modelling specific types of regional energy systems within an integral energy system model.

Adapting an optimisation model for the Dutch energy system

Research approach
As part of the research ECN's optimization model OPERA[1] has been adapted. Using a large database of over 300 energy technology options, this model optimises the cost-efficient mix of energy technologies over time (until 2050), given a large set of constraints and policy goals, while taking into account the different time profiles for energy demand and supply. The key model adaptation that was realised concerns the ability to (instantaneously) optimise the integral Dutch energy system taking into account different energy network levels (i.e. voltage and gas pressure levels) and a range of different regional energy systems (i.e. a particular clustering of energy-related activities and potentials). By adding this complexity to the existing model it enables stakeholders to learn about interdependencies between different network levels and different regional energy systems in the context of the energy transition by testing a range of different model simulations.

Results
A range of model simulations have been performed with the adapted optimization model OPERA, with some including and some excluding the feature of regional energy

[1] OPERA stands for Option Portfolio for Emissions Reduction Assessment.

systems. Analysis of the model output of these simulations provided the following results:

1. The adapted model has been successfully calibrated as simulations with the adapted model provide plausible overall energy system results that are very similar to earlier model analyses with the previous model version;
2. The differentiation into regional energy systems uncovers significant differences between the regional energy systems with respect to the optimal mix of energy technologies over time (in terms of capacity, flows and flexibility). Energy profiles and the potential to provide energy system flexibility vary across the different regional energy systems, both in magnitude and in source (i.e. type of flexibility option)
3. The differentiation into regional energy systems has effect on the deployment of specific technologies: introducing regions increases the possible mismatch between required type of energy demand and the potential available which increases the use of location-flexible technology options (e.g. hybrid or electric heat-pumps) over location specific technology options (e.g. geothermal or ground water-based heat pumps).

Conclusions

Analysing regional energy system issues while taking into account the national, integral energy system to which it is connected

1. The regional differentiation feature is successfully incorporated in the model and readily allows analysis of regional energy system issues that at the same time take into account developments, constraints, goals, potentials and the like elsewhere in the system;
2. Distinguishing regional energy systems in complex energy system models is not necessary when the focus is on analysing national energy transition issues, but is recommended when the focus is on analysing regional and local energy transition issues or analysing particular technologies;
3. Differentiation into separate regions in an integral energy system model uncovers significant differences between regions concerning the cost-optimal mix of technologies, their deployment throughout the year, and their deployment from hour to hour;
4. Further research may concern the role of energy infrastructure in energy transition and the modelling of smaller-sized regions (i.e. communities, neighbourhoods).

1 Introduction

1.1 Background

EU and Dutch climate policy have set out challenging targets for the de-carbonization of the energy system in 2050: an 80% reduction of CO_2 emissions in 2050 compared to the 1990-level. This requires profound changes in the manner in which the energy is operating. In addition, energy system developments are heavily influenced by policies in the areas of renewable energy and energy efficiency. This combination of policies gives rise to a number of important questions regarding how the energy system should be shaped in the future:

- Where to locate low or zero-carbon energy production facilities (central, de-central), and which technologies to adopt (wind, solar PV, CCS)?
- How to coordinate technology and production choices with infrastructure development? Are we going to continue using existing infrastructure to the maximum extent possible or are we going to build completely new infrastructures?
- And given that in order to reach CO_2 emission reduction and renewable energy targets a large amount of intermittent renewable energy sources will need to be implemented: how should we deal with the issue of system flexibility? Should we aim for large centralised solutions (building cross-border interconnections and overlay networks across Europe, invest in large-scale energy storage) or for small—scale decentralised solutions (increase demand response via implementation of smart grid applications)?

Ideally, we want to deal with these issues in such a way that energy transition is not unnecessarily expensive but rather as cost-efficient – from a societal perspective – as possible. An important aspect is the relation between centralized and de-centralised activities in the Dutch energy system. This project explicitly focusses on an effective and efficient energy transition on the local and regional level. The line of reasoning is that energy transition could be more effective and efficient if local energy systems, consisting of different type of energy infrastructures (electricity, gas, heat) are assessed in an integrated manner.

1.2 Research goal and research question

The goal of the overall EDGaR D1 project was to *"… contribute to the development of an efficient and effective low-carbon energy system in the Netherlands by a further integration of the energy infrastructure at the regional level, both from a technical and socio-economic perspective".*

From the perspective of EDGaR, especially the role for gas and gas infrastructure in the future Dutch energy system is of interest. In ECN's view, it is important to consider the integral energy system when analysing future developments and possible increasing integration of energy infrastructures at the local and regional level: developments in regional systems cannot be assessed in isolation of the overall energy system.

ECN's contribution to the overall project goal was to analyse different future regional energy systems from a techno-economic perspective, taking into account different scenario backgrounds for the Dutch energy system, different possible technology developments, and different choices on investment in energy production and energy infrastructure assets. In doing so, ECN in particular contributes to the following research question: *How do different technical opportunities contribute to the realization of low-carbon energy systems, both from a technical and economic perspective?*

1.3 Structure of the report

The remainder of this report is structures as follows.

- Section 2 describes the methodological framework and includes a description of the energy system model deployed;
- Section 3 presents the results from the model simulations performed with the newly adapted energy system model;
- Section 4 provides the conclusions and recommendations based on the analysis in this project.

2

Methodology

2.1 OPERA model description

2.1.1 Introduction

This part of the report gives a concise description of the OPERA-model, which has been applied for the system analysis.

OPERA (Option Portfolio for Emissions Reduction Assessment) is an integrated optimisation model, and the successor of the *'Optie Document'*. It is a bottom-up technology model that determines which configuration and operation of the energy system combined with other sources of emissions meets all requirements, whether market-driven or policy imposed, at minimal energy system costs. These requirements generally include one or multiple emission caps. In addition to energy related emissions and technologies, the model is capable to include emissions and technologies that are not energy-related as well.

OPERA is an optimisation tool that finds a mix of energy technologies that satisfies energy system restrictions (for example CO_2 emission reduction targets) at least cost for society

For the choice of technologies (technology options), it draws upon an elaborate database containing technology factsheets, as well as data on energy and resource prices, demand for energy services, emission factors of energy carriers, emission constraints and resource availability. The technology fact sheets for electrolysis, methanation and electricity storage used in the OPERA model are based on the findings of the techno-economic assessment by DNV KEMA (2013).

When used for the Dutch energy system, OPERA derives various scenario data from the Dutch Reference Outlooks and National Energy Outlooks. These provide a baseline based on extrapolation of existing and proposed policies. Among others, this baseline provides the demand for energy services (e.g. space heating, demand for transport, demand for products) that must be met. In addition, OPERA uses the baseline to compare its results with regarding additional emission reductions, additional costs and changes in energy demand and supply.

OPERA can tackle either fixed or exploratory policy targets, and the calculated effects include physical energy flows, emissions quantities as well as costs. Where in the past, the tool could only present the difference with a given background scenario, the new version does include the background scenario as well, so that also absolute remaining emission levels can be present, including the cost of the remaining technologies in the background scenario.

The baseline scenario is represented by a technology portfolio based on the complete energy balances of the Netherlands as reported in MONIT (www.monitweb.nl). These energy balances distinguish between energetic energy use (with energy in- and output of CHP separately reported), non-energetic use (feedstock in e.g. petro-chemical industry) and other conversions (e.g. cokes furnaces or refineries). Energy service levels are also derived from the baseline, whether as energy demand (electricity and/or heat) or a projected activity level expressed in physical units (e.g. iron and steel, ammonia, ethylene, passenger road transport, freight road transport).

In this study, the OPERA model simulations combine this baseline scenario and energy balance with three different target levels for GHG emissions: 110, 70, and 30 Mton in order to represent three different target years. The 30 Mton target level corresponds with a reduction of the CO_2 emission level by 85% (as compared to the 1990 level of CO_2 emissions). The 110 Mton and 70 Mton levels correspond with reductions of about 50% and 70% (again compared with the 1990 reference). These CO_2 emission reduction levels may be associated with particular target years: an 85% emission reduction target may correspond with a 2050 setting, while the other emission reduction targets reflect intermediate years.

Emissions currently covered are the greenhouse gases CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and SF_6. The model is also complemented with air pollutants such as sulphur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), particulate matter (PM10 and PM2,5) and non-methane volatile organic compounds (NMVOC). Thereby, climate targets as well as air pollutant targets and effects are taken into account.

Being a flexible and versatile tool, OPERA can incorporate any other target pollutant or substance, given that they are accompanied by factsheets that contain the required information on their effects.

2.1.2 Energy system representation

The model covers both the supply and demand side of the Dutch energy system, as well as the energy networks connecting the various parts of the energy system.

The energy supply sectors covered are:

- Electricity: covering both centralised and decentralised technology, and both fossil fuel and renewable-based.
- Gas: covering both natural gas as well as biomass-based gas, with both possibly combined with carbon capture and storage (CCS).

- Heat : covering both centralised and decentralised technology, and both fossil fuel and renewable-based.
- Hydrogen: centralised and decentralised based on fossil fuels (without and with CCS), renewables and electricity.
- Grids: differentiated levels and storage.
- Energy conversion: refineries, liquid fuels from fossil and biomass (without and with CCS).

Energy technology representation
The model database contains traditional technologies describing the actual energy system on supply and demand sides, as well as existing and future alternatives. Generally, the alternatives are favoured over traditional technologies as emission constraints get tighter. More specific limiting constraints, such as additional technology or energy limitations (e.g. limits on nuclear expansion or CCS or biomass availability) will limit the role of the directly affected technologies and technologies linked to these, while favouring the position of other technologies that fulfil the same functions. Constraints imposing minimal values (e.g. target to meet a certain amount of wind or solar energy) favour the affected technology while placing competitors at a disadvantage). There are various ways in which technologies influence each other: technologies may compete with each other, but they may also favour each other. For example, a lot of intermittent renewable energy may favour the position of storage and peak load technologies, and a lot of electricity supply is likely to favour the position of technologies that convert electricity to other energy carriers.

For all end-use demands, at least one alternative technology is available. In most cases a small portfolio of technologies that draw upon different energy sources (e.g. fossil, biomass, solar) is present, that all satisfy the same demand. In this way, the model does not contain biases towards the one or the other energy source.

Table 1 provides a list of the different elements in the modelled energy system chains.

Table 1: Broad overview of technology options included in the energy value chain as modelled by OPERA

Production / supply	Conversion	Infrastructure	mand
• Centralised electricity (and heat) plants based on: - coal - gas - biomass (without and with CCS) - nuclear - renewables: wind on shore and off shore - hydrogen FC • Decentralised electricity plants	• Fossil fuel conversion: - Refineries (without and with CCS) • Biomass conversion (without and with CCS): - Into gas - Into liquid fuels • Hydrogen production based on: - Electricity - Natural gas (without and with CCS)	Electricity network Natural gas network Hydrogen network	• Boilers based on fossil fuels (without and with CCS): - Coal - Liquids - Gas o Boilers based on biomass (without and with CCS) - Hydrogen - Industrial processes: - Iron and steel - Ammonia - Ethylene

Production / supply	Conversion	Infrastructure	mand
CHP based on: - Gas - Biomass - Hydrogen - Solar PV	- Biomass (without and with CCS)		• Electric appliances • Saving technologies: - Heat based - Electricity based - End use technologies like different vehicle types

GHG emission reduction sources

GHG emission targets are an important issue in explorations of future energy systems. Basically, there is a limited range of primary resources for GHG emission reduction: end use energy savings, CHP, nuclear energy, CCS, biomass, other renewables (e.g. wind, solar, geothermal), fuel switch and reduction options for other greenhouse gases. All categories are represented in OPERA. Individual technologies may exploit only a single source (e.g. nuclear energy) or multiple sources (e.g. biomass based CHP with CCS). Generally, the technologies that directly exploit primary resources produce energy in a form that can be directly applied (biofuels, biogas, electricity, heat, hydrogen).

However, there seldom is a perfect match between supply and demand. Therefore, secondary transformations are required to deliver energy in form that is directly applicable for the various end-use sectors (e.g. electricity to hydrogen, electricity to heat, biogas to heat, and biogas to electricity).

Generally, the small scale end-use sectors such as the built environment and the transport sector have less often direct access to primary resources, while the large scale end-use sectors and the energy supply have more direct access. As a consequence, transformation technologies such as P2G may play an import role in decarbonizing the energy system, as they convert carbon free energy harvested in the energy supply sector into a form which better meets the requirements of some end-use applications.

Table 2: Availability of energy related GHG emission reduction primary resources in sectors (direct application only)

Sector	Energy supply	Industry	Agriculture	Built environment	Transport
Savings	+	+	++	++	++
CHP	++	++	++	+	
Nuclear	+++				
CCS	+++	+++			
Biomass	+++	+++	++	+	
Other renewables	+++	+	++	++	
Fuel switch	++	+			++

+++: large, ++: medium, + small

2.1.3 Representation of infrastructure

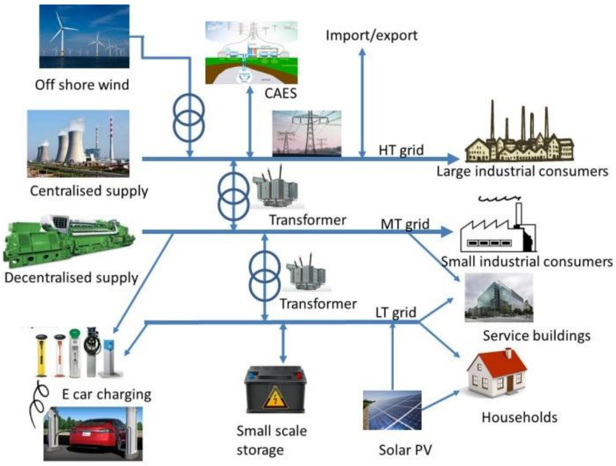
Given the diversity of levels of demand (households consume low voltage electricity, industry medium or high voltage), it is important to take into account that energy, electricity, and gas, is not directly consumed at the suppliers site. To transport energy from the suppliers to the end-users, a network capable of transmitting sufficient amount of energy at any moment is required.

A high-level representation of the different grids is included in the model (see **Figure 1** below). The electric network is differentiated in three voltage levels (high, medium, low) with on each levels the appropriate supply options as well as the demand and consumers. In order to be able to convey energy at different grid levels, electric transformers are included as well. They can ensure the flow of electricity between the voltage levels. Based on discussions with network companies, it is our understanding that it is particularly the capacity of transformers that is generally the limiting grid component. Therefore, in addition to the estimated existing capacity in transformers (based on Liander and Enexis data); several expansion transformers (different MVA/kVA) are included in the database. OPERA may choose to invest in these transformers if the required peak flows between two voltage levels exceeds the existing capacity.

In addition, a number of specific elements have been included in the electricity network representation in the model:

- On the high voltage level, there is the possibility to make use of compressed air energy storage (CAES) as well of balancing by import/export.
- Off shore wind electricity may be connected at the high voltage grid, with a dedicated off-shore grid which is connected to the land grid by special transformers. These three elements (turbine-grid- transformer) are connected but not rigidly: the model can choose each capacity independent of the other: this allows for instance that ,in order to avoid high investments in transformers to convey peak production to the land grid, the model can chose to limits this capacity investment and to perform curtailment if this would be more cost-effective. Thus is the capacity of the transformer sufficient for the baseload/bulk output of the wind turbines, but not for the peaks.
- On the low voltage grid , stationary end users may use solar PV to provide (part of) their electricity demand and in the case of excess production, deliver into the grid.
- Also on low voltage, small scale storage is possible, mainly by means of battery technologies (see DNV KEMA, 2013) for an overview of options and technologies.
- The model includes charging stations for pure electric or hybrid cars.

Figure 1: Schematic illustration of the electric supply, infrastructure and demand



For the natural gas grid, the model applies a similar but much simpler representation, as it is expected that any imbalance between demand and domestic production, both from traditional gas extraction as from biomass sources (green gas), will be covered by imports or additional production.

The gas grid has different pressure levels, similar to the electricity voltage levels: a high pressure with most production facilities feeding in as well as the hydrogen mixing-in. The medium pressure grid and a distribution network serve most end users. Between the pressure level, connectors are modelled which reduce pressure from high to low. In contrast with electricity no pressurising from a lower to a higher pressure is envisaged as this go against quality assurance of the gas on the different levels (e.g. odorisation and dilution with N_2 to maintain low caloric quality for most end users vis-a-vis high caloric gas consumption by a growing number of industrial end users). Distribution and transmission system operators generally expect the existing capacity of the gas grid to be sufficiently large for meeting current and future demand for gas, as the projected gas demand in the built environment is expected to show a stagnant or declining trend (related to the adoption of energy efficiency measures).Therefore, increases do not require expansion technologies, but do result in increased energy consumption for pressurizing the transported amount of gas.

2.1.4 Representation of time units and relevant demand and supply profiles

OPERA explicitly deals with needs to achieve a match between supply and demand at any moment. In order to do so within computability limitations, the OPERA model applies a time slice approach, in which the 8760 hours of the years are attributed to separate time slices. OPERA adopts an innovative approach in utilizing all relevant patterns in energy demand and supply covering the 8760 hours of the year, while not explicitly modelling each of these hours separately.

The basic approach is to smartly group together those hours of the year that have very similar characteristics with respect to the demand and supply of energy and the time sequence. Energy supply and demand exhibits particular patterns over the hours of the day, over the week, across seasons etc. Based on historical hourly data on all relevant supply and demand patterns (i.e. wind and solar profiles, heat and electricity demand profiles), time slice algorithms smartly combine those hours of the year that are (most) similar, and take account of the sequence of a particular hour relative to the daily peak in demand. In this way, model simulations can capture the different energy system balances throughout the year, while not putting to heavy requirements upon computing power capacity. The approach is flexible as the desired amount of time slices (and associated computing time per scenario run) can be varied in the OPERA interface. In live interactive sessions a lower number of time slices is used than in model simulations performed for reporting purposes. For a more elaborate explanation of the time slice approach we refer to Appendix A.

2.1.5 Representation of archetypical regions

For the first implementation of different regional energy systems within the OPERA model we have chosen to model three archetypical regional energy systems based on the rough characteristics of a *rural*, *urban* and *industrial* area, where all regions in principle cover energy production, conversion, transport and consumption technologies that are connected to the energy system on (at least) the *distribution* level. These three typical regional energy systems have been characterised using a number of variables:

- The technology options that are typically present, or could become present in the future.
- The mix of energy consumers represented (including their energy demand profile).
  - Households
  - Services
- Transport (electricity).
- The size of the region (i.e. energy demand in absolute terms).
- The density / concentration of energy demand (technologies) (which relates to population density).
- The density / concentration of energy supply (technologies).

The archetypical **rural** regional energy system is characterised by a relatively low population density and relatively long energy infrastructure connections. Furthermore, there is a relatively large potential for (onshore) wind, solar PV and biomass production. Moreover, there is less or no scope for heat networks, implying that heating demand is primarily based on decentralised technologies. The actual size of a rural energy system modelled assessed in this study will be defined once first test results give an indication of the 'relevant size'. If it turns out that the size matters a lot for results, we may want to report on two different region sizes, implying a sensitivity run / analysis for a larger or smaller region size.

The archetypical **urban** regional energy system is characterised by a relatively high population density, and relative short infrastructure linkages. Heating demand may be fully or partly based on central heating networks. The potential for solar PV and wind is only limited. Regarding size of the system, the same holds as for rural region.

The archetypical **industrial** regional energy system is characterised by energy consumers in predominantly the industry and services sector and has connections with both the distribution and transmission levels. There is only limited space for renewable electricity based technologies.

Table 3 and **Table 4** present the data used in allocating energy demand per sector and location-specific energy technologies across different regions. Apart from the archetypical rural, urban and industrial region this includes a region for offshore activities (i.e. primarily offshore wind).

Table 3: Assumptions regarding the allocation of energy demand across regions

Sector	National system[2]	Urban	Rural	Industrial
Households		80%	20%	
Built environment (excl. households)		80%	20%	
Industry (excl. metal and chemical)		20%	10%	70%
Chemical industry				100%
Metal industry				100%
Electricity supply (large-scale)	80%			20%
Gas supply system	100%			
Agriculture			100%	
Transport		60%	20%	20%

[2] Excluding the energy demand in the rural, urban and industrial regions.

Table 4: Allocation of application potential of number of technology options

Technology options	Urban	Rural	Industrial	Offshore	Remarks
Wind onshore		95%	5%		Different availability of suitable space
Wind offshore				100%	
Solar PV (households)	70%	30%			Different types of 'average' housing type, with relatively more rooftop space per household.
Geothermal heat (utility buildings)	70%	20%	10%		Potential per type of building
Geothermal heat(agriculture)		100%			
Geothermal heat (households)	95%	5%			Collective systems are predominantly present in high population density areas
Heat pump – ground-based (households)	60%	40%			Rural areas have on average more ground space per house (more low built buildings)
Heat pump – ground-based (utility buildings)	40%	40%	20%		Rural areas have on average more ground space per house (more low built buildings)
Heat pump – groundwater (utility buildings)	70%	20%	10%		Rural areas have on average more ground space per house (more low built buildings)
Heat pump – groundwater (households)	50%	50%			
Solar boiler	70%	30%			Different types of 'average' housing type, with relatively more rooftop space per household.
Solar PV (large scale)	10%	80%	10%		Different availability of suitable space
Solar PV (utility buildings)	70%	20%	10%		Rural areas have on average more ground space per house (more low built buildings)

2.2 Hypotheses for analysis

The model setup with a distinction between regional energy systems and the national energy system allows for the testing of a number of possible hypotheses. These are described below. These hypotheses give direction for the discussion of model results in Section 3 and at the same time illustrate the possible applications of an energy system model that is capable of differentiating different regional energy systems.

a. There are (significant) differences in the optimal technology mix between (a) different regions, and between (b) regions and the centralized energy system
The inclusion of separate regions leads to a different mix of technology options being deployed in the centralized system and the regional energy systems. Differences may concern the type of options deployed, or the options (share) deployed, where differences may be significant or rather insignificant.

b. There is a particular single technology option (or a set of similar technology options) that is linked to the introduction of (a) regional energy systems in general, or of (b) a particular type of regional energy system (i.e. residential, urban, industrial)
A centralized model that is not capable of distinguishing regional energy systems may contain biases in its optimal choice of technologies. The emergence of a particular technology option (or a set of similar options) may crucially depend on the model specification of regions. This may concern technologies that have a particularly strong performance in terms of cost / efficiency in local settings and are ‘overlooked’ when all energy activities are assumed to take place within one single node in a centralized energy system model. Within the model results we may find that a technology is a robust part of *all* regional energy systems, irrespective of for example type of energy activities, load characteristics etc., or is part of one regional energy system in particular.

c. The impact of a particular technology X or Y has (no) significant impact on the optimal, overall energy system configuration
This hypothesis is similar in nature as the previous hypothesis but here the focus is on a limited set of ‘new’ technologies that KIWA – research partner in the project – is testing and / or developing for distribution system operators (DSOs). The question of interest for DSOs is: does technology X or Y make a difference within the larger energy system? The particular technologies in question have been discussed and added to the extensive technology database of the OPERA model.

d. Adding ‘regions’ to a centralized energy system model raises overall system cost
Although in reality energy systems comprise both assets and infrastructure at the national level (i.e. high voltage networks, high pressure gas pipelines) as well as the local and regional level (i.e. low voltage networks, low pressure gas pipelines, district heating systems), energy systems models – including the previous versions of OPERA - generally refrain from modelling energy activities at lower levels and assume all activities to take place within one ‘node’ at the national level. Compared to model runs with a single node on a national level, model runs with the newly developed OPERA version with distinct regions is expected to lead to higher overall system cost. The latter

is a more realistic setting but compared to the previous but adding additional restrictions to the system will make it more costly for the model to meet all set targets (i.e. meeting the energy balance given a.o. infrastructure and policy-based restrictions). Model observations regarding this hypothesis provide new insight into the added value of explicitly modelling regional energy systems within a larger, centralized energy system.

2.3 Model simulations performed

In exploring the impact of differentiating archetypical regions in the integrated energy system model OPERA from the perspective of the various hypotheses the following model simulations have been performed (see **Table 5**). The variety in model simulations depend on two dimensions: (1) whether or not the new model feature of regional energy systems was used in the simulation, and (2) whether or not additional renewable energy targets and priority access for renewable energy were included as model constraints. The reference scenario represents a hypothetical policy setting in which there are only targets for reducing CO_2 emissions and no separate targets for renewable energy technologies. In this setting, a cost optimal mix of primary energy sources and technologies for different level of CO_2 emission reduction levels is derived. Therein, each technology and primary energy source achieves its cost-optimal share. For the reference scenario data input we link to the reference scenario as used in the recent model-based analysis of the role for power-to-gas in the future Dutch energy system. Details on scenario input can be found in De Joode et al. (2014). **Table 6** presents the assumptions regarding fuel prices.

Table 5: Overview of scenario input for model simulations

	Scenarios			
Parameter	Reference	Reference + regions	Target & priority access renewables	Target & priority access + regions
Regions	No	Yes	No	Yes
Max. CCS capacity (Mton / yr)	50			
Max. biomass potential (PJ)	500			
Min. wind capacity (GW_e)	-		36.5	
Priority access wind & solar	No		Yes	
Min. solar capacity (GW_e)	-		45	
Max. nuclear capacity (PJ / yr)	5,000			

Table 6 provides the assumed fuel prices for 2050 for a range of energy carriers.

Table 6: Overview of fuel price assumptions for 2050 used in the model analysis

Energy carrier	Reference value [€/GJ]
Natural gas	7.9
Coal	2.7
Oil	15.2
Uranium	0.7
Waste	-9.0
Biofuels	20.9
Biomass	6.4

The next Section presents and discusses the observations from the model analyses.

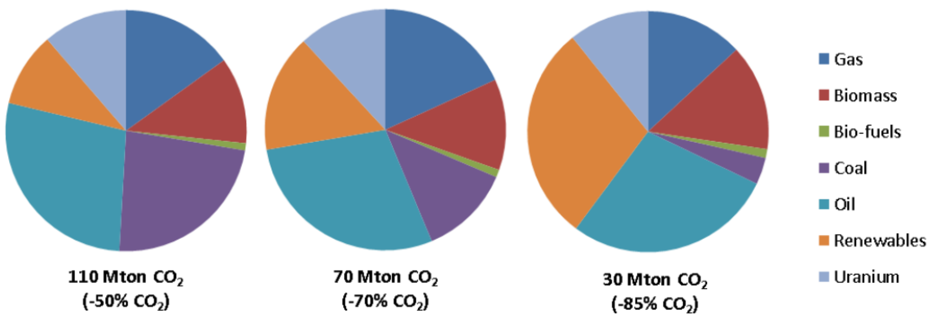
3

Model results

3.1 Overall future energy system observations

Model simulations have been performed for three CO_2 emission levels (110, 70, 30 Mton), for three different scenario contexts, in the case with and without explicit modelling of archetypical regional energy systems. Below we first briefly describe the overall observations regarding the cost optimal future mix of energy sources. **Figure 2** presents the optimal mix for the reference scenario excluding regions.

Figure 2: Mix of primary energy sources at different levels of CO_2 emissions in the reference scenario (excluding archetypical regions) [3]



From the above figure it is clear that the role of non-biomass renewables increases with increasingly stringent CO_2 emission reduction targets. A push for lower CO_2 emissions increases the share of renewable energy, while reducing the share for fossil fuels. Another observation is that oil continues to deliver a significant share in the primary energy mix. This is the result of the fact that a large share of the oil is used for the production of plastics. The carbon is stored in the plastic and process emissions from the productions of plastics.

[3] Note that the figures represent the net consumption of energy carriers. Since the net trade balance for electricity, heat, hydrogen, waste and biogas shows a net contribution of zero, they are not represented in the figure.

Reduction in gas demand in the regions

The decarbonisation targets have large consequences for the use of natural gas in the energy system. Gas demand in most regions reduces when moving from 110 to 30 Mton of yearly CO_2 emissions, with the largest reduction taking place during the phase of the 110 to 70 Mton CO_2 emission level. Gas demand in urban regions decreases from 146 to 26 PJ (-82%), and in rural regions from 42 to 14 PJ (-66%). Only industrial regions show significantly smaller reductions due to the role of gas in industrial processes.

Increasing use of hybrid and electrical heat pumps

Electrification of heat demand takes place across all regions with a particular large role for electric and hybrid heat pumps. This comes at the expense of the currently dominating reference high performing central heating boilers. This can be explained by the fact that given the different ways to make energy carbon free, renewable electricity is relatively abundantly available at relative little cost. For example, an alternative route for the de-carbonisation of gas demand in the residential sector – gasification of biomass – would require relatively large amounts of biomass that are not available domestically, and may only be available on the international market at relatively high cost. Hybrid pumps have an advantage over all electric heat pumps as these do not require a dimensioning of the electricity network at peak heating demand and thus save cost of electricity network expansion.

Observations on the role of CHP

CHP-based options, including micro-CHP, running on gas are generally not part of an optimal energy mix in 2050, unless combined with either the use of biomass or CCS (or both), main reason being that CHP options are not reducing CO_2 emissions as compared to renewables-based electricity generation technologies. Deployment of gas-based CHP options in 2050 would give rise to higher system costs as the CO_2 emitted would need to be additionally compensated elsewhere in the system. A further penetration of CHP technology options would generally oppose the expected trend of (renewable-based) electrification. However, there may be a role for CHP (either combined with CCS or biomass) in the transition period when CO_2 emission levels are not that constraining as yet. Robust conclusions with regard to the role for hydrogen-based (micro) CHP cannot be drawn from the current analyses, but it seems to be a relatively expensive option in the wider range of technology options. Its possible role is likely to be related to the developments in the transport sector where a possible roll-out of hydrogen infrastructure could benefit the use of other hydrogen-based options in other sectors. This could be a route for further research surrounding the question 'how could parallel developments in different end consumer sectors affect the optimal technology mix each other. For example, standalone developments in the transport sector such as the facilitation of hydrogen-based transport, could change the relative costs of hydrogen-based options in industry or the built environment, and thereby affect the optimal technology mix when striving for deep decarbonisation over time.

3.2 Impact of modelling regions on national system results

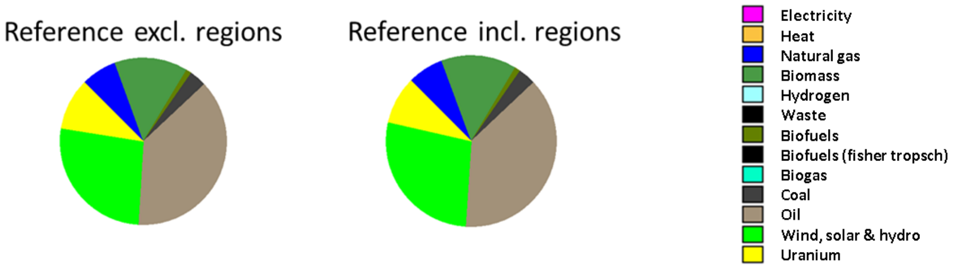
Differentiation in regions hardly affects the overall energy system mix

From a methodological perspective an important question is whether the differentiation into different archetypical regions affects the results for the overall energy system: does the additional differentiation into regions alter the optimal mix of energy technology options and associated overall system costs? Changes in the latter also imply changes in the shadow price for CO_2[4] emissions by the system. **Table 7** presents the system costs and CO_2 shadow price results for the two scenarios: a reference scenario excluding and including a differentiation into archetypical regions. **Figure 3** presents the overall energy mix of net consumption in the overall energy system at the level of 30 Mton CO_2.

Table 7: Model results for overall system costs and CO_2 shadow prices

Scenario	Unit	Reference			Including regions		
CO_2 level	Mton	110	70	30	110	70	30
CO_2 shadow price	€/ton	41	105	578	47	108	632
Total system costs	Mln€/yr	55,574	58,454	66,608	57,202	60,224	68,200

Figure 3: Net consumption in reference scenario excluding and including archetypical regions[5]



Relatively small increase in system costs and CO_2 shadow price due to increase in geographical mismatch

The above table indicates a small increase in both system costs (2-3%) and the associated CO_2 shadow price at which CO_2 emission targets are achieved (2-16%). These may be explained by the fact that the additional regional differentiation imposes additional constraints to the system when compared to the reference scenario. At best, we could have anticipated an overall system cost exactly equalling the overall system cost in the case without regions. Apparently, the specific allocation of energy demand and supply potentials and technologies gives rise to a geographical mismatch to some

[4] The CO_2 shadow price indicates the cost of the last unit of CO_2 abated in order to meet a CO_2 emission reduction target. The CO_2 shadow price is a model output and is dependent on the imposed CO_2 constraints on the one hand, and the assumptions regarding all CO_2 reduction options offered to the model via the technology fact sheets on the other. The CO_2 shadow price should not be confused with the CO_2 price in the EU ETS. The CO_2 shadow price depends on the emission level of the integral energy system at large, whereas the ETS only covers part of this energy system.

[5] Net production is not visible in the pie-charts. Based on 20 time slices model runs, at 30 Mton CO_2.

degree. Whereas the reference scenario excluding regions was 'free' to choose the cost-optimal mix of technologies, the scenario including regions changes cost considerations for some options, leading to a slightly different energy mix. Due to the additional constrains and resulting mismatches, somewhat more expensive technologies now enter the mix of options. However, the pie charts on the overall energy mix in **Figure 3** indicate that shifts in the energy mix are very small and can't be observed in this format. Underlying differences will be referred to in subsections below.

The reference scenario doesn't contain archetypical regions but does include different network levels for the gas and electricity system
A reason for the relatively limited changes in system cost when differentiating between regions is the fact that the reference scenario already reflected different network levels for both the gas and electricity system. For both gas and electricity there is one infrastructure network at the national level, and two network levels for regional levels. The explicit modelling of the lower level networks ensures that model simulations take into account that particular energy demand and energy supply technologies are more or less suitable for implementation at different network levels. The addition of archetypical regions uses the same hierarchal structure but adds specific constraints that reflect a combination of demand and supply technologies for archetypical regions. The impact of adding archetypical regions to the model would have been significantly larger if the reference scenario did not contain the differentiation in network levels[6]. In other words: the network structure of the energy system is crucial in determining the overall system cost of energy transition.

Differentiation into regions has limited implications for impact of separate RES targets and priority access
The differentiation into archetypical regions in a different scenario context involving separate targets for intermittent renewables and including / excluding priority access for the electricity generated from intermittent renewables does not lead to fundamentally different observations than reported previously (Section 3.1 and 3.2 thus far). Put differently: the impact of these contextual factors on the optimal mix of energy technologies is not fundamentally different when including or excluding regions. Separate intermittent renewables' targets and priority access increase the potential regional mismatch in electricity demand and supply, and thereby increase the total system cost and the energy system configuration to limited degree.

The results of implementing additional renewables and priority access (see **Table 5**) were earlier reported in de Joode et al. (2014) and are confirmed in this study:

- The combination of targets and priority access leads to a significantly higher amount of wind or solar-based electricity in the system, partly because curtailment is no longer allowed.
- The increased amount of renewable electricity encourages a stronger electrification of the energy system, at the expense of the competing low carbon options of CCS and biomass.
- The increase in the availability of renewable electricity leads to an increased use of this source in transport via the electrolysis route (i.e. hydrogen).

[6] In fact this describes the situation as modelled by the predecessor of OPERA that was known as the 'option document' model. The previous model simulated the integral Dutch energy system as if all energy related activities took place in 'one node'. The expansion of the model with different network levels took place within the TKI gas financed P2G project (de Joode et al., 2014).

- As the additional electrification is most difficult to realise in the industrial sector, this particular sector attracts relatively more renewable gas, at the expense of the penetration of renewable gas in for example the built environment.
- The combination of targets and priority access for intermittent renewable electricity give rise to a stronger need for system flexibility, which translates in a larger role for options such as electricity storage, electrolysis (i.e. production of hydrogen), and exchange with neighbouring electricity systems.

Implications for previous modelling analyses

The limited impact of modelling explicit archetypical regions for overall energy system analyses imply that the conclusions drawn in recent studies using the OPERA model are still valid. Daniëls *et al.* (2014) and de Joode *et al.* (2014) used the OPERA model to respectively study (1) the implications of possible EU 2030 targets for the Dutch energy system and (2) the role for P2G in the future Dutch energy system. The adding of archetypical regional energy systems to these previous analyses would have slightly changed the quantitative results, but not the qualitative conclusions that were drawn from them.

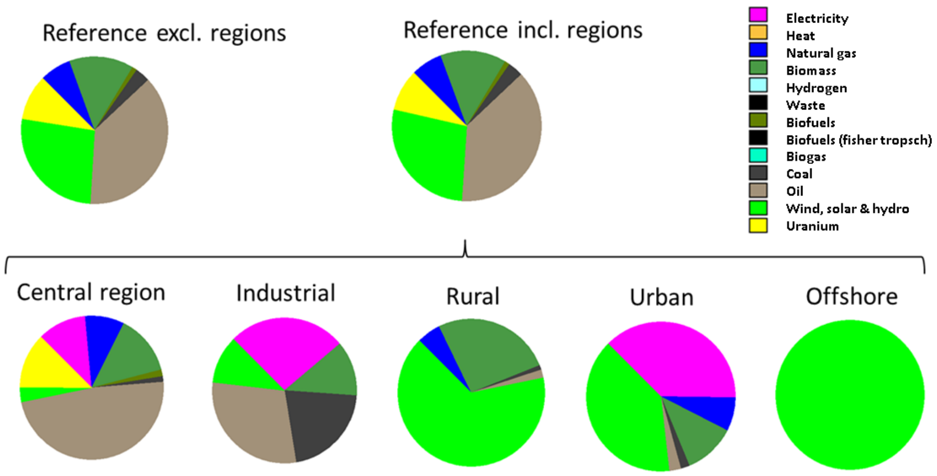
3.3 Regional energy system results

Differentiation between regions uncovers important differences in the regional energy system

Although the conclusion on the basis of overall energy system results must be that the modelling of archetypical regions does not significantly alter overall energy systems results, it does matter for results on the level of regional energy systems. As illustrated in **Figure 4** the average energy mix for net consumption for the integral Dutch system is the result of a significantly different mix of options in the respective archetypical regions.

Analogue to the above conclusion regarding energy system analyses, similar conclusions may be drawn for energy policy. In ***national*** policy in the field of energy and climate there does not seem to be a need for taking into account particular regional energy system specifics ***if*** network structure is properly accounted for. This means that it must be acknowledged that (1) there is a very distinct network structure (with different network levels) and (2) there are individual technology options that may not or may not be suitable for implementation at specific network levels and that have distinct impacts on network level operations and long-term capacity requirements. In contract to national energy and climate policy, ***regional*** policies do need to take into account regional energy system specifics.

Figure 4: Net consumption in reference scenario excluding and including archetypical regions[7][8]



Note that electricity is referred to as an energy source for consumption in industrial and urban regions (besides the central region, which represents the system activities connected to the national energy infrastructure). This is the case because these two regions are importing energy, in the form of electricity, from the other regions (rural, offshore). The overall Dutch energy mix does not mention electricity as energy source as the Netherlands as a whole is – for the sake of analysis – assumed to be neither a net importer nor net exporter of electricity throughout a year.

Results indicate that *rural energy systems* are pre-dominantly (about two thirds) reliant on renewable electricity-based sources such as wind, solar and geothermal energy, and use an additional one quarter from biomass resources. The remainder of energy consumption is gas or heat based.

Energy consumption in *industrial energy systems* is based on a more diversified set of resources. Firstly because of the fact that consumption for feedstock purposes maintains is largely fossil-based (oil and coal) and secondly because these type of regions typically have relatively less potential for renewable electricity-based technologies. An important share of CO_2-free energy in this type of regions is imported electricity (about one quarter).

Energy consumed in typical *urban* regions is predominantly acquired from either imported electricity or from locally produced renewable electricity, of which PV is the largest source. Furthermore, heat regional heat demand is increasingly provided by heat networks and geothermal heat boilers.

The observations listed above demonstrate the necessity to differentiate into regions and network levels when addressing energy transition issues with a significant local energy system component. Refraining from doing so would give rise to results for an average energy system only that does not do justice towards the inherent differences

[7] This figure is based on model runs for an emission level of 30 Mton CO_2 distinguishing 20 time slices.

[8] Note that although the pie charts for the different regions presented are equal in size they represent different energy volumes.

between regions. Although only three archetypical regions were selected to together cover energy system activities across regions in the Netherlands, it is not difficult to hypothesize that other 'groupings' of energy demand and supply technologies in 'mixed' regions would lead to other mismatches and potentials in respective regions and to other results on the regional level. For very specific regional and / or local issues to be addressed, the current model set-up may be used for an explicit modelling of the region of interest.

3.3.1 Impact of modelling regions on technology choices

The previous section demonstrated large differences in the energy mix of archetypical regional systems but did not go into detail about specific technologies used. Each model simulation produces a detailed account of the energy technologies that are used in the case of minimisation of system costs under the set of model constraints. The role of individual technologies is indicated by the capacity installed and the energy produced. Comparison of the results from the reference scenario with and without archetypical gives two particular insights:

- An increasing 'mismatch' within a region between regional energy demand and regional energy supply potential increases the costs of particularly decentralized technologies.
- The role of some individual technologies is particularly sensitive for small incremental changes in the scenario-assumptions.

A more detailed description and explanation of the two observations is provided below.

Increasing 'mismatch' in regional energy demand and potential supply increases costs of decentralized technologies

There are multiple technology options to fulfil energy demand at regional or local networks but some of them are location-specific. Geothermal-based technology options are an example in case. The potential of such location-specific options is used to the maximum extent if considered part of a cost-optimal mix of technologies from a societal point of view. In the scenario including archetypical regions we see that these type of location-specific technology options are implemented to a lesser extent than in the reference scenario without regions. In the latter scenario, part of the location-specific options is substituted for generic options: options that have no particular location specific feature, such as heat pumps. Apparently, distinguishing archetypical regions influences the relative cost of deployment of location technology options in such a way that from a society's perspective they are no longer part of the cost-efficient mix of options. This may be explained by the fact that explicitly modelling regions – in other words, decreasing the model's degrees of freedom in finding cost-optimal solutions – leads to an increasing mismatch between demand and (potential) supply technologies particular regional energy systems. Although mismatch problems at a regional level can be solved by expanding network capacity, the cost of such expansion is in some cases apparently high enough to justify a partial substitution of location specific technology options to technology options that have no location specific features.

Some technologies are particularly sensitive for contextual changes

Looking at the large range of options included in the model's database it becomes clear that certain technology options are in fact very similar in terms of costs, efficiency, performance etc. Although the context of the model run can further influence these properties (think about specific policy targets, network constraints, environmental

constraints and the like) model results make clear that there are some 'thresholds' present in the model that can either push the one or the other type of technology into the optimal mix. Examples of this are the numerous boilers and CHP-based technology options in the model. Small cost differences for those options between those can lead to significant changes in the role for a very specific technology option.
This implies that one needs to be careful when it comes to evaluating the role of one particular technology option in the optimal mix and should rather focus on a somewhat aggregated category of similar technology options. However, if the focus of analysis is on a particular type of technology then it would be worthwhile to further uncover the particular mechanisms and the contextual dependencies underlying the choice of type A over type B within the same category of technology.

3.3.2 Role of regional energy systems in energy system flexibility

Whereas the previous section reported and discussed results on the level of aggregated results based on a whole year, this section expands on the underlying dynamics with regard to the integration of intermittent renewable electricity technologies and the type of technology options deployed in accommodating these. I.e. what does the system adaptations over time mean for the demand and supply of flexibility? Flexibility in this study refers to the mismatch in supply and demand in the energy system and the change in this difference from one moment in time to the next (ranging from hour-to-hour to 'season-to-season'). In assessing system flexibility the focus is on the model results for the electricity system, as the main drivers for additional future demand for flexibility are the increasing amount of intermittent renewable electricity technologies (wind, PV) and the electrification of final energy demand.

Mix of options provide electricity system flexibility

Figure 5 presents the electricity balance for a cost-optimal energy system that meets the target of 30 Mton CO_2 emissions. This figure graphically illustrates the contribution of different options in providing a sufficient level of flexibility. These options are the following (in random order).

Temporary curtailment: Temporary curtailment of variable sustainable electricity generation sources is an important flexibility option.[9] Curtailing electricity temporarily is not a free option but leads to a 'social cost' that is implicitly taken into account in the model. The amount of curtailments in the case of realising a target level of 30 Mton CO_2 emissions is about 9 TWh per year, or about 6.5% of total electricity generation of intermittent renewables. The deployment of this option implies that even for situations with high CO_2 reduction targets – and thus a high value for CO_2-free energy – temporary curtailment is sometimes cheaper than the deployment of any of the other flexibility options mentioned below. From the modelling results for lower CO_2 emission targets we learn that as targets become more stringent, also the social cost of 'throwing away' carbon free electricity is becoming increasingly high, leading to lower levels of curtailment.

[9] Note that the flexibility option of curtailment is not illustrated in Figure 5 as the figure is based on realised electricity demand and supply (i.e. after curtailment) rather than forecasted electricity demand and supply.

Cross border electricity exchange: Exchanging electricity surpluses or balancing deficits with other countries. Note that we in our analysis we have assumed a net cross border electricity exchange over a whole year of zero. Import and export of electricity is allowed from hour to hour, but over the whole year the net exchange is assumed be zero.[10] In the particular case of 30 Mton CO_2 emissions the yearly cross border exchange of electricity is about 2 TWh.

Demand side response: More flexible utilization of part of existing electricity demand (demand side response). This for example includes the time switching of particular parts of final demand so that overall peaks in demand can be reduced.

Flexible electrification of energy demand: Substitution of energy demand - in the form of for example gas – in combination with options that make overall energy demand more flexible. An example is the electrification of heat demand, with added storage options. This flexibility option is similar to the previous but now concerns *additional, new* electricity demand.

Dispatchable conventional generation: Use of dispatchable gas-based electricity generation units (using natural gas or biogas, possibly combined with CCS). To the degree that coal or even nuclear units can also be designed to operate in a more flexible manner, these should be considered in this category as well. **Figure 5** indicates that both conventional gas and nuclear generation units provide system flexibility: gas-fired units run between about 700 to 1700 hours per year while nuclear units run about 5500 to 7000 hours per year.

Temporary storage of electricity: Implementation of some type of electricity storage (such as Compressed Air Energy Storage (CAES) and batteries in electric vehicles). The storage option may concern large-scale or small-scale options at central or de-central locations in the system. **Figure 5** indicates significant charging into storage systems during time slices with high levels of electricity generation from intermittent renewables, whereas the discharge is spread out over a larger number of time slices with relatively smaller contributions of intermittent sources. Across the whole year, a total of about 12 TWh is put into storage.

Power-to-X: The conversion of electricity to another energy carrier (e.g. gaseous energy carrier such as hydrogen or synthetic methane, or heat), or to products / chemicals. From a system perspective this may also referred to as new, additional energy demand with particular flexibility properties or potential. **Figure 5** separately highlights the role for power to gas in providing system flexibility in this particular scenario (about 7 TWh per year). The other conversion options are categorised under electrification.

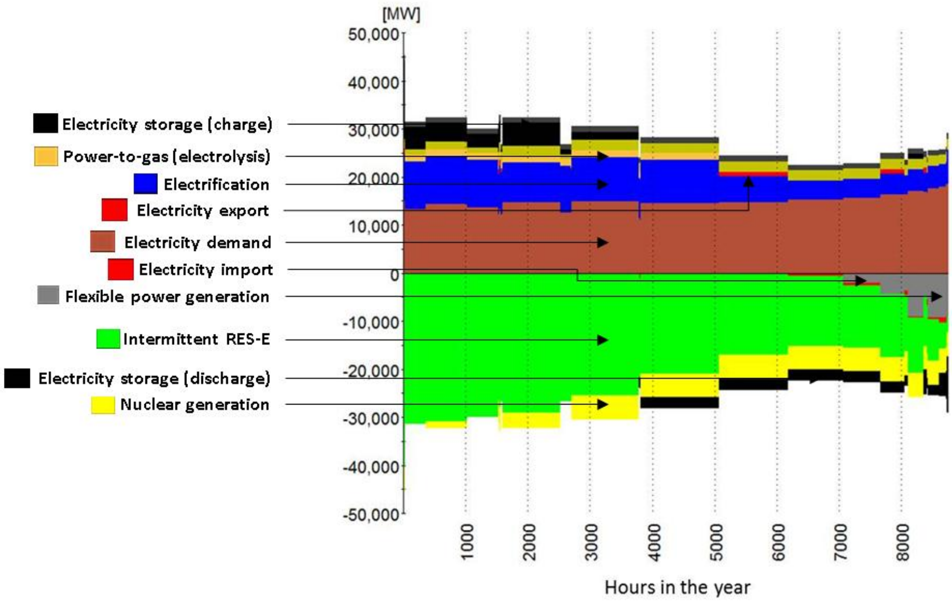
Introducing regions does not significantly alter the system wide optimal mix of flexibility options

Figure 6 presents the electricity balance of the overall system in the case with and without differentiation into regions. Comparison of the graphs demonstrates the very limited changes in the optimal mix of technology options throughout the hours of the year that result from differentiating the overall system into a centralised part and three archetypical regions. The main reason for this observation is that the non-differentiated

[10] In practice, the Netherlands could be a net importer or exporter of electricity. As the simulation model does not capture the whole of North-western Europe but only the Netherlands, we cannot project whether the Netherlands will become a net importer of exporter in the future.

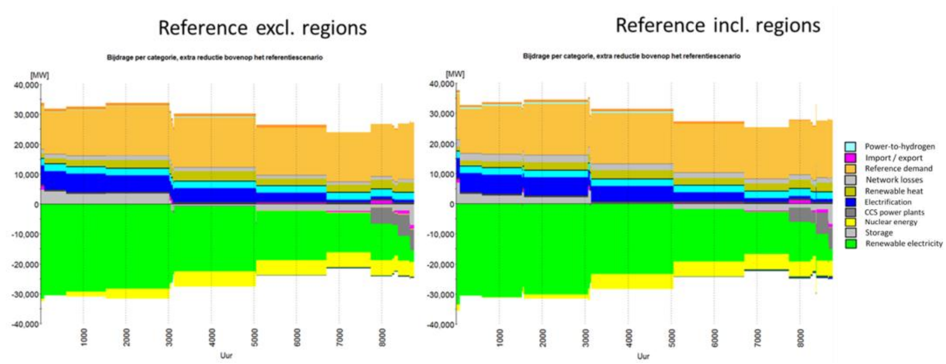
model setup already takes into account different system levels (i.e. voltage and gas pressure levels). This network distinction already seems to mimic the feature of typical regions quite close.

Figure 5: Electricity balance of the overall system by time slice



As noted earlier (Section 3.2), the introduction of regions leads to an increase in the amount of intermittent renewables entering the electricity system (about 10 TWh per year). The increase in the amount of flexibility needed across time slices seems relatively small, but does lead to an increase in electricity demand (which is the total of the categories 'conventional electricity demand' and 'electrification') and a somewhat different flexibility profile of those categories.

Figure 6: Electricity balance of the overall system by time slice in the case with and without differentiation into archetypical regions (in case of a 30 Mton CO2 emission level)



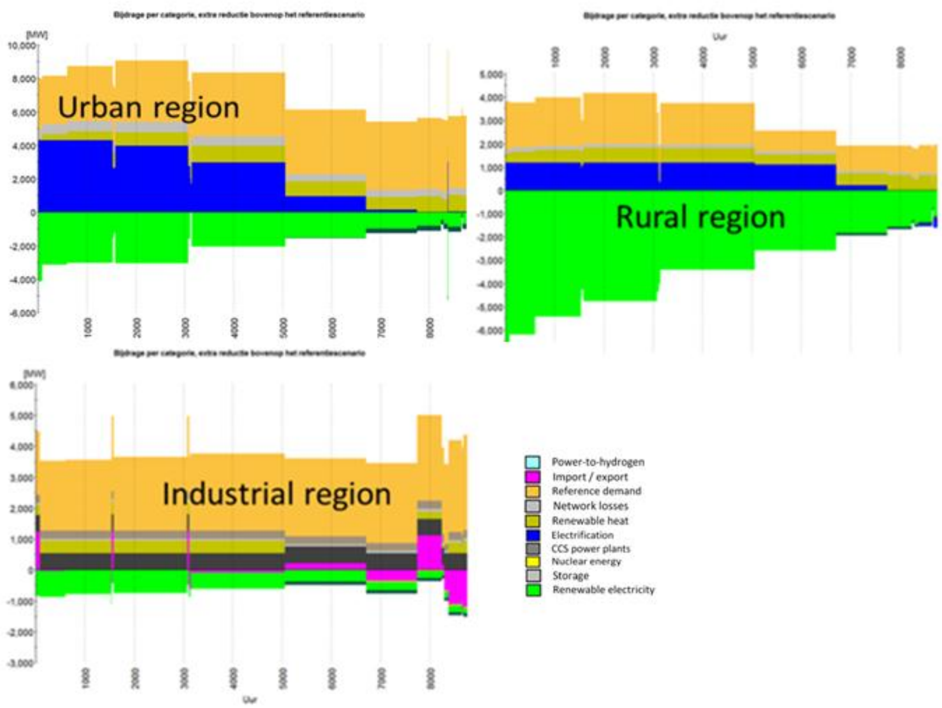
Introducing regions uncovers differences in flexibility requirements and potential

The differentiation into 3 archetypical regions shows the dynamics of the demand and supply side of the electricity system (see **Figure 7**). From the time slice-based electricity balances we may infer that each of the three regions has a distinct position in the degree to which flexibility is *required* and flexibility is *provided*.

The *urban* region has a relatively small amount of intermittent RES (predominantly solar PV) compared to regional electricity demand. It seems that the fluctuation in the regional supply of electricity is mostly met with an increased flexibility of electricity demand via electrification. In addition, Biomass-based CHP units provide some back-up in case of absent electricity production from intermittent resources, with about 2000 running hours. On a yearly basis, this region is dependent on electricity flows from the central region (the national transmission level) and judging from the variation in the patterns of regional intermittent electricity supply and new electricity demand via electrification it seems that this region is able to provide some level of flexibility to the overall national system as well.

The *rural* region on the other hand is characterised by a relative large amount of intermittent electricity generation from renewables. It is not only an 'exporter' of electricity to other regions, but also an importer of flexibility. This implies that from the perspective of the energy system as a whole it is more cost efficient to solve the flexibility problem that originates in this region elsewhere rather than in the region itself. This makes sense as (1) the potential to for example install wind turbines is much larger in this type of regions, and (2) the amount and density of demand is relatively lower than in the other two types of regions. The graph for the rural region in **Figure 7** does indicate significant electrification of energy demand, but this seems mostly inflexible in nature with running hours of about 6800 hours.

Figure 7: Electricity balances by time slice for the three demand regions



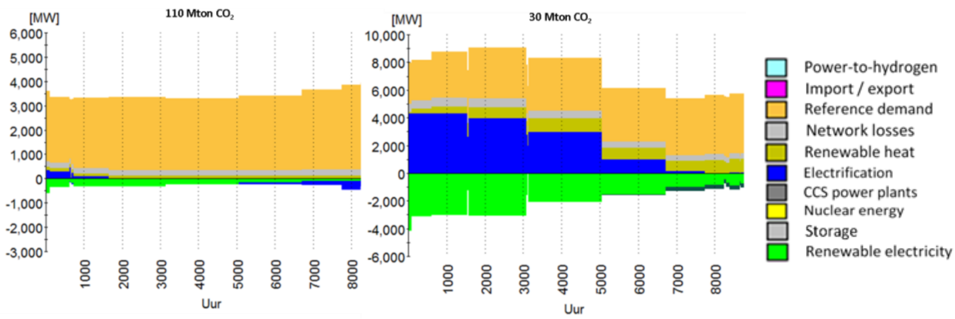
Out of the three regions, the archetypical *industrial* region shows relatively the most flat pattern on both the supply and demand side. The results depicted in **Figure 7** also raise some questions regarding the fine-tuning of the way in which particular technology options are represented and allocated across regions. For example, there seems to be hardly any electrification of energy demand in the industrial region. This seems in contradiction with the general notion that further electrification of industrial energy demand is required for cost-efficient long-term decarbonisation and the idea that this may also offer significant additional system flexibility via for example power to heat. The results as obtained indicate that industrial regions neither contribute to the flexibility challenge nor contribute to addressing it, but further research on the true potential and representation of electrification technologies in this type of regions is definitively required.

Increasing level of CO_2 emission reductions affects the flexibility challenge differently across regions

Whereas the previous paragraph demonstrated the dynamics of the electricity balance throughout the year in the case of deep CO_2 emission reductions (30 Mton ≈ -85% CO_2 reduction), this paragraph sketches the transformation that takes place within this regional electricity balances when moving from the 110 Mton CO_2 emissions level (≈-50% CO_2) to 30 Mton CO_2.

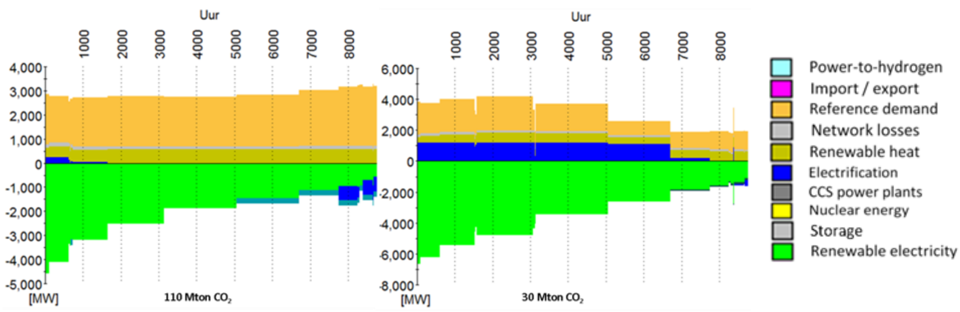
In **urban** regions we observe a large increase in both the (flexible) electrification of energy demand (blue) and the flexibility of conventional electricity demand (light brown) (see **Figure 8**). From comparing the demand and supply side of the electricity balance we learn that overall the level of flexibility offered exceeds the flexibility required within the archetypical urban region, even though the penetration of intermittent renewables increases enormously. Finally, on the electricity supply side we observe a switch from fossil-based CHP units at times of low contributions from intermittent renewables to biomass-based CHP units.

Figure 8: Electricity balance by time slice for the urban region at different CO_2 emission levels



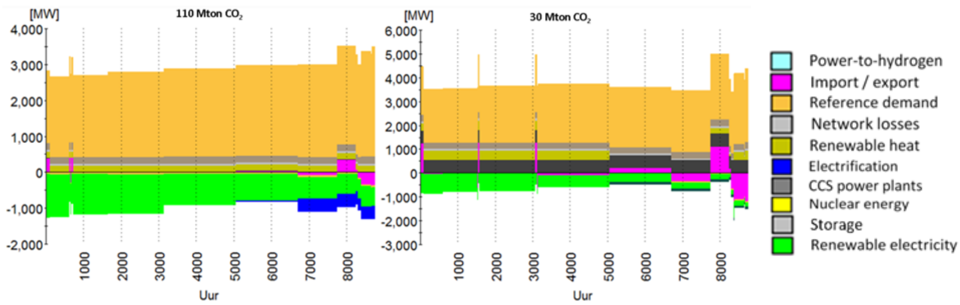
In **rural** regions we observe that electrification of energy demand (blue) is limited and relatively less flexible compared to electrification in urban regions: electrification options demonstrate about 6,600 full-load operating hours (see **Figure 9**). However, there is some additional flexibility in conventional electricity demand when moving to low carbon energy systems. Although rural regions exhibit a net export of electricity to the remainder of the system, it seems that the need for electricity system flexibility can largely be provided within the region, except for the peak supply of intermittent electricity in about 1,000 to 1,500 hours of the year. Finally, whereas fossil-based CHP provides back up electricity in an energy system with a level of 110 Mton CO_2, there is hardly any CHP back-up in an energy system with a level of 30 Mton CO_2. Apparently, the energy system and model set-up allows for the provision of flexibility in the electricity system at lower costs elsewhere (i.e. at the national system level) rather than within the rural regions.

Figure 9: Electricity balance by time slice for the rural region at different CO_2 emission levels



The electricity supply and demand profile in an archetypical industrial region remains relatively flat in an energy system with either a high or low CO_2 emission level (see **Figure 10**). This is mainly due to the relatively small share of intermittent renewables located in the area. Although there is an increase in electricity demand in the region, the overall profile throughout the year remains relatively flat. The significant share of fossil-based CHP in industrial regions under relatively weak CO_2 emission restrictions does not re-appear in an energy system under strong CO_2 emission restrictions. We observe that electricity supply back up in this region is for large part obtained from interconnections with neighbouring electricity systems (pink): the reason for this particular link needs to be analysed further in future model runs. Also the lack of electrification on the electricity demand side may have to do with the used definition for the electrification category (i.e. which technology options are categorised and do these include all possible technology applications in the industry sector?) warrants further analysis.

Figure 10: Electricity balance by time slice for the industrial region at different CO_2 emission levels



4

Conclusions and recommendations

The results from the model simulations discussed in previous section lead to the following conclusions and recommendations.

Overall national energy system results from the adapted model are in line with previous analyses
Model results for the energy system in total are in line with earlier model analyses. This indicates that the significant adaptations to the model have not led to overall system results that are to considered unlikely and negatively affect confidence in the model as a tool in analysing energy transition paths. Differentiating network levels – an earlier adaptation of the model – thus seems more relevant for integral energy system analysis than differentiating between archetypical regions. Common observations from earlier analyses that have been confirmed in this study are for example the large increase in the share of intermittent renewables, the decline in gas demand, the competition between different low-carbon sources (renewable electricity, biomass, CCS), electrification of final energy demand and an increasing need for a mix of flexibility options within the integrated energy system.

But differentiation into regions uncovers significant differences between archetypical regional energy systems
Underlying the national energy system is a number of very diverse energy systems with very distinct characteristics and energy profiles that are ‘averaged out’ in standard national energy system based models. Differences between the separate archetypical regions used in this study and the national average system concern the mix of technology options in terms of installed capacity, in terms of energy use over the year, and the energy use from hour to hour.

Differentiation into regions seems to favour centralised/large scale options and options that are not location specific
The model differentiation into regions causes an increasing ‘mismatch’ between energy demand and energy supply potentials within regions and increases the increases the costs of particular decentralized options and leads to some switches between the type

of technologies, sometimes in favour of more centralised options. Some specific technologies are particularly sensitive for these and other type of contextual changes. For example, hybrid heat pumps are more flexible than geothermal or groundwater based heat pumps that are connected to specific locations. Further analysis needs to address the impact of the way in which energy infrastructure is modelled on the optimal mix of centralised and decentralised technology options in the integral energy system.

Differentiating regions is a must when focusing on local / regional issues, but not necessary or useful when focussing on national issues
The previous result also suggests that it may not be necessary to use the more complex model version that distinguishes different regions when the focus of analysis is only on national issues. Since the results on the national level are not much different when including or excluding the regional differentiation, the added value of modelling regions lies pre-dominantly in analysing particular regional (or local) issues and in analysing particular (type of) technologies of interest.

Application areas of regional energy system modelling
The integral energy system model and its specific regional energy system features can provide useful insights be used in different issues in the field of energy transition and network developments.

Firstly, the model can provide insights into the business case of particular technology investment decisions on the decentralised / regional level. As the model captures both the centralised part and the decentralised part of the energy system it explicitly takes into account the competition and interactions between different technology options on both levels. This is a particular advantage over energy transition models that only capture the decentralised part of the energy system. An example in case would be an evaluation of larger-scale investments in storage in distribution systems: what is the competition for the considered technology investment on other system levels? And: how would implementation of other flexibility or storage options affect its business case?

Secondly, the integral energy system model can provide a normative benchmark for future energy system developments for the centralised energy system as well as separate regional energy systems. The typical question that may be addressed is: what would be the least-cost development of the energy system in the next decades? Based on the insights from the model analyses private or public stakeholders active in the energy system can take necessary policy actions or investment decisions. In this process, a simulation analysis of multiple scenarios rather than one reference projection may be of particular value.

Recommendations
We recommend further research on the representation and role of energy infrastructure in the model because the model analyses thus far indicate that this is an important determinant in analysing different energy transition paths. The current model already incorporates data on existing energy infrastructure (capacity, cost of expansion, bottlenecks) on a rudimentary level that ensures that infrastructure

considerations enter the overall energy system optimisation challenge, but this may be implemented in further detail and tested on sensitivity.

Another recommendation would be to explore the added value and options of further downscaling of the size of the energy system region modelled because that would allow for more specific analyses on local energy communities, while maintaining the interactions with the higher level energy systems at the regional and national level. Taking this additional step would allow for a linking of bottom-up local energy system optimisation tools or models (for example based on load-flows) and top-down integral energy system modelling. This would have particular value in analysing future energy systems that are more and more integrated and will show an increasing number of interdependencies.

References

Weidenaar, T., E. Bekkering, R. van Eekelen (2012), *Scenarios for the Dutch gas distribution infrastructure in 2050*, Energy Delta Gas Research, Working Paper nr.1, Groningen 2012.

Daniels, B., B. Tieben, J. Weda, M. Hekkenberg, K. Smekens, P. Vethman (2012), *Kosten en baten van CO_2-emissiereductie maatregelen*, ECN report ECN-E--12-008, mei 2012.

Netbeheer Nederland (2011), *Net voor de toekomst: Een verkenning*, Netbeheer Nederland, Februari 2011.

De Joode, J., B. Daniëls, K. Smekens, J. van Stralen, F. Dalla Longa, K. Schoots, A. Seebregts, L. Grond, J. Holstein (2014), Exploring the role for power-to-gas in the future Dutch energy system, Final report of the TKI power-to-gas system analysis project, ECN / DNV GL, ECN-E--14-026, July 2014.

Appendix A. Time slice approach adopted in OPERA

Explanation of adopted Time slice approach
Demand and (variable) supply profiles are input into the model with hourly resolution. This means that there are 8760 values per profile input into the model. Such a high temporal resolution would lead to excessive runtime and memory use of the model. It was therefore decided to decrease number of time periods used in the optimization loop by grouping the hours of the year into sets, called *time slices*. The methodology and algorithms to allocate the hours of the year into time slices have been devised to meet the following requirements:

- The set of time slices should enable the identification of significant time periods where supply and demand vary (e.g. seasonal variations, daily variations);
- The set of time slices should enable the identification of periods with shortage/excess of supply vs. demand;
- The user should have full flexibility in choosing the number of time slices in order to achieve the desired compromise between runtime and temporal resolution;
- The user should have full flexibility in choosing what the underlying criterion for the time slices allocation is:
    1. Fixed time periods (seasonal and/or daily);
    2. Variations in the demand patterns for electricity, heat or total;
    3. Variations in the supply patterns for electricity, heat or total;
    4. Variations in the excess/shortage of supply vs. demand patterns for electricity, heat or total, and the possibility of using storage.

    For each of these 4 criteria a set of special *allocation indicators* has been built in the model. After running several tests it was established that the 4th criterion yields the most valuable output for the P2G project. Therefore the following paragraphs will focus exclusively on the description of the set of allocation indicators for this particular criterion.

Intermittent energy supply profiles
Hourly variable supply profiles concern electricity from wind energy and electricity and heat from solar energy. They are further specified per year (*y*), region (*r*), and option (*o*): $s(y, h, r, o_w)$ for wind profiles and $s(y, h, r, o_s)$ for solar profiles.

An aggregated wind (solar) supply profile per year is created by summing and normalizing all separate wind (solar) profiles:

$$s_w(y,h) = \frac{1}{N_w}\sum_{r,o_w} s(y,h,r,o_w)$$

$$s_s(y,h) = \frac{1}{N_s}\sum_{r,o_s} s(y,h,r,o_s)$$

where N_w and N_s are the normalization factors.
An overall aggregated supply profile is then created using the following equation:

$$s(y,h) = \frac{1}{N}\sqrt{s_w^2 + s_s^2}$$

where *N* is a normalization factor.
It is important to remark that the aggregated supply profile does not represent a physical quantity. It is used to construct the desired indicator. If new, or additional supply profiles are input in the model, the aggregated profile will change and this will influence the final indicator.

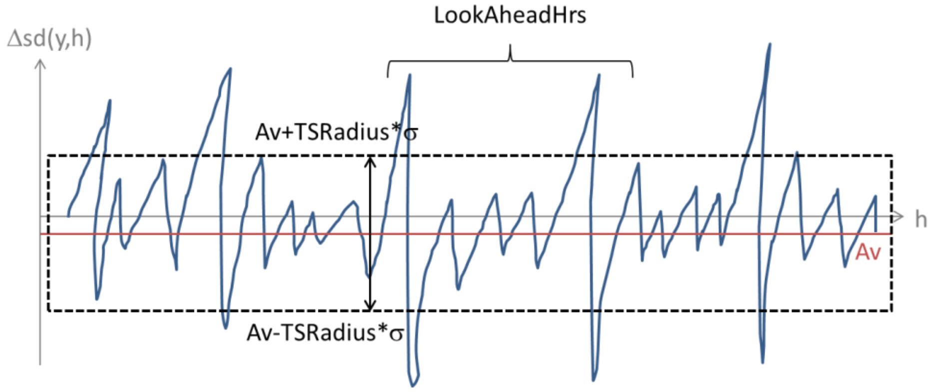
Energy demand profiles
Hourly demand profiles for electricity and heat are provided per year and sector. Following an analogous procedure as for the supply, aggregated profiles for electricity and heat demand, d_e and d_h respectively, are created by summing over the sectors and normalizing. An overall aggregated demand profile, *d*, is then created by taking the square root of the sum of squares and normalizing.

Allocation indicators
Based on the aggregated demand and supply profiles described above, the following allocation indicators have been created:

$$\Delta sd_e(y,h) = s(y,h) - d_e(y,h)$$
$$\Delta sd_h(y,h) = s(y,h) - d_h(y,h)$$
$$\Delta sd(y,h) = s(y,h) - d(y,h)$$

The first two indicators represent a probability of having an excess (positive values) or shortage (negative values) of supply vs. demand of electricity and heat, respectively. The last indicator represents the probability of of having an excess or shortage of overall supply vs. demand.

Allocation algorithm



The figure above shows a sketch of the Δsd indicator, and the parameters that are used by the algorithm to perform the time slices allocation. The meaning of the different parameters and the procedure steps are briefly summarized in the following bullets:

- Av = Average of Δsd.
- σ = Standard deviation of Δsd.
- *TSRadius* controls the height of the black dashed rectangle; initial value = 1. The values outside the rectangle correspond to extreme situations. Maxima, or *valleys*,

are likely excesses of intermittent supply. Minima, or peaks, are likely shortages of intermittent supply vs. demand.

- *LookAheadHrs* controls how many hours to look from a maximum (peak outside the rectangle) to find a minimum (valley outside the rectangle); initial value = 24 hrs.
- The algorithm selects all peaks (valleys) outside the rectangle, and find all valleys (peaks) within *LookAheadHrs* (-*LookAheadHrs*) hours. These valleys and peaks are then stored in the first half of the time slices, in ascending order depending on the value of AVDiff (hence first the valleys then the peaks). The remaining hours are stored in the rest of the time slices, in ascending order depending on the value of AVDiff.
- All parameters can be adjusted in the model via the user interface, at the page 'TS Indicators - overview'.

The algorithm allows us to isolate the hours where an excess of intermittent supply is likely to occur and a use for this excess is likely to arise in the near future. Analogously, the algorithm isolates the hours where a shortage of intermittent supply is likely to occur and this shortage can be "filled" with an excess supply from the near past. Depending on the degree of likely excess (shortage) and on the total number of time slices, these hours are allocated within a certain time slice.

ECN

Westerduinweg 3
1755 LE Petten
The Netherlands

P.O. Box 1
1755 ZG Petten
The Netherlands

T +31 88 515 4949
F +31 88 515 8338
info@ecn.nl
www.ecn.nl