System Integration – Hybrid Energy Infrastructures

Dutch Ministry of Economic Affairs, Netherlands Enterprise Agency (RVO)

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Objective: Review contribution of hybrid energy infrastructures to electricity system reliability and security. Assess opportunities fot the Dutch Economy and provide recommendations for the innovation agenda of the Top sector Energy.

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AC	Alternating Current
aFRR	automatic Frequency Restoration Reserves
CHP	Combined Heat and Power plant
COP	Coefficient of Performance
CSP	Concentrated Solar Power
DC	Direct Current
EED	Energy Efficiency Directive
HEI	Hybrid Energy Infrastructure
HRSG	Heat Recovery Steam Generator
HT	High Temperature
LT	Low Temperature
mFRR	manual Frequency Restoration Reserves
P2H	Power-to-Heat
P2G	Power-to-Gas
PEM	Proton Exchange Membrane
PMC	Product Market Combination
PTU	Program Time Unit
RR	Replacement Reserves
SOE	Solid Oxide Electrolysis

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EXECUTIVE SUMMARY

The European energy market is undergoing structural changes in many areas. Different developments are observed, for example:

- Conventional production of natural gas is in decline.
- Supply will diversify, for example with an increasing share of biogas supply.
- Demand as such for natural gas in the Netherlands will decrease.
- Environmental concerns and the climate change mitigation drive are high on the political and social agenda.

All these developments, occurring in parallel, are usually referred to as the energy transition. The common view is that the energy transition will trigger an increasing need for flexibility in the energy system. As a consequence the expectation is that the value of flexibility in the energy system will also increase. This need for flexibility is particularly pronounced in the electricity system.

The Dutch Ministry of Economic Affairs – division Rijksdienst voor Ondernemend Nederland (RVO), issued a tender to acquire insights on the role of system integration in the future Dutch energy system. This particular report provides insight on the role of infrastructures in relation to the future energy system (which is one of the four lots in the tender).

> The overall goal is to provide recommendations for the innovation agenda of the Top sector Energy with respect to hybrid infrastructures. More specifically, the research question of this project is: how can hybrid energy infrastructures (electricity, gas, heat, cooling) provide flexibility to help balancing demand and supply in the electricity system.

This study focusses on the flexibility which links between infrastructures can provide towards. In this report these links are referred to as concepts. The concepts considered should be at a coupling point between at least two networks and should have a form of third party access (multiple users should have access to the concept, either regulated or negotiated). Particular focus is on the value of the flexibility that these concepts provide.

Vision on future flexibility needs and infrastructures

In order to explore the future need for flexibility and to identify relevant energy infrastructures, the study adopted six energy scenarios for 20130 which DNV GL and CE Delft developed earlier (report publically available). Below some key findings from the scenarios analysis are summarized.

- Electricity
    - Heat demand - Electrification of heat demand is prominent in all scenarios, advocating enhanced implementation of electric boilers and electric heat pumps. Industrial electric heating infrastructures (high temperature) and domestic district heating infrastructures (low temperature) become increasingly important.
    - Volatility - In all scenarios the electricity grid shows persistent growth with an increasing volatility and increasing "seasonal gap". The residual load could add up to 6,5 GW residual hourly load in 2030 (compared to 2 GW residual hourly load in 2012).

- Peak (heat) demand – The increased use of electricity for heating purposes is a persistent trend in all scenarios. This provides an opportunity fo hybrid concepts to connect the electricity grid with local heat distribution grids and thus provide flexibility to the electricity grid using head storage capacity. The threat is that electrification of the heat demand will lead to higher seasonable differences in electricity demand and therefore higher need for seasonal flexibility options (reserve power, gas storage).
- DC-grids - We do not perceive that the introduction of local DC-grids will have a major impact on the flexibility requirements of the national grid.

- Gas
  - Lower throughput in networks - Scenarios signal that gas network utilization is expected to be lowered significantly because of electrification of heat demand and district heating concepts.
  - High energy density - Gas infrastructure networks and gas storage facilities provide much more power and volume than other electricity storage alternatives (although a conversion efficiency must be factored in).
  - Large flexibility potential - Gas transmission infrastructure particularly plays an important role for energy containment, i.e. providing longer term flexibility and storage (months/seasons/years). Hybrid energy infrastructure concepts which provide a link between the natural gas grid and the electricity grid can unlock a vast flexibility potential (e.g. via power-to-gas).
  - Competition with other networks - In all scenarios heat grids emerge, these heating networks will compete with gas networks.
  - Role of gas - The role of natural gas will change from commodity to strategic fuel to deliver fast and reliable peak capacity.
- Other gasses (industrial gasses)
  - Other gas grids - Already today the Netherlands is connected to 2700 km industrial utility networks (oxygen, nitrogen, hydrogen). These networks are expected to get a more explicit role on the energy domain. These networks provide some form of third party access. These networks also have intrinsic storage capacity.
  - Facilitating hybrid solutions – Grids for industrial gasses allow for fuel switch concepts (e.g. electrolysis versus steam reforming for hydrogen production) to enhance energy system flexibility.
  - Fuel switch potential – Hydrogen and oxygen/nitrogen can be produced on the basis of excess power on the grid (or production can be ramped down in case of shortages). Another option is to opt for an alternative way of generating the industrial gas. For example, hydrogen can be produced by water hydrolysis (the classical route is via steam reforming of natural gas). This fuel switch route is more efficient than the power-to-gas route.
- Heat
  - Most scenarios show an increase in the application of small and large heat distribution grids.

- Combining heat grids with (intrinsic or extrinsic) heat storage, electric or hybrid heat pumps, direct electric heating, combined heat and power (CHP) and boilers, provides opportunities for hybrid energy infrastructures.

- Cold
    - Emerging networks - It is also observed that cooling networks emerge (common source for electric heat pumps, utility building cooling with river water/aquifer).
    - Limited role – The analysis does not see viable reasons for developing public cooling grids based on compression cooling. Public cooling grids would only make sense if 'free waste cooling' is available locally. This limits the potential for utilizing flexibility, also storage of cold is rather voluminous due to the low delta in temperatures. Therefore its applicability strongly depends on the specific local situation.

Concepts enabling hybrid infrastructures

The overall energy system's flexibility can be enhanced by connecting and combining the capacity and flexibility available in different infrastructures. This connection is typically an energy conversion technology. In this report we refer to these technological solutions as concepts enabling hybrid energy infrastructures.

Many concepts could be considered. The concepts which remain after the initial screening are shown in the figure below. Horizontally we illustrate how the concept connects to different energy carrier networks (electricity, hydrogen, natural gas, heat and cold). Vertically we differentiate the geographical scope which is relevant for a concept.

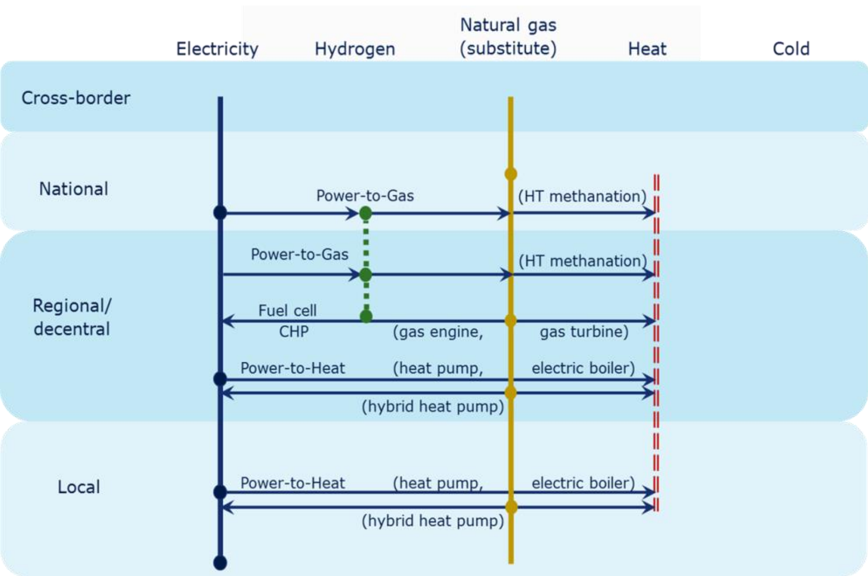

Figure 0-1 Short listed concepts for infrastructral system integration

Summarizing, the following concepts were subject to detailed evaluation in our analysis:

1. Electric heat pumps in heating network
2. Electric industrial boilers
3. Flexible CHP
4. Hybrid district heating (electric heat pump with gas fired boiler or CHP-unit)
5. Power-to-hydrogen
6. Power-to-methane

Related to the heat concepts considered in the analysis, two types of heat storage have been included; heat storage in district heating and industrial high temperature heat storage.

In order to establish the position and value of the different concepts a distinction should be made between different types of flexibility. Gas-to-power concepts are important for (reserve) power generation and frequency restoration but can provide flexibility for accommodation of longer term variations as well. The power-to-heat and power-to-cooling concepts are typically more relevant for the 'short-term' services, both in terms of reaction time as well as in terms of the 'containment period' the period that the infrastructure combination is able to maintain the energy). Finally, the power-to-gas options are primarily relevant for accommodation of long-term variations in residual demand.

We assessed the potential technological, economical, managerial, institutional and societal barriers for these shortlisted concepts. Below we highlight some selected key findings.

Technological and economic barriers

Potential technical and economic barriers of the hybrid energy infrastructure concepts differ in terms of technological development. Where concepts like application of industrial electric boilers, flexible CHP's, low temperature heat pumps and hybrid district heating essentially involve established technology, power-to-methane and power-to-hydrogen still offer an outlook on potential for technological improvement, particularly with regard to efficiency. For the power to methane concept also gas quality requirements in gas networks can pose a technical barrier. Hence, it are particularly these technologies that show a relatively significant economic barrier as investment costs are relatively high. Also concepts that include heat pumps show technical barriers arising from significantly lower efficiency at low ambient temperatures and economic barriers related to high investment costs.

Managerial, institutional and societal barriers

Next to the techno-economic barriers also an assessment was made of the systemic barriers which could hamper the implementation of hybrid energy infrastructures. The focus was on so-called managerial barriers lying within the realm of corporate governance (what are the risks of revenue streams), on barriers that arise from the typical institutional setting (regulatory aspects) and ultimately societal factors that can hamper implementation. These three aspects are discussed separately below.

Managerial and corporate governance barriers

Barriers relating to the business models for each of the concepts were evaluated. The assessment focussed on the potential risks in revenue streams of hybrid energy infrastructure concepts. Price risks were found to be large because the revenue streams depend on the sufficient occurrence of low electricity prices. There is a clear difference on how sensitive the concepts are to this risk. For example power-to-methane faces very high price risks, and also the concept of increased CHP flexibility faces high price risks. General market risks are considered comparable for all concepts. Operational risks are highest for power-to-methane (and less so for power-to-hydrogen) due to a number of technological process condition challenges that do not exist in the other concepts.

Institutional barriers

The institutional barrier analysis mainly shows that the current regulatory framework limits the involvement of network operators (TSO's and DSO's) in realizing energy infrastructure coupling. This in turn limits other stakeholders to pro-actively facilitate the integration of networks into hybrid energy infrastructures.

Another relevant development is the Heat Law ('Warmtewet'), in place since 1 January 2014. The Law is only applicable for the heating demand in space heating and cooling, hot water and domestic use. Industrial or process heat is not subjected to the Heat Law. There are a number of reasons why the Heat Law can act as a barrier to energy-efficient heating / cooling technologies. In particular two aspects are important to mention. First of all, the Heat Law imposes requirements on the maximum prices that may be charged for connections and energy commodity, based on a calculation by the regulator (only for customers with a heat load less than 100kW). Any amount that is higher is forbidden and can be challenged by the Authority for Consumers and Markets (ACM). The heat law causes uncertainty because the definitions of what is covered by the law are not clear in practice and there has not been much experience with the interpretation of the law in practise.

Societal

Societal factors are factors resulting from the activities that are 'external' to the economic activities. At first instance, societal factors are not incorporated in the business case decisions. However, if they adversely impact others, it can be important to address them; otherwise strong opposition to a project can arise that negatively affects the realisation. Overall expectation is that concepts for hybrid energy infrastructures will not face major societal hurdles, as the concepts are typically realised 'out of sight', generate no pollution, do not cause significant safety impacts, etc.

From the assessment of market, operational and regulatory risks, the following concepts are shortlisted having the lowest risks to their revenue stream:

- Electric heat pumps in heating network
- Hybrid district heating
- Heat storage options
- Power-to-hydrogen

Valuation

The valuation of the shortlisted concepts is based on three aspects: the value added in terms of economic value, the value added in terms of employment and the value added in terms of sustainability (CO_2 emission reduction potential).

The economic value of the concepts would ideally be based on a valuation of the underlying costs associated with investment and operation, revenues generated in the different electricity market segments, and finally revenues (or cost reductions) generated in sales (avoided costs) of alternate products like heat or hydrogen. Such an assessment would however rely heavily on the assumptions regarding future development of electricity market prices in the market segments and the development of alternate commodity markets involved. Instead, therefore, the economic valuation was evaluated on the basis of the impact the various concepts may have on overall system costs and benefits.

In order to offer a generalised outlook on the net system costs, the classic methodology of screening curves was applied in order. Net system costs relate to the investment costs and (fixed and variable) operating costs involved with each concept on the one hand, as well as system savings on the other. In the figure on the next page the screening curves for the different concepts are shown.

Next to the screening curves of the various hybrid energy infrastructure concepts also two conventional technologies are included as a comparison in order to establish the value of the concepts with respect to a conventional alternative. As a conventional options for the injection of electricity gas turbine technology is used as a reference. Hybrid energy infrastructure options for absorption of electricity may be compared to curtailment of onshore wind energy.

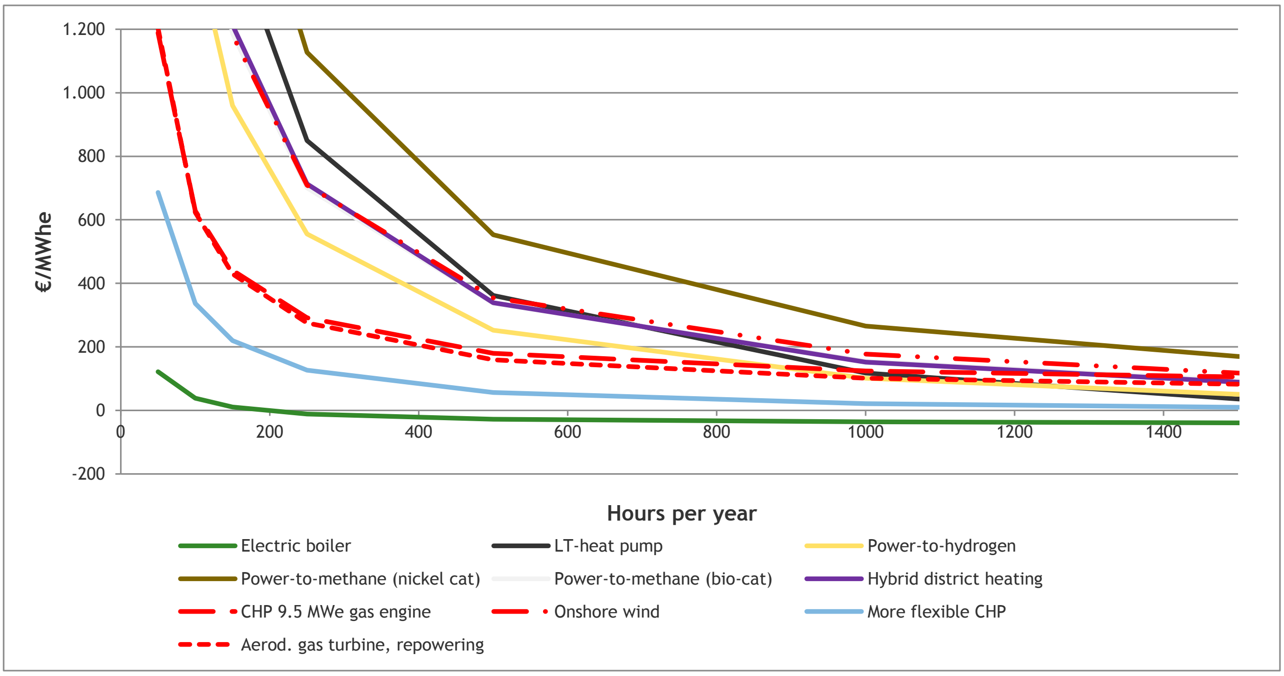

Figure 0-2 Screening curves for each of the hybrid energy infrastructure concepts and reference technologies (red dashed lines).

In principle, concepts that offer the lowest net costs and high benefits are expected to be of highest value to the system as a whole, while distributional effects regarding differing elements of these underlying system costs and benefits may impose a barrier upon introduction of the concept in the Dutch energy system.

Both the industrial electric boiler and flexible CHP's are valuable concepts which can provide services across the full spectrum of flexibility demand in the electricity system at relatively low net system cost. A more marginal value in terms of both flexibility provision as well as cost-effectiveness is offered by the power-to-hydrogen concepts and hybrid district heating. These options show to offer an increasing benefit in terms of lowering net system cost in case of deployment above 1000 hours yearly. The remaining concepts, electric heat pump in heating network and power to methane (nickel cat) offer a distinctly differing potential in terms of flexibility provision as these concepts show a better fit with seasonal flexibility demand in the electricity system. Power to methane (bio-cat) shows only moderate net system costs and provides an attractive option for such flexibility needs in comparison to the significantly higher net system cost alternatives of power to methane (nickel-cat).

In terms of CO_2 emissions, all options offer improvement over their respective reference technologies. Here, all concepts show savings in the order of 0.1-0.2 tonne/MWhe, except for the flexibilization of the CHPs and the low temperature heat pump. The first shows somewhat lower saving, as these older CHP facilities were assumed to show relatively low electrical efficiencies, while the latter shows relatively high savings at 0.63 tonne/MWhe if compared against a reference heating boiler.

Additionally the potential impact on gross employment is assessed. This reflects the economic activities relating to project development as well as operation and maintenance of the systems. The results are shown in the figure below.

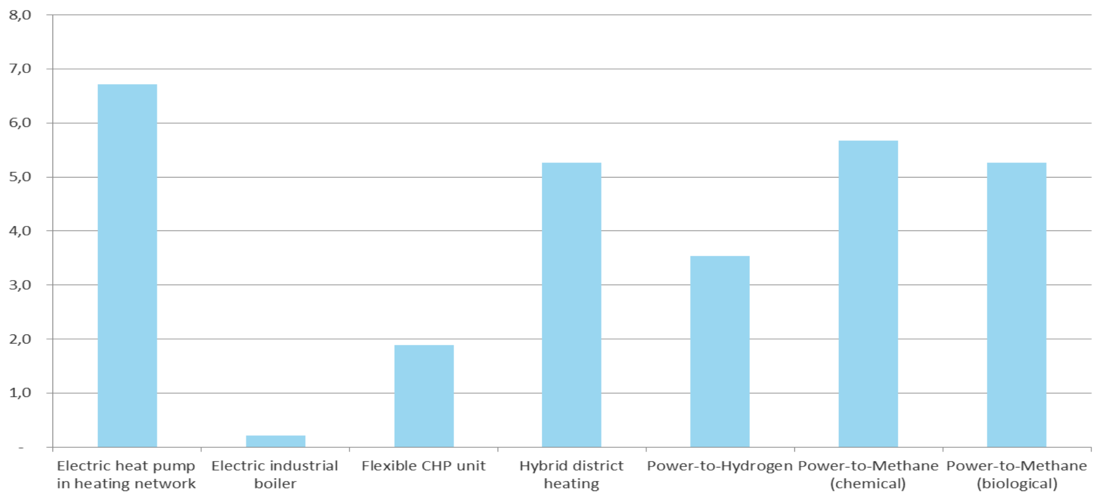

Figure 0-3 Number of FTEs per MWe of capacity for the various hybrid energy infrastructure concepts

Here the more capital intensive concepts like the low temperature heat pump, hybrid district heating and the power-to-gas concepts show somewhat higher levels of FTE´s created, while the flexible CHP shows a lower impact. Notably the electric industrial boiler shows only a marginal impact on employment.

Given the results presented, the industrial electric boiler and flexibilization of CHP can be characterized as highly flexible, highly cost-effective measures to enhance system flexibility, offering limited outlook positive impact on employment, while performing reasonable well on sustainability in terms of the potential to reduce CO_2 emissions in comparison to the reference technology.

The power-to-heat options, electric heat pump in heating network and hybrid district heating provide for options that may offer flexibility for short-term flexibility needs, from an economic perspective one may note that impact on net system cost is only marginal, but performing relatively well in terms of employment and sustainability.

The power-to-gas options all perform predominantly well in term of longer-term flexibility provision, with notably power to hydrogen and biological power to methane performing well in terms of reducing net system costs while performing well in terms of employment and sustainability. Chemical power to methane stands out among these options as a relatively costly option, unable to outperform conventional options for flexibility provision in terms of net system cost reduction.

Selection

The valuation of the selected concepts and an analysis of the potential barriers these concepts face are an indication of the potential these concept have in general. Next to that an analysis was carried out to determine the most likely concepts to be successful for the Dutch economy.

Two criteria were applied:

1. National market potential - Good implementation into a market can be reached by favourable market conditions that match the characteristics of the concept. The analysis was executed by mapping the potential product-market-combinations (PMC) in both The Netherlands and NW Europe. A PMC gets a high score if the PMC has a large potential in terms of turn-over.
2. Development potential - If a concept has a high potential for successful product or concept development in The Netherlands, the concept potentially has a high contribution to the Dutch economy. To analyse this contribution, a SWOT-analysis of the concept in the Dutch context is performed.

By combining the two criteria and rankings, an overall assessment is made of the concepts and the high-potential concepts are identified. The highest ranking concepts are considered the high-potential concepts. The table below shows the result of this analysis.

Table 0-1 Combined ranking of hybrid energy infrastructure concepts

Concept	Ranking national market potential	Ranking development potential	Combined ranking (with weight = 2 for development potential)
Electric heat pumps in heating network	1	3	7
Electric industrial boilers	5	1	7
Flexible CHP	2	3	8
Hybrid district heating (electric heat pump with gas fired boiler or CHP-unit)	4	5	14
Power-to-hydrogen	3	4	11
Power-to-methane	3	2	7

The concepts are scored such that the highest ranking concepts receive the highest points. A 5-point scale is used to emphasise that the scoring is relative, with a (high) degree of uncertainty. A 6 or 8-point scale would suggest an accuracy that is not present.

All of the mentioned concepts are basically high potential concepts, but all have different accents. The electric industrial boiler for instance, has a high market potential and the power-to-hydrogen a high development potential. Eventually, the focus of this study is to investigate those options that have the highest value and highest potential for the future innovation agenda of the Netherlands. This is why the development potential is weighted extra, in comparison with the market potential (last column in the table above). Straight from the shelf concepts, which are already implemented in The Netherlands, have limited or no development potential and are therefore not of primary focus to the innovation agenda recommendations.

Recommendations for the innovation agenda

Based on our analysis and assumptions we identified and shortlisted the following high potential concepts which have the highest value and the highest potential for the Dutch context. The future innovation agenda should put emphasis on these concepts:

- Hybrid district heating
- Power-to-gas options (power-to-hydrogen for industrial application or grid injection and power-to-methane (biological) for regional application and injection)
- Flexible CHP units (or upgrading existing CHP units to enhance their flexibility)

All the heat options can be supplemented in flexibility by integration of heat storage (district heat storage or industrial heat storage), this is why the heat buffer concepts are not specifically listed as high potential options, as they are rather to be considered in all power-to-heat concepts to enhance flexibility.

For these concepts we have identified a number of technical barriers which can be addressed by innovation projects, e.g. aspects like developing operating philosophies of hybrid district heating or continuous efficiency improvements and gas network quality issues related to power-to-gas options and redesigning technical components in CHP allowing for ramping up and down flexibly.

But overall we would like to advise RVO to consider in particular the following recommendations in the establishment of the innovation agenda:

1. Reconsidering the roles and responsibilities of network operators in relation to hybrid energy infrastructure concepts.

The current regulatory framework limits network operators and potential operators of hybrid concepts to actively pursue opportunities towards implementing concepts of infrastructural system integration. To give an example, grid operators are currently not allowed to operate power-to-gas installations. In order to do so, they have to apply for several regulatory exemptions in order to obtain their permits. It should be noted that the development of such concepts is not solely the responsibility of regulated parties; also other market players can take the initiative to develop hybrid energy infrastructure concepts. Irrespective of who takes initiative, regulatory uncertainty can form a business risk. At this moment the potential stakeholders in hybrid energy infrastructures experience regulatory resistance or uncertainty to their potential pro-activity. We therefore recommend putting effort in evaluation and possibly revision of the roles and responsibilities of network operators in relation to their potential value in order to unlock energy system flexibility by coupling of energy infrastructures.

2. Explore the potential impact of RES providing flexibility to the electricity market in relation to the value of hybrid energy infrastructure concepts.

On the one hand increased shares of renewable energy sources have an impact on residual system load and trigger the need for flexibility. On the other hand, generators based on renewable energy sources can potentially also offer renewable reactive power. This will impact the value of hybrid infrastructures concepts which are especially suitable for frequency restoration since these solutions might compete. We advise to explore this potential impact in order to gain understanding on the robustness of the value of hybrid infrastructures.

3. Validate high-potential concepts through demonstration in operational environments

The macro level role and value of high potential concepts has been analysed and identified. In order to validate and understand their value in real life environments, we advise to gain operational experience through demonstration and validation projects. Validation of these concepts in operational environments will bridge the gap between R&D knowledge and actual implementation of the concepts. Operational experience offers to identify barriers and explore practical solutions for regulatory, contractual and operational issues as well as to validate its technological performance and to identify additional infrastructural requirements (like e.g. ICT requirements).

4. Development of alternative tariff structures for hybrid energy infrastructure concepts

Concepts like power-to-heat and power-to-gas require (large) capacity connections to the electricity grid. In the current set-up of the tariff system, the costs of the electricity networks are being paid by the consumers via the network tariffs. Grid connection costs for consumers are determined by the capacity of the power connection. There is currently both a fixed monthly tariff for the nominal capacity and a monthly tariff for the peak use in a month's time. At the moment conventional electricity producers do not pay a network tariff. Hybrid energy infrastructure concepts can be seen as both a producer and a consumer. In some cases they are net consumers, whereas in other cases they help balancing the network. A mismatch between the tariff set-up and new system roles creates a significant risk in the business of these concepts, preventing stakeholders and investors taking initiative. Therefore we recommend exploring alternative tariff structures for hybrid energy infrastructure concepts and assess the regulatory options and limitations.

5. Explore the value of feedstock infrastructures in providing flexibility to the electricity grid.

Flexibility captured within (industrial) feedstock networks could be germinated and offered to the electricity infrastructure. For instance, the hydrogen network present in the Botlek area offers great energy capacity, both in terms of supply to as demand from the network. We advise to explore the technical, regulatory and organizational possibilities to make this flexibility available to the energy system in a structured fashion. The potential role of industry in this matter seems to be very significant and should further be exploited. A large scale pilot with industrial stakeholders could be one of the possibilities to rapidly gain insight in the viability of fully integrating feedstock networks in the energy system.

6. Impact assessment of the differences in regulatory set-ups of heat networks and other networks, regarding the impact on hybrid energy infrastructures.

Providing flexibility using hybrid energy infrastructures requires the involvement of three actors: the operator of the electricity network, the operator of the energy conversion concept at the connection point between networks and the operator of the network of the other energy carrier (gas, heat, cold). Currently the regulatory arrangements in these networks are different. The regulation of heat networks is particularly different from the regulation in electricity and gas networks. There is also the issue of privately owned networks which are not regulated. In order to facilitate the development of hybrid energy infrastructure concepts we recommend mobilizing innovative power towards reassessing the existing regulatory frameworks with a view on the future infrastructure combinations/interactions. Key is to take an holistic approach seeking alternative, fair and optimal solutions from an overall integrated energy system perspective.

7. Risk assessment of electricity system stability in relation to the current trend of electrification of heat demand in extreme meteorological scenarios.

The current trend of electrification of the heat demand is driven by cost, efficiency and emission considerations. This trend will only be proven to be successful whenever the robustness of a full-electric heat demand sector is similar or better than the current levels of security of supply (currently delivered by the gas infrastructure). Additionally, in extreme cold or hot periods (taking into account cooling by air-conditioners) flexibility by the power-to-heat (or cold) options can be limited or even eliminated by the fact that the equipment is running on full power. We strongly advise to assess the risks of infrastructural energy system integration in relation to energy systems' robustness and security of supply. Such risk assessments to be based on extreme weather scenarios and potential increased extremeness of weather changes and temperature outliers resulting from climate change (as robustness will become increasingly important).

1 INTRODUCTION

1.1 About the top sector Energy

The Netherlands Enterprise Agency (RVO), part of the Dutch Ministry of Economic affairs, stimulates entrepreneurs in the sustainable, agricultural, innovative and international business. RVO has defined so-called top sectors aiming at stimulating innovation in the Netherlands in order to maintain an international top position. These top sectors are knowledge intensive, export oriented and can potentially provide a valuable contribution to solving societal issues. Both large and medium-to-small enterprises (SMEs) active in the internationally operating top sectors provide welfare and employment to the Netherlands. In order to allocate the scarce financial research means efficiently, enterprises, researchers and government work closely together in Top consortia for Knowledge and Innovation (TKI).

One of these TKI's it the Top sector Energy. Within this top sector, RVO issued a tender in November 2014 consisting of four research topics (lots). The topics of these lots are:

1. The relation between the changing mix of renewable and fossil energy generation and system integration.
2. The role of energy storage in relation to system integration.
3. The role of energy infrastructures in relation to system integration.
4. The role of end users (household consumers, industry and mobility) in relation to system integration.

This report presents the results, analysis and recommendations of the research done for lot 3: the role of energy infrastructures in relation to system integration.

1.2 Background and main question

The European energy market is undergoing structural changes in many areas. Different developments are observed, for example:

- Conventional production of natural gas is in decline.
- Gas supply will diversify, for example with an increasing share of biogas supply.
- Demand as such for natural gas in the Netherlands will decrease.
- Environmental concerns and the climate change mitigation drive are consistently high on the political and social agenda.

These developments, occurring in parallel, are an important part of the energy transition.

The common view is that the energy transition will trigger an increasing need for flexibility in the energy system. As a consequence the expectation is that the value of flexibility in the energy system will also increase. This need for flexibility is particularly pronounced in the electricity system.

The overall goal is to provide recommendations for the innovation agenda of the Top sector Energy with respect to hybrid infrastructures. More specifically, the research question of this project is: how can hybrid energy infrastructures (electricity, gas, heat, cooling) provide flexibility to help balancing demand and supply in the electricity system. This study focusses on the value that concepts of hybrid infrastructures can offer and potential barriers towards unlocking this value.

The research and analysis for this question is divided into two parts. Part I focusses on identifying and assessing concepts for hybrid infrastructures. The sub questions in part I are:

- Flexibility – Based on the CE Delft / DNV GL scenarios (2030)[1].) what will the future need be for flexibility in the electricity system.
- Concepts - What links between infrastructures can be identified which can provide flexibility for the matching of demand and supply in the electricity network in a reliable and cost efficient fashion. In the remainder of this report these links are referred to as concepts.
- Vision - What is the vision on the value of hybrid energy infrastructures (electricity, gas, heat, cooling) and future role based on CE-Delft / DNV GL scenario's (2030)?
- Barriers - Do barriers (technological, economical, managerial, institutional, societal) exist which may limit the development of this options?

Part II of the analysis focusses on the identification of measures which facilitate the implementation of hybrid infrastructures. The sub questions in part II are:

- Selection – What are the most promising concepts in the business-as-usual scenario of the aforementioned scenario report which can already be materialized in the short term (before 2020).
- Overcoming barriers – Which short term actions can be taken to overcome the barriers identified in part I.
- R&D topics - Which actions are required in order to overcome these barriers, more particular which topics should be on the R&D agenda 'Hybrid energy infrastructures' of the Top sector Energy?

This report comprises the results for part I and II.

1.3 Scoping in relation to other lots

As indicated in the introduction to this section, the overall TKI Energy program consists of four research topics (lots). All lots focus on system integration but from different perspectives.

The scope of the analysis and recommendations presented in this report includes the following:

- Flexibility provision to electricity network, through transformation and/or storage in other networks for transportation or distribution of gas, heating/cooling and hydrogen.
- Only coupled networks with a form of third party access are considered (either regulated or negotiated), as flexibility provided through coupling with private networks should be classified as demand response.

The following items are not within the scope of the analysis in this report:

- Energy storage systems which are connected to one energy carrier only. These systems are addressed in lot 2.
- Energy conversion systems which are connected unidirectional to one energy carrier only. These systems are addressed in lot 4. The focus of lot 4 is on the role of end users (household consumers, industry and mobility) in relation to system integration.

[1] Scenario-ontwikkeling energievoorziening 2030,CE Delft report 14.3C93.34, June 2014

- Energy conversion systems at final end consumers. We consider these concepts demand response solutions. These systems and solutions are assessed in lot 4.

1.4 Approach

The approach used is centred on hybrid energy infrastructure concepts. Main steps in this approach are:

- identify various concepts based on stakeholder interviews and literature review
- describe various concepts in a template format
- evaluate concepts and determine the value of concepts that enable infrastructural system integration.

Starting point of our analysis is the DNV GL and CE Delft report 'Scenario-ontwikkeling energievoorziening 2030'. That particular study identified energy systems' flexibility needs toward 2030 and explored the long term role of infrastructures in different scenarios. This report assesses the system integration possibilities for connecting relevant infrastructures, unlocking the value of infrastructure interaction for providing flexibility to the energy system. Key complementary information and insights were gained by stakeholder interviews.

This has resulted into a description of technological concepts to interconnect grids with different energy carriers. Each concept has been evaluated based on the following items:

- Technological: per concept the technologies used are examined based on maturity, development rate and expected improvement.
- Economic: the economic bottlenecks are identified based on the business case of each concept.
- Business: to find the business opportunities and bottlenecks for each concept business opportunities for each concept have been evaluated. These opportunities are based on evaluating market risks and the development of markets based on the scenarios
- Institutional: this consists mostly of evaluating the impact of regulations on the concepts based on current regulations.
- Societal: the societal bottlenecks are mainly found in the area of public resistance based on security, privacy and environmental aspects.

A long list of concepts has been evaluated on the abovementioned assessment criteria. This has resulted in a short list with promising concepts. This short list is evaluated through a SWOT analysis resulting in a better view of the strengths and weaknesses of the concepts within the Dutch market and in a list of "high potential" concepts. Finally, this study was concluded with an assessment of R&D issues and identification of relevant issues for the R&D agenda with regard to promising "high-potential" hybrid energy infrastructure concepts.

1.5 Structure of this report

In Chapter 2 we identify and describe the role of infrastructures in the energy scenarios from the CE Delft/DNV GL study. Next in Chapter 3 we present a long list of potential concepts of system integration and selection criteria based on which concepts are selected for detailed analysis. In Chapter 4 we present and discuss the features of the selected concepts in detail. We assessed the value of the short listed concepts in Chapter 5. In Chapter 6 we identified barriers (technological, economical, business, institutional and societal) which may limit the deployment of the concepts. In Chapter 7 we selected the most promising concept for the situation in the Netherlands using defined selection criteria.

In Chapter 8, the final section of our report, we provide recommendations for the innovation agenda ‘Hybrid energy infrastructures’ of the Top sector Energy. The appendix to this report comprises detailed factsheets on the concepts considered in this study.

2 ROLE OF INFRASTRUCTURES IN SCENARIOS

2.1 Overview of scenarios used

To estimate the (future) potential of hybrid energy infrastructures is a challenge. It is necessary to obtain a picture how demand for and production from energy transported and distributed through electricity, gas, heating and cooling infrastructures will develop in the coming years. The challenge to determine the potential for hybrid energy infrastructures (HEIs) has two aspects:

- the demand and production (e.g. volume, volatility, predictability) of electricity impact the requirement for flexibility to accommodate supply and demand. This basically determines the requirement for flexibility and thus the potential for HEIs do contribute
- the demand for natural gas, heat and cold impact the availability of HEIs to accommodate the flexibility demand of the electricity grid.

The demand for flexibility in the electricity grid is expected to rise, e.g. due to the increasing penetration of solar-PV and wind generation. The challenge here is to accommodate these renewable energy sources in an efficient way without compromising the system stability of the electricity grid. There are several competitive ways to achieve this (conventional measures, hybrid energy conversion systems (dual fuel) storage, demand response etc.) and hybrid energy infrastructures add an option to these.

In order to explore the wide range of possible future energy developments, this study adopts six energy scenarios for 2030, one business-as-usual (BAU) scenario and five scenarios (named A till E) that represent different ambitions for CO_2-reduction and different ways to reach this goal. These scenarios are described in detail in the CE Delft/DNV GL study 'Scenario-ontwikkeling energievoorziening' [2]. The main characteristics of these scenarios are summarized in table 2-1. These characteristics include energy demand for transportation.

The achieved CO_2-reduction shows that the scenarios A till E are sorted in order of increasing ambition for this goal. Scenario D and scenario E achieve 100% reduction. Scenario E is a 100% renewable scenario, scenario D achieves this CO_2-reduction partly by Carbon Capture and Storage (CCS). The scenarios differ further in the availability and the use of decentralized generation potential (e.g. solar PV and micro-CHP). Energy conservation refers to the reduction of the final energy use ("behind the meter") because of energy conservation measures (better insulation, more economical appliances, process improvements etc.).

[2] Scenario-ontwikkeling energievoorziening 2030,CE Delft report 14.3C93.34, June 2014

Table 2-1 Overview of main characteristics of the scenarios (2030)

	BAU	A	B	C	D	E
Achieved CO_2-reduction	%	40%	40%	55%	100%	100%
Renewable energy share		25%	25%	25%	25%	100%
Potential for decentralized generation of electricity		low	low	low	low	high
Use of decentralized potential		100%	<25%	100%	<25%	100%
Energy conservation		medium	low	medium	high	high

The quantification of the energy conservation measures is summarized in table 2-2. It shows ambitious targets, especially for scenario D and scenario E for reduction of electricity demand and low-temperature heat demand (space heating and hot tap water). Energy conservation for high-temperature heat (industrial process heat) is lower because many conservation measures are already implemented.

Table 2-2 Overview of energy conservation assumed in the scenarios (2030)

	BAU	A	B	C	D	E
Reduction of low-temperature heat demand	%	25%	10%	25%	50%	50%
Reduction of high-temperature heat demand		10%	5%	10%	20%	20%
Reduction of demand for transportation fuels		15%	0%	15%	35%	35%
Reduction of the electricity demand		25%	10%	25%	50%	50%

Table 2-3 shows the dominant fuels used in each scenario. Natural gas and coal for electricity generation, oil for transportation and natural gas for heat are the main scenario choices. Exceptions are scenario D where low-temperature heat is mainly generated by electricity (direct electric heating, electric heat pumps) and scenario E where biomass is dominant, even for transportation by means of conversion to biofuels.

Table 2-3 Dominant fuel use in the scenarios (2030)

	BAU	A	B	C	D	E
Electricity generation	coal	nat. gas	coal	nat. gas	nat. gas	biomass
Transportation fuel	oil	oil	oil	oil	oil	biomass
High-temperature heat	nat. gas	nat. gas	nat. gas	nat. gas	nat. gas	biomass
Low-temperature heat	nat. gas	nat. gas	nat. gas	nat. gas	electricity	biomass

Table 2-4 summarizes some main generation characteristics for the scenarios. The scenarios are not optimized with respect to hydrogen and storage power. Straight forward heuristic rules were used to determine the storage and hydrogen power. Decentralized storage is sized to level the generation of solar PV. Centralized storage is sized to accommodate seasonal variations in electricity demand and supply. Scenario E with more than 80 GW of solar-PV requires most storage capacity (almost 40GW). Scenario D and scenario E both include significant electrical hydrogen production capacity.

Table 2-4 Dimensioning of renewable generation, storage and hydrogen production in GW (2030)

	BAU	A	B	C	D	E
Onshore wind	6.0	6.0	1.5	6.0	1.5	10.0
Offshore wind	2.7	2.3	6.0	2.8	3.6	5.8
Solar-PV	11.7	11.7	2.9	11.7	2.9	81.9
Storage (centralized)	0.0	0.0	0.0	0.0	0.0	11.0
Storage (decentralized)	0.8	0.8	0.0	0.8	0.0	28.0
Hydrogen production	0.0	0.0	0.0	0.0	6.5	12.0

2.2 Role of energy-infrastructures in the scenarios

2.2.1 Electricity infrastructure

2.2.1.1 Conventional electricity structure (AC Grids)

Electricity grids play a major role in any of the 6 scenarios described previously. There is no major change in the current configuration of the electricity infrastructure expected in these scenarios, although grid capacity may differ. Figure 2-1 gives an overview of a characteristic grid structure envisioned in the scenarios. The high voltage (HV) grid (50 kV to 380 kV) provides for the transportation of electricity and connection to large producers and consumers. Electricity distribution is realized through the medium voltage (MV) and low voltage (LV) distribution grid.

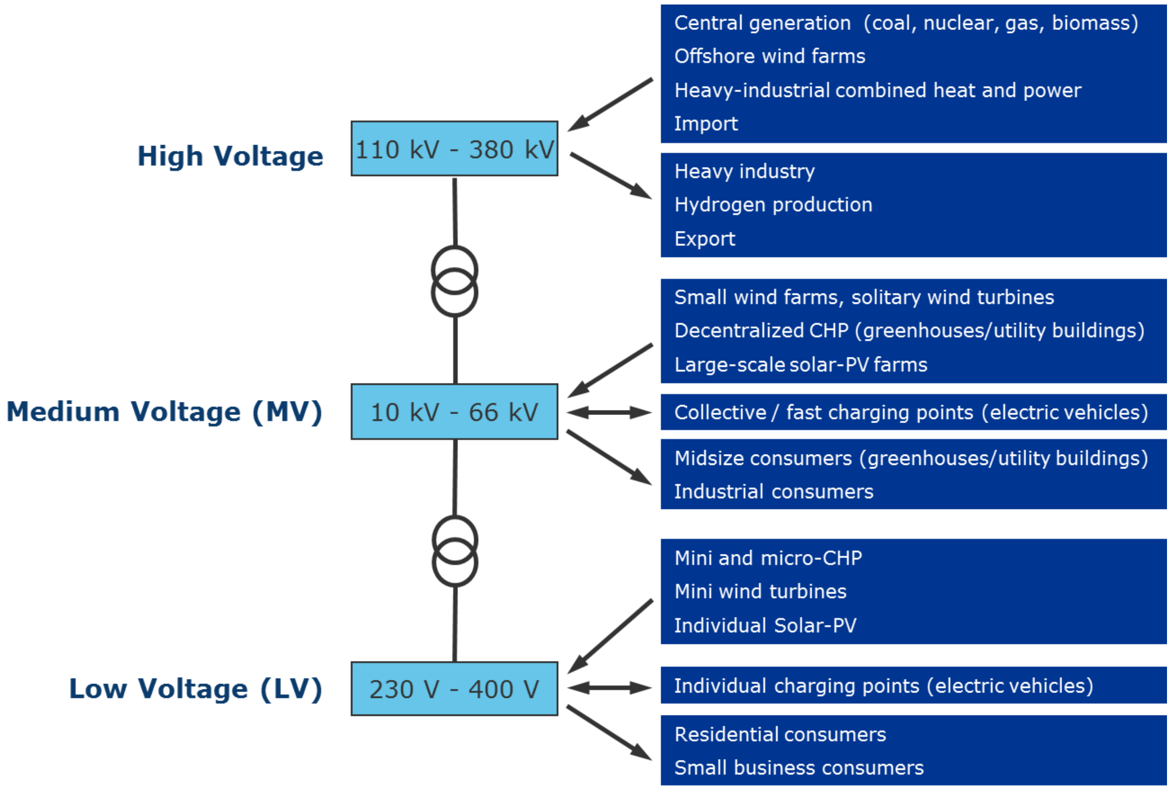

Figure 2-1 Characteristic structure and typical users of the Dutch electricity grid

The HV-grid is has to comply with strict rules for redundancy. A single or even double fault should not affect normal grid operation. For distribution grids (MV and LV) these strict rules do not apply. MV-grids are generally ring shaped that are designed to feed in from both sides. This increases the reliability. Low voltage grids are generally designed in a radial configuration.

This configuration is more or less the same in most European countries. There is one significant difference. In the Netherlands, most of the low and medium voltage grids consist of underground cables. Most other countries in Europe have a higher share of overhead lines. Generally this leads to higher grid losses (due to lighter and therefore thinner lines used). Also the higher grid resistance and higher grid reactance from overhead lines may lead to voltage problems for a lower penetration of solar-PV than in the Netherlands. These are grid local problems.

Table 2–5 shows final electricity use for each scenario in 2012 and 2030. It shows the functional use and added use for charging electric vehicles, for conversion to heat and for conversion to hydrogen. Hydrogen is used both for electric transportation and as an alternative for natural gas (either through an additional infrastructure or by mixing it with natural gas). Use as feedstock was out-of-scope for this scenario study.

Table 2–5 Overview of final use of electricity in 2012 and 2030 (PJ)

Final electricity demand [PJ]	2012	2030					
		scen. BAU	scen. A	scen. B	scen. C	scen. D	scen. E
Total	**431**	**529**	**455**	**550**	**523**	**506**	**571**
Functional demand	415 (96%)	456 (86%)	380 (84%)	456 (83%)	380 (73%)	253 (50%)	253 (44%)
Electric mobility	0 (0%)	11 (2%)	10 (2%)	11 (2%)	29 (6%)	37 (7%)	82 (14%)
Conversion to HT-heat	14 (3%)	28 (5%)	26 (6%)	35 (6%)	64 (12%)	56 (11%)	26 (5%)
Conversion to LT-heat	2 (0%)	33 (6%)	40 (9%)	47 (9%)	50 (10%)	65 (13%)	37 (6%)
Conversion to hydrogen	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	94 (19%)	174 (30%)

Table 2–5 shows that all scenarios assume a significant increase in electrification of the heat demand This increase is especially large for low-temperate (LT) heat generation. This is partly direct electric heating associated with a possible overproduction of renewable electricity and partly consumption by electric heat pumps. This offers potential for HEIs, power-to-heat, assuming that at least part of the heat is delivered through a third-party access heat grid.

Electrification of the heat demand opens up a possibility for power-to-gas options as well. Especially in scenarios were a significant volume of low-temperature heat is generated electrically, large seasonal variations may be expected. Power-to-gas offers seasonal storage capacity as will be discussed in section 2.2.2. The requirement for this seasonal storage capacity is diminished by significant energy conservation measures that diminish the demand for low-temperature heat.

Figure 2-2 shows the estimated residual load curves per scenario for the gross electricity consumption minus renewable generation. It includes all electric loads (conventional loads, heat pumps, electric vehicles etc.) and renewable (non-dispatchable) generation (solar-PV, wind). Hydrogen production and storage are excluded from the residual load because they can be dispatched (although there is a yearly production constraint for hydrogen). This graph shows some particulars of the scenarios:

- All scenarios show an increase in volatility, compared to 2012.
- The expected increase in load volatility because of solar-PV and wind generation is especially visible in scenario E.
- There are two extreme cold day's included in the reference weather conditions for these scenarios. In scenarios with a significant electrification of the low-temperature heat, this leads to a high initial consumption peak in de duration curves.

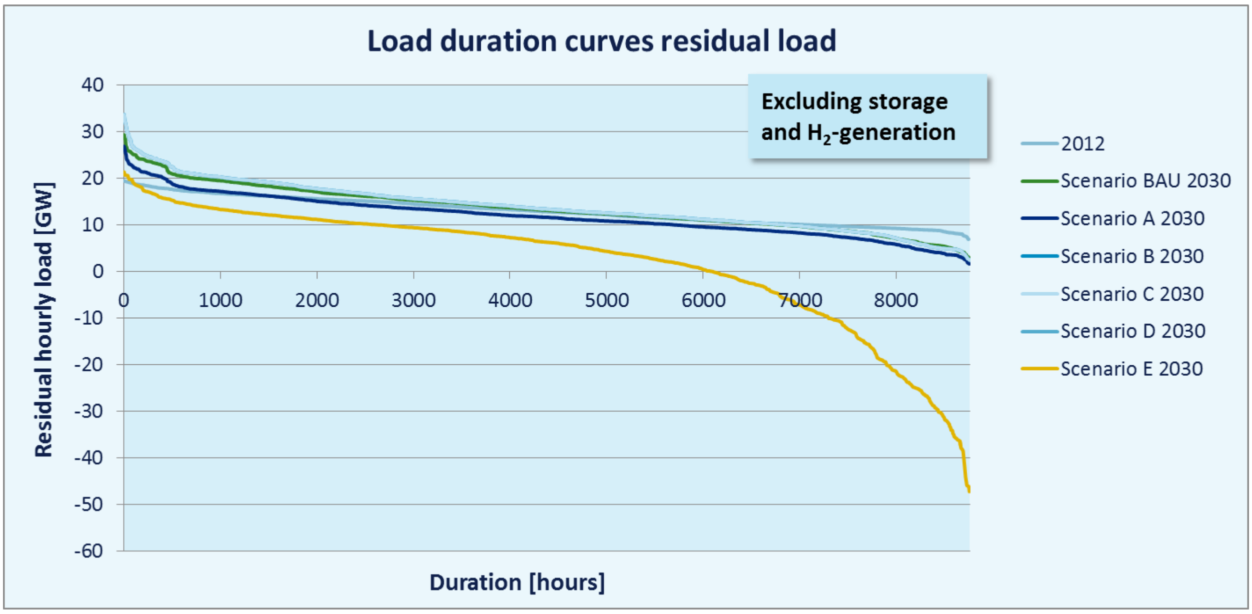

Figure 2-2 Load duration curve for the residual load per scenario

Figure 2-3 provides more detail in the seasonal variation of the electricity demand. The gap between average hourly load in the summer and in the winter increases in all scenarios, mainly due to electrification of the low-temperature heat generation. This will impact the requirement for reserve capacity to bridge seasonal variations and the potential for certain HEI-concepts. We want to stress that this seasonal variation depends significantly on the heat-pump technology used and the assumptions for representative climate conditions. In these scenarios, water-to-water heat pumps are assumed. Air-to-water heat pumps will significantly increase the electricity demand during cold days. The reference climate conditions refer to an average year that contains extreme days but not to an extreme (cold) year. Both may lead to higher seasonal variation in the electricity demand and for an increasing potential for certain HEI-concepts.

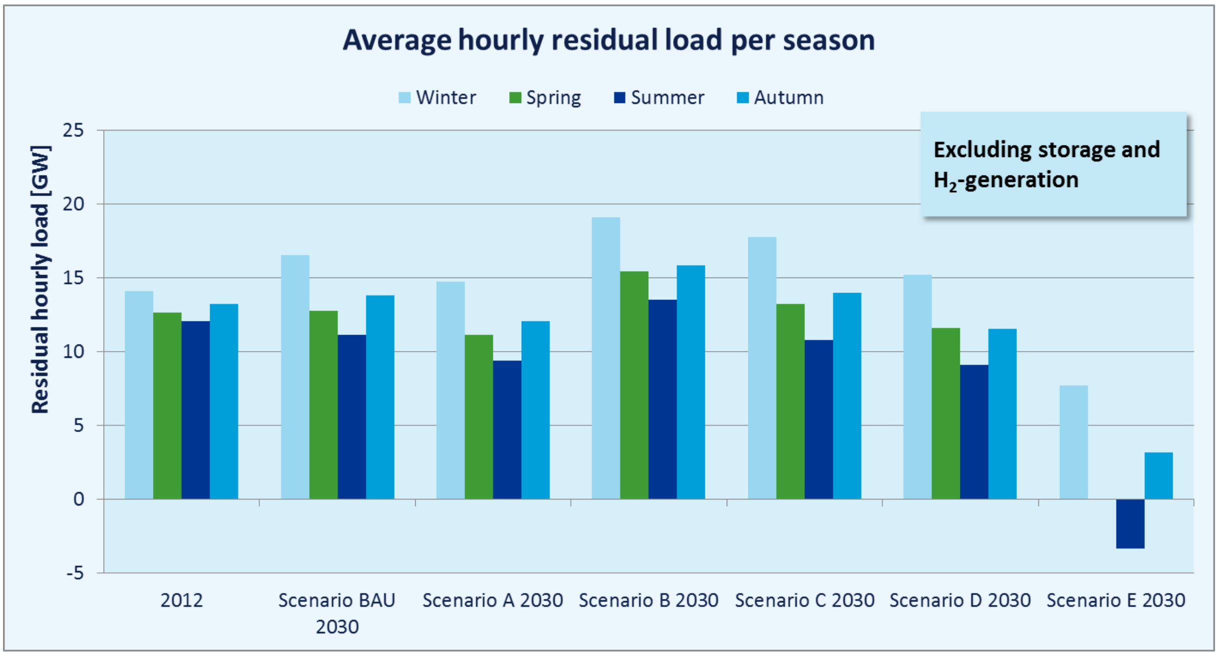

Figure 2-3 Seasonal variation of the average hourly residual load per scenario

The required grid capacity per grid section is shown in figure 2-4. Except for the LV-grid in scenario E the general picture for each scenario is the same: the HV- grid load and the MV-grid load are comparable to each other, the LV-grid load is much lower. In every scenario, the required grid capacity in 2030 increases despite electricity end-use conservation. For scenario B the required HV- and MV-grid capacity doubles compared to 2012.

The high LV-grid load in scenario E is caused by the high penetration of solar-PV on this grid level. Despite a relatively high penetration of electric vehicles and electric heat pumps, the LV-grid load in scenario D is not significantly different from the other scenarios (except scenario E). A higher grid load might be expected but this is probably offset by the significant conservation of end-use of electricity (50% compared to 2012).

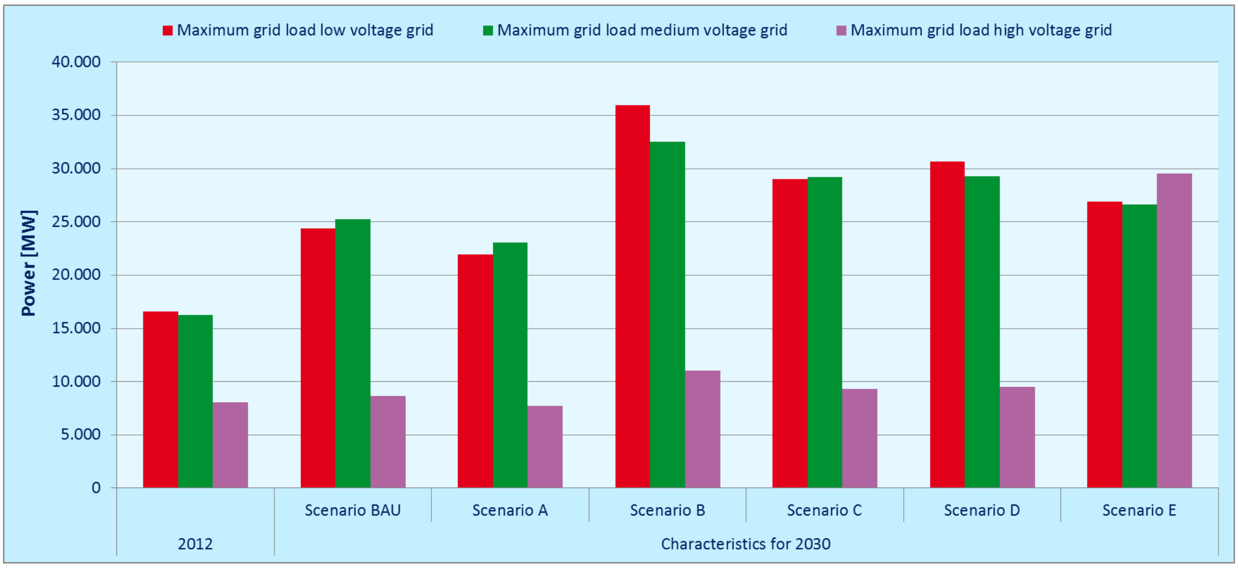

Figure 2-4 Grid load for the electricity grid for each scenario in 2012 and 2030

All scenarios show a significant increase in the application of electricity for heating purposes, both high-temperature (HT) and low-temperature (LT). The implications will be discussed in section 2.2.3. Scenario D and scenario E require significant hydrogen transportation and distribution capacity. This will be discussed in section 2.2.2.

The conclusion from this analysis is that electricity grids play a major role in each scenario. The required grid capacity increases for each scenario and major changes in grid configuration are not expected. A high penetration of solar PV will require a significant increase in LV-grid capacity, but most scenarios are not affected as the penetration of solar-PV is limited. The increased use of electricity for heating purposes is also a persistent trend throughout the scenarios. It suggests both an opportunity and a threat. The opportunity is the use of hybrid concepts to connect the electricity grid with local heat distribution grids and thus provide flexibility to the electricity grid using heat storage capacity in the heat distribution grid. Another opportunity is the use of the hybrid heat pump, which is power by either electricity or natural gas depending on the excess or surplus of energy or capacity in either network. The threat is that electrification of the heat demand will lead to higher seasonable differences in electricity demand and therefore higher need for seasonal flexibility options (reserve power, gas storage).

2.2.1.2 Alternative electricity structure (DC grids)

In the Netbeheer Nederland scenario study, DC-grids (direct current) are not explicitly included. The grid load and grid cost calculations are based on the traditional AC-grid configuration (alternating current). Currently DC-grids in the Netherlands on significant scale are limited to the DC transmission grid cables to e.g. Norway and the Dutch 1500 VDC traction grids for electric trains.

However, some parties[3]) envision a bright future for DC distribution grids. Possible advantages are lower grid losses and lower conversion losses (AC/DC-conversion). DC-grids are envisioned to accommodate electric charging, solar-PV generation and local electricity storage better than conventional AC-grids. Main question for this report is whether it has impact on the requirement for flexibility in the grid and for the development and assessment of hybrid infrastructures.

[3] Groot Gelijk, de toekomst van gelijkspanning in Nederland, ISBN/EAN 978-94-6186-334-8, 2014

We do not perceive that the introduction of local DC-grids will have a major impact on the flexibility requirements of the national grid. Although DC-grids as described in the document 'Groot Gelijk, de toekomst van gelijkspanning in Nederland'[4] suggest a local grid with local storage and local balancing of generation and load (including power-to-heat), this is not an exclusive feature of DC-grids. AC-grids offer these possibilities too. DC-grids will have an impact on grid losses and conversion efficiency, but we do not perceive significant impact on the potential for HEIs.

2.2.2 Gas infrastructure

2.2.2.1 Natural gas infrastructure

Currently, the main gas structure in the Netherlands is the natural gas infrastructure. The Netherlands has the largest connection density to the public natural gas grid in the world. Connection to the gas grid is common for most Dutch households. Exceptions are households that are connected to a distributed heating system (see section 2.2.3) and households in an all-electric residential area with electric heat pumps (see section 2.2.4).

One of the typical properties of the Dutch gas infrastructure system is the existence of three different gas qualities within one system. Households are supplied with Groningen-quality natural gas from the large 'Groningenveld' containing approximately 82% methane and 14% nitrogen (G-gas). This is the standard quality gas in the gas distribution grid. Exploration of other gas fields provides high calorific gas (H-gas) and an intermediate quality gas (L-gas). For gas transportation there are three different infrastructures, one for H-gas (used in Dutch electricity production units and industrial consumers), one for L-gas (export to Germany) and one for G-gas for domestic supply. Rather unique in Europe is that the Dutch TSO Gasunie provides services to maintain quality levels of G-gas, H-gas and L-gas. It operates several gas mixing units to this end.

Figure 2-5 shows the structure of the Dutch gas transportation and distribution grid for G-gas[5]. The transmission grid is divided into a national and a regional transmission grid. The nation grid (66-80 bar) accommodates production wells, import, export, gas storage facilities and probably very large industries that require unodorized natural gas for feed stock. The regional transmission grid supplies gas to large industrial consumers. Measure and control stations reduce the pressure to 40 bar and inject odorant into the natural gas. Central electricity generation and heavy industries are directly connected to the transmission grid by their own gas receiving station. Regional distribution grids distribute gas to mid-sized industrial customers. The national grid is operated by Gasunie Transport Services, the Dutch TSO.

[4] Groot Gelijk, de toekomst van gelijkspanning in Nederland, ISBN/EAN 978-94-6186-334-8, 2014

[5] Betrouwbaarheid van gasdistributienetten in Nederland, Resultaten 2013, Netbeheer Nederland report GT 140068 d.d. 24-04-2014

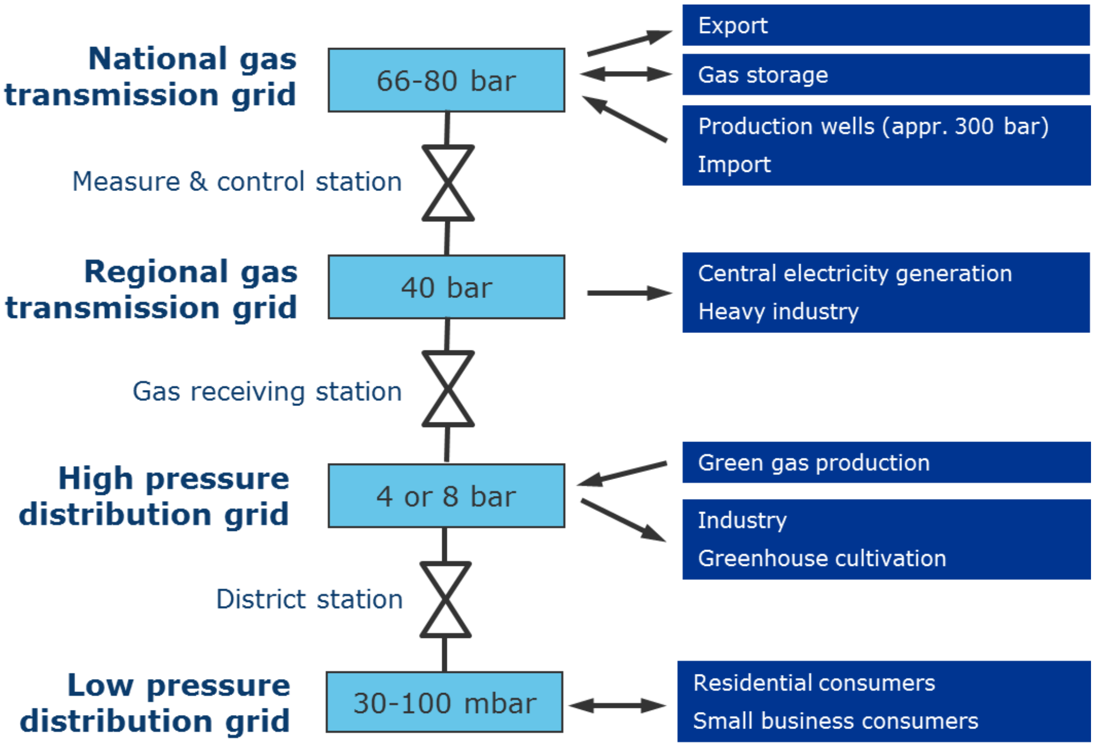

Figure 2-5 Schematic overview of the Dutch natural gas grid.

Distribution grids are divided into high pressure grids (4 or 8 bar) and low pressure grids (30-100 mbar). Industrial consumers, greenhouses and green gas production facilities are connected to the high-pressure distribution grid. Residential and small business consumers are connected to the low pressure grid.

The high pressure distribution grid is (like the 10 kV electricity distribution grid) ring shaped to increase the reliability of supply. Contrary to the low-voltage electricity distribution grid, the low-pressure gas grid is meshed with multiple feeding district stations.

Intrinsic storage capacity is available in the gas system itself (line pack). This provides capacity to more or less accommodate daily variations in the gas grids. For seasonal variations, subterranean gas storage is used (depleted gas fields or salt caverns). Dutch TSO Gasunie Transport Services (GTS) also operates a liquefied natural gas (LNG) terminal in the Maasvlakte (Rotterdam) for peak shaving during cold winter days. Table 2–6 shows current gas storage facilities in the Netherlands[6].

It is obvious from table 2–6 that gas storage provides much more power and volume than other electricity storage alternatives (although a conversion efficiency of e.g. 60% for a steam-and-gas unit must be factored in). If there is an absolute need for seasonal storage capacity, power-to-gas is probably the only feasible option. As such HEIs providing a link between the natural gas grid and the electricity grid unlocks a vast flexibility potential. We stress however, that this potential is in use already as every gas-fired unit uses the gas grid and the flexibility it provides. Hourly flexibility is not priced, as the imbalance settlement period (ISP) within the gas grid is internationally set on one day. Longer term flexibility (days to years) is priced in the natural gas market itself.

[6] Oil & Gas security, Emergency Response of IEA Countries, IEA report, 2012

Table 2–6 Overview of gas storage facilities in the Netherlands

Storage location	Type	Gas quality	Capacity (GW)		Working gas volume (TWh)
			input	output	
Grijpskerk (NAM)	depleted gas field	H-gas	13	22	32
Norg (NAM)	depleted gas field	G-gas	6	27	18
Alkmaar	Depleted gas field	G-gas	1,6	16	5
Zuidwending (GasUnie)	Salt cavern	G-gas	8	17	2,1
Bergermeer (TAQA)	Depleted gas reservoir	H-gas	20	28	48
Maasvlakte (GasUnie)	Gas storage tank	Liquefied G-gas		0,6	

Figure 2-6 provides insight in the maximum load of the natural gas grid. This load is excluding seasonable storage based on power-to-gas. The first observation is that the load of the gas transmission grid is very large (165 GW) compared to electricity transmission (16 GW). The energy density of the system is very high. The graph also shows a diminishing required capacity for natural gas grid. This is mainly due to factors discussed before:

- electrification of the heat demand
- energy conservation.

Especially in scenario D, the requirement for natural gas is low. In scenario E the gas grid capacity is used for transportation and distribution of green gas and hydrogen. Large part of the green gas volume is imported, the rest is produced locally. Table 2–7 show the gas mix used in each scenario. Notable is the decrease in green gas contribution in the BAU scenario compared to 2012, most likely a reflection of the current policy towards green gas.

Another important factor is the introduction of heat grids. In all scenarios heat grids emerge. EU-policy to reduce energy use of buildings will lead to an increased penetration of heat distribution grids. This will lead to an increase of "gasless" areas, mainly newly build areas but possibly also existing areas that switch from natural gas to heat distribution.

The role of natural gas will change from commodity to strategic fuel to deliver fast and reliable peak capacity to support the electricity system.

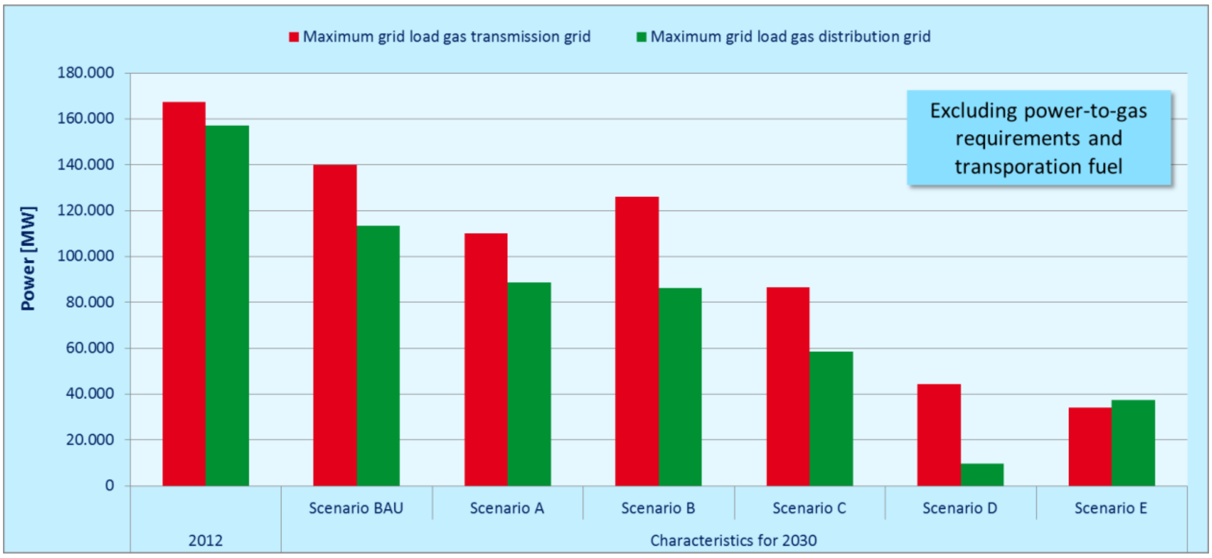

Figure 2-6 Grid load for the gas grid for each scenario in 2012 and 2030

Table 2–7 Average mix of gaseous fuel use

	2012	BAU	A	B	C	D	E
Natural gas	86%	95%	80%	80%	80%	60%	0%
Green gas	14%	5%	20%	20%	20%	20%	80%
Hydrogen	0%	0%	0%	0%	0%	20%	20%

2.2.2.2 Industrial gasses infrastructure

Besides the natural gas grid, other gas grids exists that may fit into a concept for a hybrid energy infrastructure grid. In the Netherlands, several pipelines for gaseous chemical components exist. These are:

- Ethylene and propylene pipelines;
- Hydrogen pipelines;
- Carbon monoxide pipelines
- Oxygen and nitrogen pipelines

Hydrogen pipeline networks and pipeline networks for nitrogen and oxygen are partly a part of a larger network operated by Air Liquide (figure 2-7). This network extends form the Rotterdam area, through Belgium to the north of France.

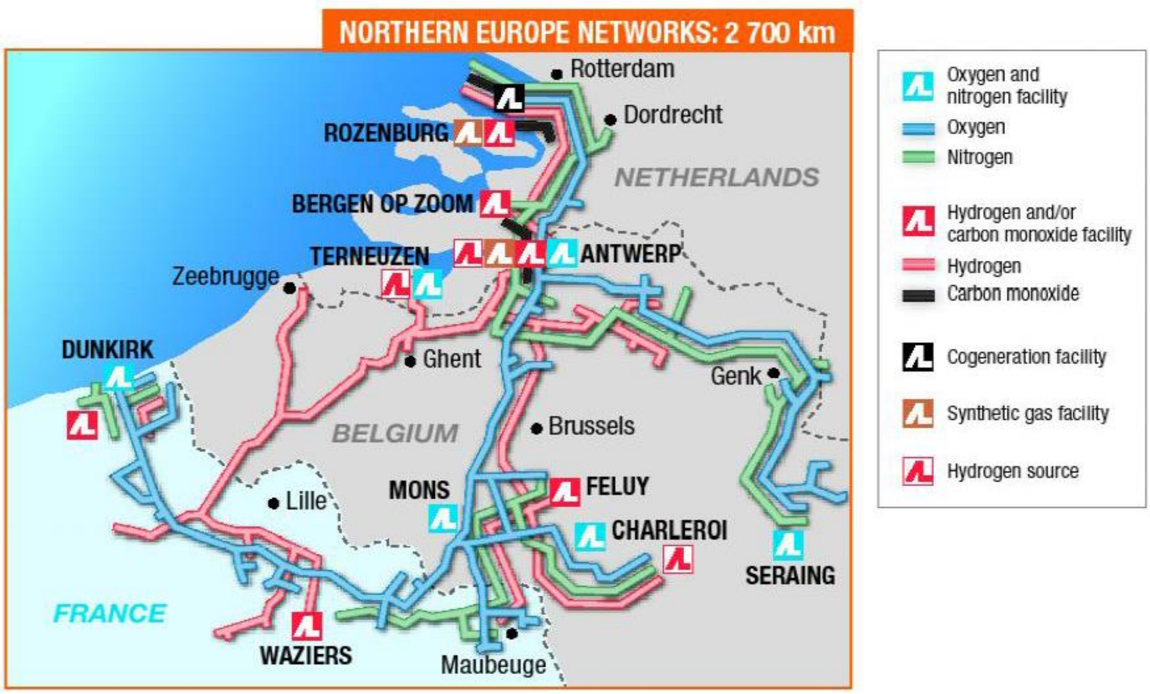

Figure 2-7 North-western European Air Liquide network[7]

Next to this network, there are several regional networks in the Rotterdam area, such as a dedicated hydrogen pipeline and a multicore pipeline (bundled pipeline for different commodities) including a nitrogen pipeline.

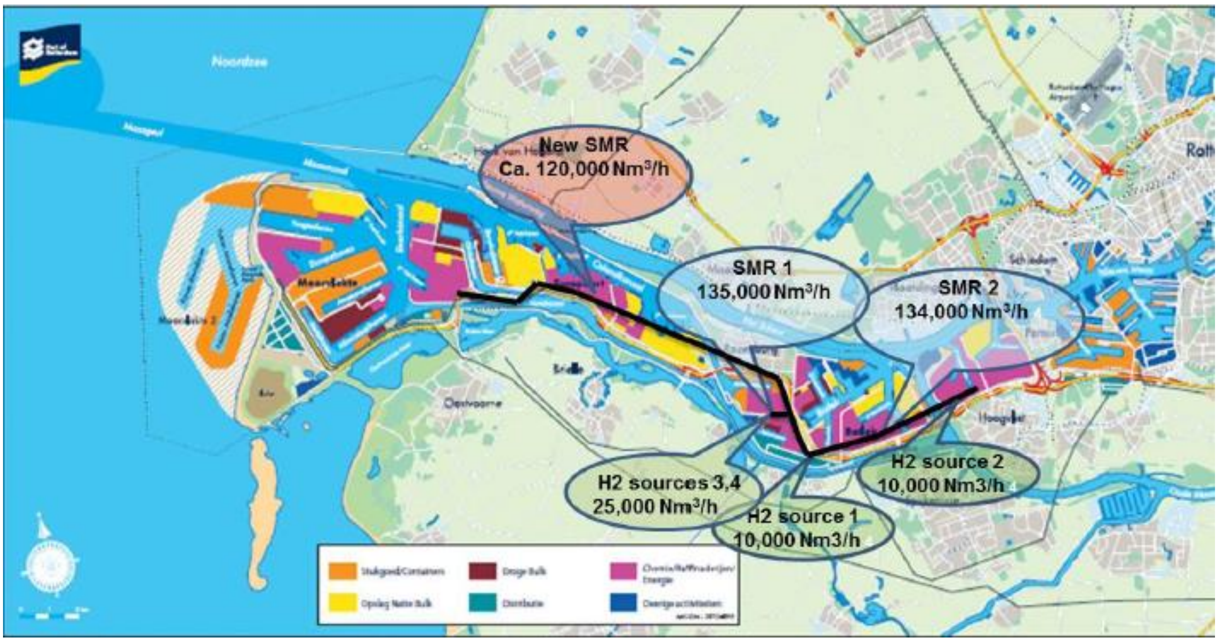

Figure 2-8 Rotterdam hydrogen pipeline[8]

[7] An Overview of the Pipeline Networks of Europe, European Chemical Site Promotion Platform (ECSPP), https://chemicalparks.eu, consulted 6 March 2015

[8] MER Project Lube Oil Hydrocracker en vergroting van de opslagcapaciteit van de kerosine, Tebodin rapport3312002, October 2013.

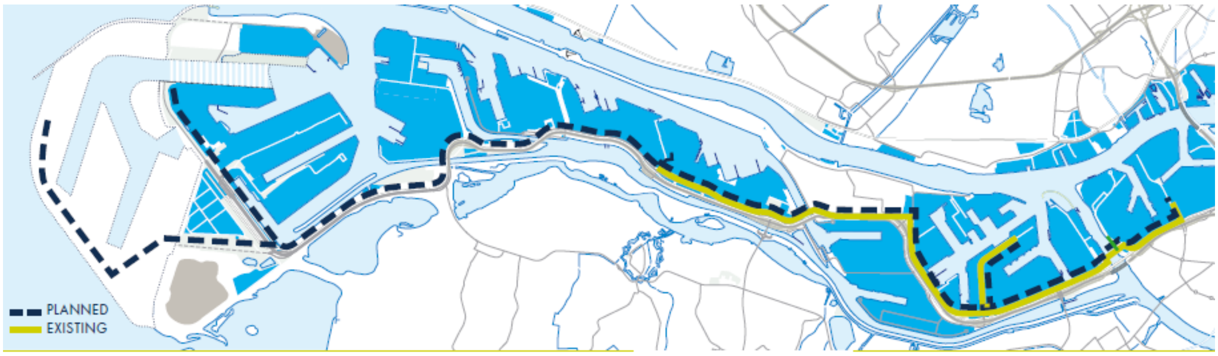

Figure 2-9 Rotterdam multicore pipeline

These pipelines provide third party access and storage capacity. Other commodities that are distributed via pipelines in this area are ethylene, propylene and carbon monoxide. A technology currently in early R&D stage is 'Plasma conversion of CO_2'[9], where electricity is used to activate a plasma that facilitates the conversion of carbon dioxide into carbon monoxide to enable further synthesis to fuels. A long term perspective is to use the local carbon monoxide infrastructure to distribute and store renewably generated carbon monoxide for fuel synthesis. However, as this technology is in early R&D stage, it will not further be addressed in this report.

The same hold for the nitrogen and oxygen production. Nitrogen and oxygen are produced by air separation, requiring electrically driven air compression and compression of commodities prior to injection into the pipeline. There is a direct link to electricity consumption:

- Maximize production with partial production and storage in cryogenic tanks of liquefied nitrogen and oxygen in periods with high power supply and low power prices and
- Ramping down production and regasification and injection of stored liquefied products in periods with low power availability and high power prices.

The electricity consumption related to the production of hydrogen and nitrogen can be adjusted. This is however the domain of demand response (see lot 4 of the TKI Energy projects which focuses on the role of end users).

Hydrogen and oxygen/nitrogen pipelines are relevant, as these commodities can be produced on the basis of excess power on the grid

- Hydrogen can be produced by water electrolysis; as described in paragraph 4.5.1. Water electrolysis allows for dynamic operation and fast start-up and shut-down provides excellent opportunities for following power excesses on the grid.

Especially in scenario D and scenario E, central generation of hydrogen can be matched with industrial hydrogen demand through existing or new industrial infrastructures. This fuel switch route is much more efficient than the power-to-gas route. Hydrogen is generally produced by steam reforming of natural gas. Switching to hydrogen from electrolysis leads to a simultaneous reduction of natural gas consumption. The alternative is the low-efficiency route of methanation of hydrogen. Thus the net effect of this fuels

[9] http://www.stw.nl/sites/stw.nl/files/Plasma_Conversion-Call_for_proposals.pdf

switch is a higher fuel efficiency. Implicitly this concept assumes that the natural gas infrastructure provides the necessary flexibility.

In scenario D and scenario E, industrial hydrogen grids are likely to be coupled to the natural gas grid to mix the imported green gas with hydrogen and thus provide a CO_2-free fuel for conventional distribution. Coupling with compression stations to supply compressed hydrogen for transportation purposes increases the flexibility of this system.

2.2.3 Heat infrastructure

Heat transportation and distribution with third party access is no exception in the Netherlands. An estimated percentage of 7-11% of the Dutch households is currently connected to a distributed heating system(10,11). Figure 2-10 shows three typical conventional configurations for heat distribution to residential customers and utility buildings.

Configuration A show an example of block heating: a group of apartments is served by a central heating system. This can be an individual boiler but might also be an electrical or gas driven heat pump combined with heat storage facility. Configuration B shows a small district heating configuration heat is generated by a combined heat and power unit (CHP) possibly with heat storage. An emergency boiler (EB) is available for peak hours and during maintenance or unscheduled outages of the CHP. Configuration C shows a heat transportation and distribution grid served by industrial waste heat. A heat transportation grid transports heat to sub stations (SS) were it is transferred to a distribution grid and metered.

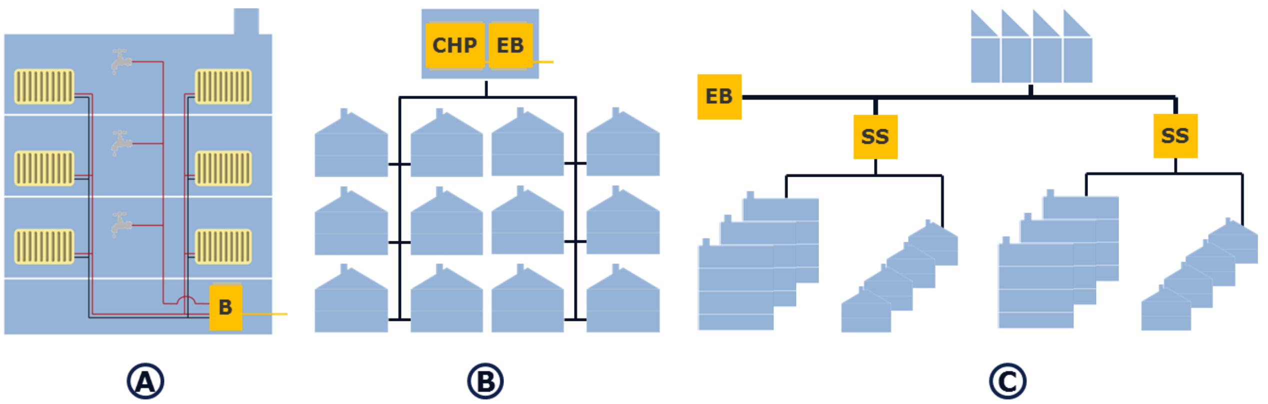

Figure 2-10 Typical configurations for heat distribution, A: block heating, B: small district heating, C: large district heating; B: boiler, EB: emergency boiler, CHP: combined heat and power unit, SS: sub station.

Figure 2-11 shows an example of plans for a heat distribution grid in the city of Roermond. Special in this project is the combination of waste heat distribution to residential areas with heat distribution to industries and distribution of cooling, geothermal heat and biogas.

Figure 2-12 is an example of a purely industrial heat grid were high temperature heat (steam) is generated by a waste incineration plant, a methanol factory and an industrial gas-fired combined heat and power unit. Low-pressure and intermediate pressure steam is delivered to other industrial plants.

10 Review weigeroptie voor de slimme (warmte)meter, DNV KEMA report 74104409-MOC/SET, 22 January 2014

11 Warmte en koude in Nederland, Nationaal Expertisecentrum Warmte, publicatie 2NECW1202, January 2013

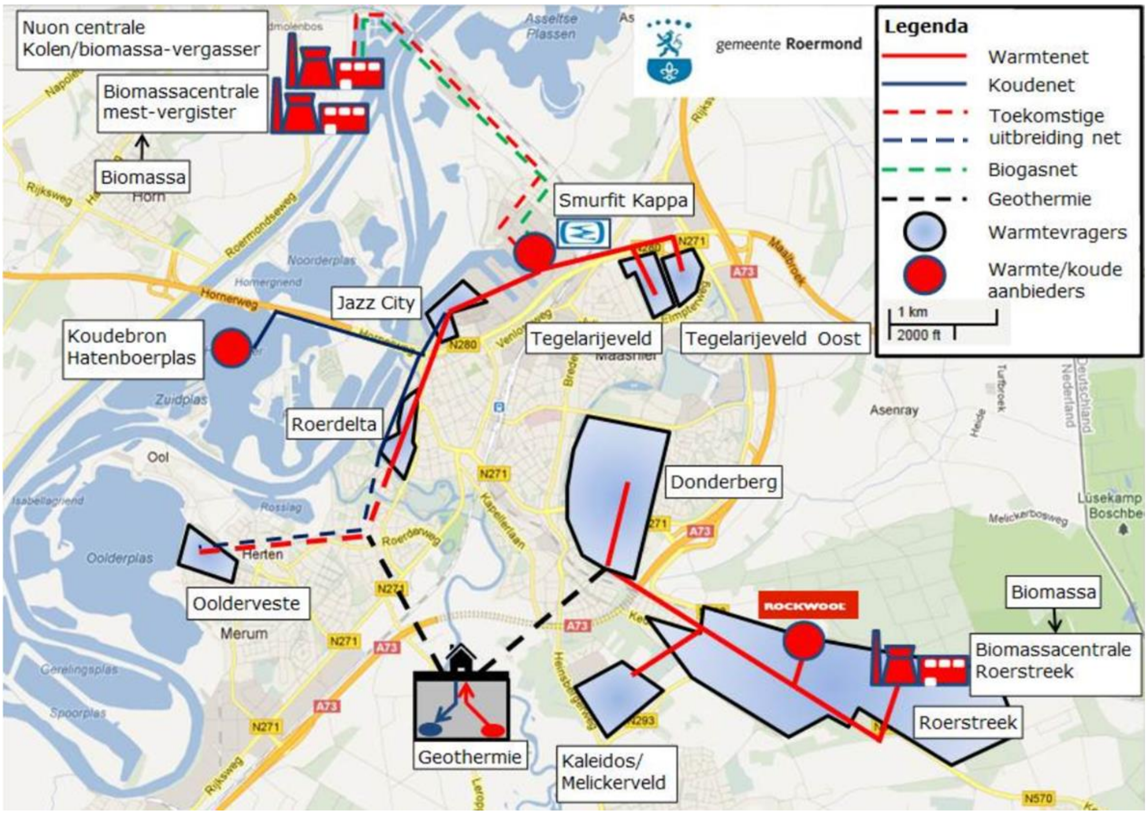

Figure 2-11 Example of plans for a heat distribution grid for residential and industrial customers, combined with distribution of cooling, geothermal heat and biogas[12].

Figure 2-12 Example of process heat distribution grid with third party access in Delfzijl[13],[14].

12 Warmtenet Roermond ontwikkelt zich, Innoforte Newsletter, Autumn 2012

13 Eneco koelt woontorens met Maaswater, nieuwsbericht gemeente Rotterdam, 17 June 2014.

14 Optimalisatie en verduurzaming Stoomnet Chemiepark Delfzijl, AkzoNobel,17 March 2014

Most scenarios show an increase in application of small and large heat distribution grids based on heat-cold storage in aquifers, geothermal heat, (industrial) waste heat and bio-CHP. These heat grids include low- and high temperature heat transportation and distribution. Table 2–8 gives an overview of main elements considered in these scenarios.

Table 2–8 Elements of heat transportation and distribution in the scenario's.

	Industry	Residential	Utility buildings	Greenhouse cultivation
Centralized high-temperature heat transportation	✓	✗	✗	✗
Centralized low-temperature heat transportation	✓	✓	✓	✓
Centralized low-temperature heat distribution	✗	✓	✓	✗
Decentralized low-temperature heat distribution	✗	✓	✓	✗

Dimensioning of heat grids is not part of the CE Delft/DNV GL scenario study. Qualitatively, heat grids evolve as follows:

- In scenario A industrial high-temperature heat demand and supply are matched by means of heat transportation. Industrial waste heat is not used in this scenario, leading to a diminishing penetration of low-temperature heat grids, compared to the BAU scenario.
- Scenario B assumes that 5% of the low-temperature heat demand is supplied by industrial heat. Decentralized generation of electricity diminishes, leading to phasing out of decentralized CHP. Both implicate a strong increase in the penetration of low-temperature heat grids.
- Scenario C assumes that 15% of the low-temperature heat demand is supplied by industrial heat. High-temperature and low-temperature heat demand and supply are matched and central generation and industrial CHP provide high-temperature heat for industrial applications. This all requires a strong increase in penetration of heat transportations and distribution grids.
- Scenario D resembles scenario B. It assumes that 5% of the low-temperature heat demand is supplied by industrial heat. Decentralized generation of electricity diminishes, leading to phasing out of decentralized CHP. Both implicate a strong increase in the penetration of low-temperature heat grids.
- In scenario E industrial waste heat is not available and/or not used. Still the penetration of high-temperature and low-temperature grids increases to be able to comply with a 100% renewable scenario.

Except for scenario A, all scenarios show an increase in the penetration of heat grids compared to the BAU scenario. All scenarios also show an increased electrification of the heat demand. Combining heat grids with (intrinsic or extrinsic) heat storage, electric heat pumps, direct electric heating, combined heat and power (CHP) units and (emergency) boilers, provides opportunities for hybrid energy infrastructures (HEIs). The CHP units and (emergency) boilers offer fuel switch capabilities while heat pumps and direct electric heating provide electricity sink opportunities, for instance if there is an overproduction of renewable energy (typically solar-PV and wind). Noteworthy are also hybrid heat pump concepts which also provide the fuel switch option (switching between electricity and gas).

Figure 2-13 provides an example of an industrial heat pump, used to upgrade low-temperature heat from a distribution grid to low-pressure steam. The residual heat from the electric heat pump is used to generate low-temperature heat for a heat distribution grid.

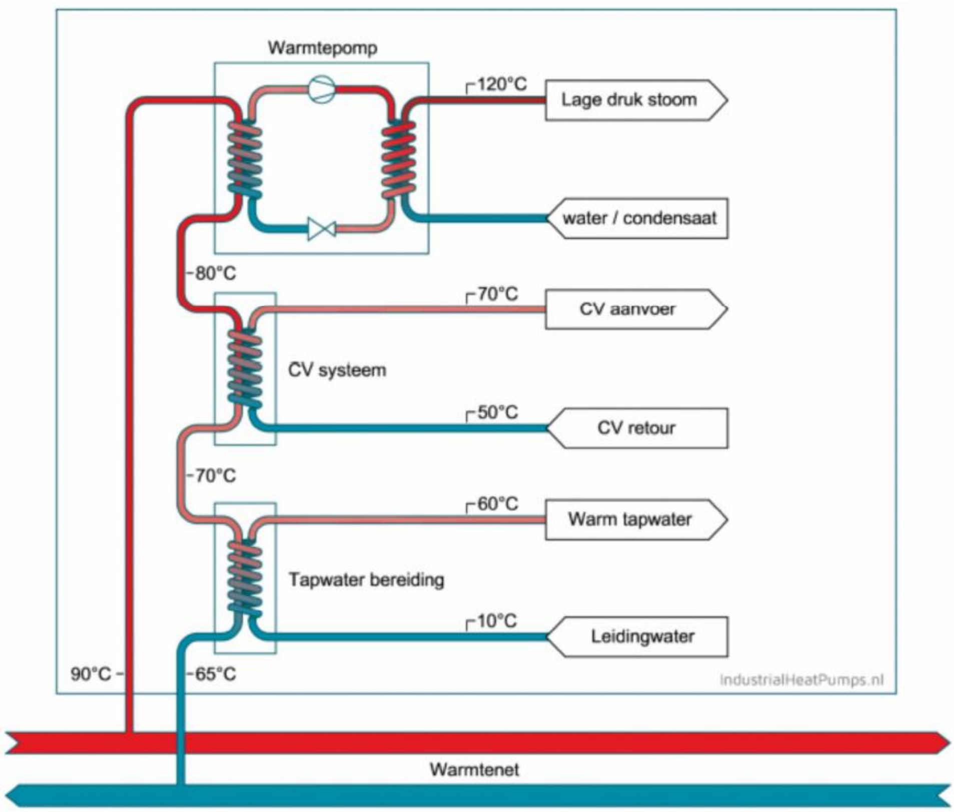

Figure 2-13 Example of heat pump in a heat distribtuion grid[15],[16].

2.2.4 Cooling infrastructure

Public cooling infrastructures are not yet common within the Netherlands. An example of such a structure is given in[17]. Office buildings and apartment buildings are cooled with water from the river Maas through an indirect cooling loop. Eneco provides this service on a commercial basis and claims 50% CO_2 emission reduction compared to conventional cooling.

Other examples of public cooling infrastructures are collective low-temperature grids for individual electric heat pumps in dwellings. These grids provide the low temperature heat (typically 12 °C) that can also be used for cooling purposes during summer time. Often these grids are sourced by aquifer storage

[15] Eneco koelt woontorens met Maaswater, nieuwsbericht gemeente Rotterdam, 17 June 2014.

[16] Industrial heat pumps, http://www.industrialheatpumps.nl/nl/toepassingen/warmtenetten/, consulted 16 February 2015

[17] Eneco koelt woontorens met Maaswater, nieuwsbericht gemeente Rotterdam, 17 June 2014.

systems. These systems store low temperature heat in aquifers 25-100 m below the surface. One of the main prerequisites for this type of storage is the yearly balance of loading and unloading the aquifer: each year must be in balance to avoid continued cooling or heating from the aquifer.

The potential for HEIs based on cooling grids is deemed low. A hybrid energy infrastructure based on cooling grids has to be coupled to the electricity grid by a compression cooler to deliver cooling power to the grid. The cooling grid concepts described above all lack a compression cooling step. The avoidance of compression cooling is one of the advantages of these cooling grids. We do not see viable reasons for developing public cooling grids based on compression cooling. Analogous to heat distribution grids, this kind of public cooling grid would only make sense if "free" cooling would available from (for instance) an industrial facility. This is an exception (e.g. LNG terminals).

Combined heat and cooling grids might offer potential. Figure 2-14 shows an example. This example is already discussed in section 2.2.3.

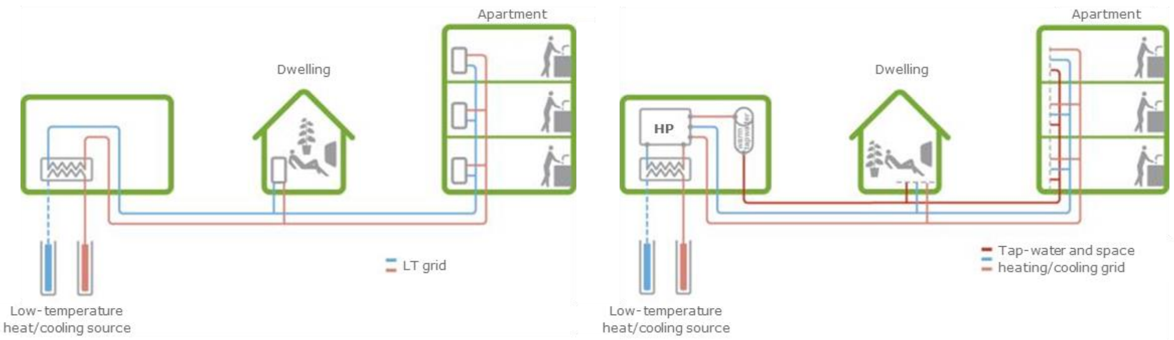

Figure 2-14 Example of a combined heat and cooling grid, to the left with individual electric heat pumps, to the right with a central heat pump[18],[19]

A feasible solution might be the control of the electric pumping capacity of the cooling grid. The pumping capacity, however, is only a small part of the cooling capacity. It might provide some potential, but is seems rather limited in volume. Furthermore, the storage capacity of cooling grids seems limited as the temperature difference is also limited.

2.2.5 Conclusion on the role of infrastructures

The electricity grid shows persistent growth in all scenarios, increasing volatility and an increasing "seasonal gap" in residual load could add up to 6,5 GW residual hourly load in 2030 (compared to 2 GW residual hourly load in 2012). Distribution gas network utilization is expected to be lowered significantly because of electrification of heat demand and district heating concepts.

Regional gas grids become increasingly important to serve peak heat demand (centralized CHP's), to accommodate green gas concepts and to provide system flexibility. Gas transmission infrastructure particularly plays an important role for energy containment, i.e. providing longer term flexibility and storage (months/seasons/years). Already today the Netherlands is connected to 2700 km industrial utility networks (oxygen, nitrogen, hydrogen). These networks are expected to acquire a more explicit

[18] Eneco koelt woontorens met Maaswater, nieuwsbericht gemeente Rotterdam, 17 June 2014.
[19] Brochures Vestia Energy Renewable Energy Systems, http://www.vestia.nl/PDFDocumenten, consulted 16 February 2015

role on the energy domain, allowing fuel switch concepts (e.g. electrolysis versus steam reforming for hydrogen production) to enhance energy system flexibility.

It is also observed that cooling networks emerge (common source for electric heat pumps, utility building cooling with river water/aquifer). Other examples are collective low-temperature grids for individual electric heat pumps in dwellings where the low temperature heat can also be used for cooling purposes during summer time. However, the potential for hybrid systems based on these cooling concepts is considered low. On the one hand we do not see viable reasons for developing public cooling grids based on compression cooling. Public cooling grids would only make sense if ‘free waste cooling’ is available locally. This limits the potential for utilizing flexibility; also storage of cold is rather voluminous due to the low delta in temperatures. Therefore its applicability strongly depends on the local situation.

Electrification of heat demand is prominent in all scenarios, advocating enhanced implementation of electric boilers & electric heat pumps and hybrid heat pump concepts. Industrial electric heating infrastructures (high temperature) and domestic district heating infrastructures (low temperature) become increasingly important.

3 LONG LIST OF CONCEPTS AND SELECTION CRITERIA

Because instantaneous electrical generation and consumption must remain in balance to maintain grid stability, variability in power generation can present substantial challenges to incorporating large amounts of intermitting renewable energy sources such as wind power into a grid system[20]. Intermittency and the non-dispatchable nature of such renewable sources can raise costs for regulation, incremental operating reserve, and (at high penetration levels) could require an increase in the already existing energy demand management, load shedding, or storage solutions or system interconnection with HVDC cables.
In situations of increased shares of renewable energy, the system will have an increasing power surplus which has to be accommodated. Theoretically two options are available:

1. Utilizing surplus power
2. Load shedding

The current study focuses on utilization of surplus power and considers a number of technical options that can be integrated into existing energy systems. In the remainder of this report these options are referred to as 'concepts'. The concepts considered in this project have been selected from a long list, compiled at project start. In Figure 3-1 we provide an overview of all potential valuable concepts, i.e. the long list. We illustrate how the concepts connect to different energy carriers (electricity, hydrogen, natural gas, heat and cold) and we provide a differentiation based on geographical scope.

In alignment with the scope of this project, these concepts are connected to at least two networks and provide access for multiple users (regulated/negotiated). For sake of completeness we also provide an overview of excluded concepts in Appendix 1.

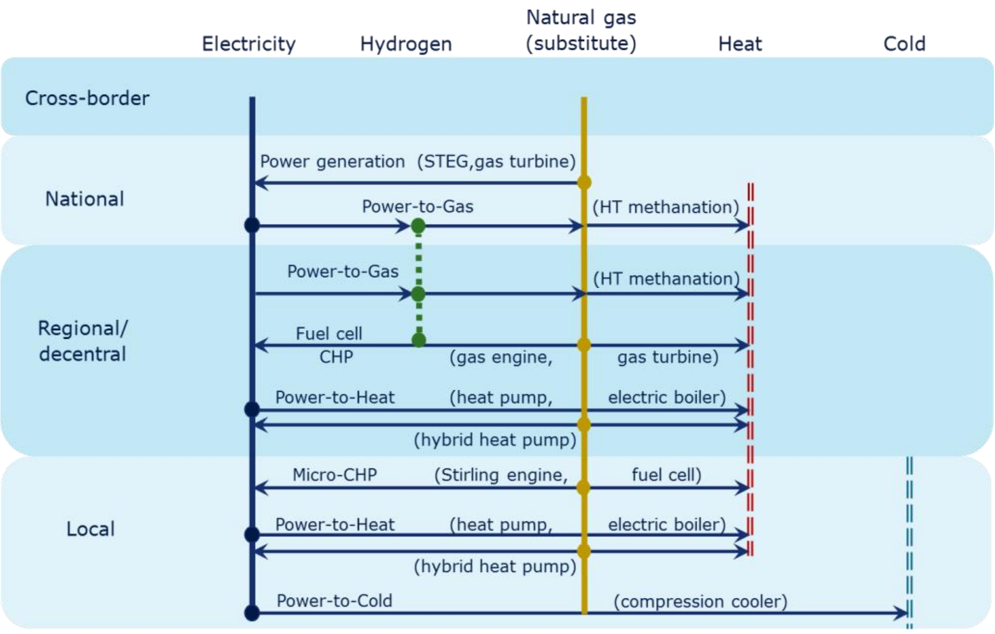

Figure 3-1 Long list of infrastructral system integration concepts.

From this list the considered concepts were selected based on following criteria:

[20] See: http://en.wikipedia.org/wiki/Wind_power_grid_integration

- The considered concept should be commercially available in the short run (<5 year).
- The concept should be implementable in existing energy system without need for critical changes in the energy system.
- The concept should be implementable on a relevant scale at least in the Netherlands and preferably also have potential on a global scale.
- The concept should allow for actively controlled utilization and should be continuously available.
- The concept should have the potential to be economic viable at occurrence of surplus situation during several hundreds of hours to a few thousands of hours per year - should e.g. generate products (hot water or steam, chemicals and fuels, etc) at compatible prices.

In view of the intended rapid short term increase in wind power and photovoltaic power there is a short term need for concepts that can be readily implemented on a relevant scale and that do not require further technological development. If the concept requires significant changes to the system into which it should be integrated, this will probably add to costs, delay implementation and reduce the available short and medium term potential.

The potential represented by the concept should be constantly and immediately available and should allow for active control. Otherwise, the potential may not be available in necessary volume when required. For storage systems this criterion means that stored energy should be readily available for transmission and transmission should allow for active control. Passive heat storage concepts for example do not meet this criterion.

Taking into account the above criteria and the criteria that concepts should be positioned at a coupling point between electricity networks and other networks and should have a form of third party access, the following concepts were short listed:

Table 3-1 Short listed concepts included in the analysis

Concept	**Reason for inclusion**
Power-to-hydrogen	Allows for coupling of power network and gas networks (dedicated H_2 networks, natural gas grids and biogas grids)
Power-to-methane	Allows for coupling of power network and natural gas or biogas networks
Electric heat pumps	Allows for coupling of power network and heat distribution networks
Electric boilers	Allows for coupling of power network and heat distribution networks
Hot water and steam storage facilities	Allows for economic optimization of management of heat supply and power generation (power generation) or power consumption (heat pump, electric boiler) on heat grids
Increased CHP flexibility	Allows for economic optimization of management of heat supply and power generation (power generation) on heat grids
Hybrid district heating systems (electric heat pump with gas fired boiler or CHP-unit)	Allows for coupling of power network, heat distribution network and natural gas network

4 DESCRIPTION AND ANALYSIS OF SHORTLISTED CONCEPTS

4.1 Introduction to selection of concepts

Energy system's flexibility is enhanced by coupling of infrastructures, enabling optimal utilization of the infrastructure's characteristics and potential. This coupling is facilitated by integration of energy conversion technologies into the energy systems infrastructures on locations where energy conversion adds value. The conversion technologies discussed in this chapter are physical assets that facilitate the following conversion:

- Conversion of a gaseous energy carrier into power (CHP, Micro-CHP, fuel cell, gas turbines and gas engines)
- Conversion of power into a gaseous energy carrier (power-to-gas concepts)
- Conversion of power into heat (power-to-heat concepts)

All concept groups and their relevant energy infrastructure and scale have been presented in the figure below. This figure no longer includes the concepts that were excluded from this analysis based on the criteria listed in chapter3.

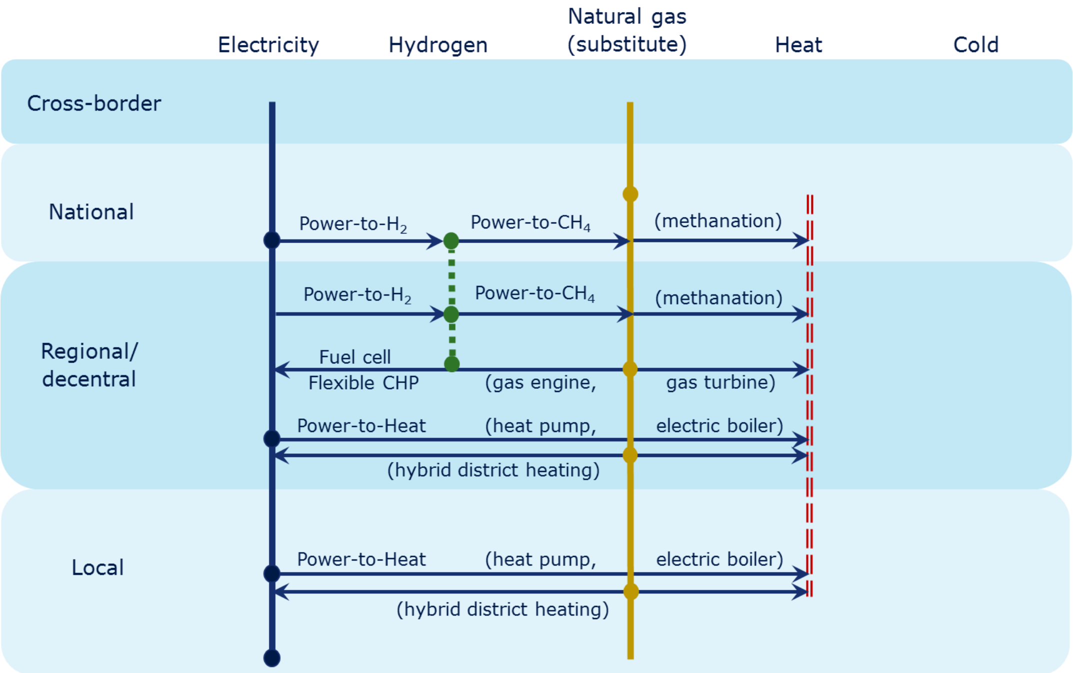

Figure 4-1 Concepts that are selected for futher analysis as concepts that facilitate in infrastructural system integration

The shortlisted concepts are discussed separately in the sections below.

4.2 Power-to-Heat

Both options discussed in this paragraph utilize low cost power for heat generation at either low level temperature (electric heat pump) or medium level temperature (electric boiler), which is subsequently supplied to a heat distribution network. Implementation of these options allows for conversion of surplus renewable power in periods of high wind power and/or PV availability.

4.2.1 Electric Heat pump in heating network

Heat pumps employ the same technology as refrigerators, moving heat from a low-temperature location to a warmer location. Heat pumps usually draw heat from the surroundings (input heat) and convert the heat to a higher temperature (output heat) through a closed process; either using compressor heat pumps (using electricity) or absorption heat pumps (using heat; e.g. steam, hot water or flue gas).

Heat pumps can deliver temperatures up to 90°C. Typical COP values[21] for heat pumps in district heating applications with CO_2 or NH_3 as refrigerant range from 2.5 – 3.2 when utilizing ambient heat.

Large heat pumps are available from 25 kW to 3-5 MW heat output. Heat pumps as heat suppliers to district heating networks are common in Denmark and are being implemented on a large scale in Germany. Large heat pumps are usually operated continuously. Large heat pumps are generally able to ramp up from cold start to full load in less than 5 minutes.

4.2.2 Electric industrial boiler

An electric boiler is used for producing hot water or steam directly from electricity. The heat can be distributed via a hot water or steam network. Two types of installations are available: electrode systems and electrical boilers.

Electrode systems

Electrode systems are used for larger applications (larger than a few MW's). In Denmark, larger electrode boilers (larger than a few MW's) are connected at 10 kV. Electrode boilers are available for capacities up to 70 MW_e. They have a net energy efficiency of 99% - 100% and can produce saturated steam up to 45 bar. One supplier also produces an electric super-heater[22], comparable to industrial electric air heaters.

The water in the electrode boiler is heated by means of an electrode system consisting of three-phase electrodes, a neutral electrode and control screens. Power is fed to the electrodes which transfer it to the water, thus heating the water. The current from the phase electrodes flows directly through the water, which is heated in the process. The current is a function of the active surface area of the electrodes and the water conductivity. The active area of the electrodes can be infinitely varied by operating the control screens, thus enabling output to be controlled between a minimum load of 10-20 % (depending on boiler size and voltage) and 100 %. One of world's leading supplier states following concerning ramp rates[23]:

- From cold to full load in less than 5 minutes
- 30 seconds from minimum to full load
- Minimum load is below 1%

Due to its very simple design, the electric boiler is extremely dependable and easy to maintain. The boiler has no built-in complex components which may impede operation and maintenance. The boiler has quick start up and is easy to regulate. From stand by to maximum production capacity requires seconds[24].

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[21] COP-value stands for coefficient of performance value and refers to the ratio between power input and produced and supplied amount of heat.
[22] See: http://www.acmeprod.com/user_pdf/ES_Series.pdf
[23] See: http://parat.no/en/products/industry/parat-ieh-high-voltage-electrode-boiler/
[24] See e.g.: http://www.gmitchell.ca/Precision/Product%20Litterature/Electric%20Products/HVJ/HVJ%20Detail%20Brochure%20Rev%206.pdf

Electrical boilers

Electric boilers are widely utilized in Sweden (> 1,000 MW_e) and Norway in both district heating systems and at industrial facilities, such as paper mills.

Electric industrial boilers have an efficiency of 99% and a technical lifetime of approximately 20 years. Nominal investment (M€/MW_{th}) amounts to 0.06-0.09 for a 10 MW_{th} boiler, and 0.05-0.07 for a 20 MW_{th} boiler. The costs do not include extra costs for connecting to the grid. Costs of strengthening the local grid and transformer station, if required, may be around 0.13 M€/MW_e.

4.2.3 Values for the power system

Penetration of electric heat pumps and electric boilers will allow useful application of surplus renewable power and avoiding of natural gas consumption and associated CO_2 emissions. At periods of high power production and low power prices, high temperature heat or steam can be produced electrically at production costs competitive to heat production based on natural gas.

For reserve power both technologies are not relevant as a direct power generation technology, the power-to-heat technologies consumes electricity and are intended for utilization of surplus power. However, as the technology can be ramped down or shut down very quickly, it could be regarded as interruptible capacity or 'negative' reserve power.

4.3 Gas concepts and hybrids

In this section gas based energy conversion technologies and hybrid configuration combining the gas based systems with electrical driven technologies are discussed.

4.3.1 Flexible CHP

The flexible operation of a combined heat and power plant (CHP) requires application of several specific technological components that allow rapid ramping up and down of production or a complete standstill for several hours, such as:

- Provisions to keep the gas turbine and the boiler warm during standstill, such as a valve in the chimney to avoid natural draft through the boiler and turbine. This allows for rapid start up and ramping up after short periods of standstill.
- Variable inlet vanes to reduce efficiency losses at part load (down to 60% - 70%).

These components, especially variable inlet vanes often are already installed in more modern CHP-plants. In case of temporary storage of heat in a buffer, the CHP-plant should also have sufficient production capacity to allow for filling of the buffer during production periods.

If no buffer for heat storage is included, heat must be supplied by supplementary firing in a Heat Recovery Steam Generator (HRSG) or by a separate boiler.

The start-up time for a CHP-plant after standstill for up to 8 to 12 hours of operation to full load amounts to 30 to 60 minutes for a large combined cycle (200-350 MW_e) system. For turbines of 20 to 50 MW_e the start-up time is 10 minutes for an aeroderivative[25] turbine to 20 minutes for a stationary turbine if measures have been included to keep the gas turbine and the boiler warm during standstill. In case of

25 Sources: http://www.power-eng.com/articles/print/volume-116/issue-1/features/large-aero-derivative-gas-turbines-for-power-generation.html

steam production by auxiliary firing in the HRSG, the gas turbine can ramp up faster, especially the smaller gas turbines (<60 MW) can ramp up at a rate of 20 %/minute. For larger combined cycle plants ramp up rate is limited to 3 to 5 %/minute.

Currently, approximately 20% of the industrial CHP-plants in The Netherlands is configured as 'must-run' or as partial spark spread configuration, concerning especially CHP-plants in chemical industry sector. CHP-plants in district heating networks also seem to operate as must run units in winter time. These plants could be made more flexible.

A number of implications and limitations related to the flexible operation of the CHP plants are observed. For example, frequent start/stop operations will result in increased maintenance costs. Also, options for part load production at 60% - 70% may be limited by the constraint that exemption from the energy taxes on natural gas is given for efficiencies higher than 30%. Efficiency in part load may decline below this constraint. In addition, for taxes exemption on natural gas more than 50% of supplied heat should be supplied by CHP-production. This precondition may limit possibilities for start/stop operations. Next to this, the more varying production profile of the CHP-plant may also have consequences on gas fees, as the gas supplier has to reserve transport capacity, while the capacity is utilized more infrequent.

4.3.2 Hybrid district heating

This concept entails the implementation of a centralized district heating system which is fed by a combination of an electrical heat pump and a gas fired heating system, i.e. CHP system or a gas fired boiler. The different options have been described below. Regarding the heat pump system, either ground water source heat pumps or air source heat pumps can be applied. Because of economic feasibility and the scale of district application it seems obvious to apply ground water source heat pumps rather than air source heat pumps, because these can also be operated when outside temperatures drop below zero.

The advantage of operating both systems hybrid is that they can be optimized in efficiency and supplement each other. Also hybrid operation enables to shift the balance between the energy sources based on the energy source commodity prices (or spot prices), i.e. when power prices are low (e.g. in times of high RES production) heating can largely be done by the electric heat pump, whereas when gas prices are relatively low, the CHP or gas fired boiler can be operated as primary heat source. Because of this, hybrid heating networks offer large flexibility, both to the power infrastructure and the gas infrastructure. Flexibility can be further enhanced when this concept is operated in combination with a heat buffer system.

Electrical heat pump / gas fired boiler combination

Hybrid heat pumps (or dual fuel heat pumps) combine normal electric heat pump functionality with a gas fired boiler system, enabling to shift between power and gas as energy source for heating. In smaller systems both functionalities are integrated in one single system, but the larger systems (including those for district heating) generally consist of a separate heat pump and a separate gas fired boiler. In order to optimize on the efficiency of the heat pump the most obvious system configuration would be a system connected in series, as presented in Figure 4-2 below.

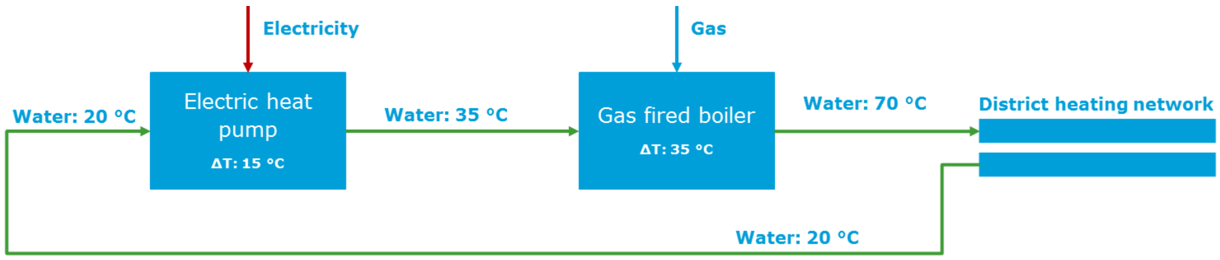


Figure 4-2 Simplefied schematic configuration of a hybrid district heating system based on an electric heat pump and a gas fire boiler.

In practice a by-pass over the heat pump is realized, enabling single source heating by the gas fired boiler. This is especially relevant in case an air source heat pump is applied, which cannot be efficiently operated when ambient temperatures drop below freezing point. In that case the operating philosophy will be as presented in Figure 4-3.

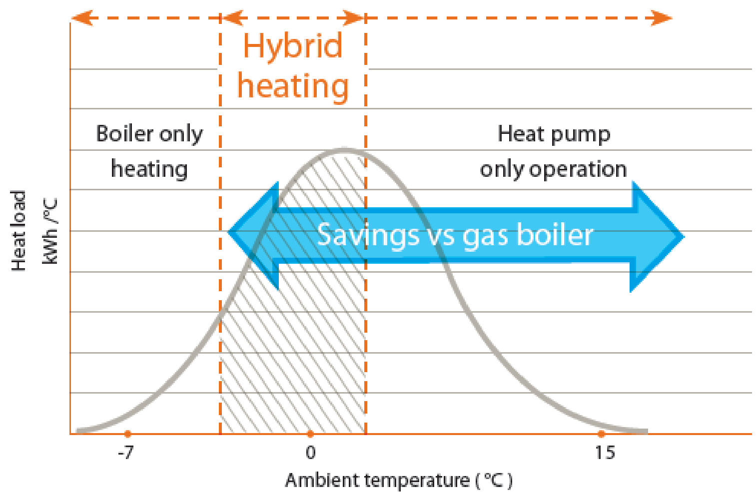


Figure 4-3 Operating philosophy of hybrid heat pump systems.

Electrical heat pump / CHP combination

The electrical heat pump in combination with a combined heat and power system enables to provide flexibility by the possibility to use both electricity and gas for the production of heat. In this system configuration the CHP produces electricity, which can be utilized by the heat pump system.

The system configuration is presented in Figure 4-4.

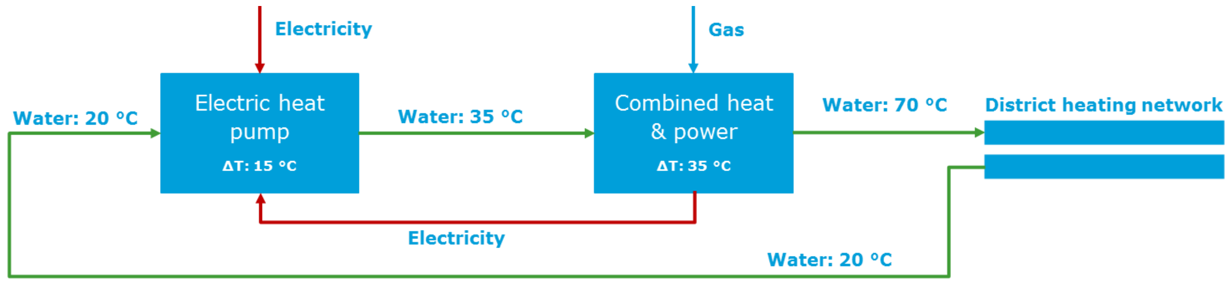


Figure 4-4 Simplefied schematic configuration of a hybrid district heating system based on an electric heat pump and a combined heat and power system.

4.3.3 Values for the power system

The concepts that include a CHP system offer (reserve) power production in times of low RES production or at times of high power prices. In combination with heat networks heat is supplied simultaneously. The combination of a flexible combined cycle plant with capacity to run in part-load mode with a storage facility for heat allows for decoupling of heat supply and power generation. This in turn allows for power generation to be limited to periods of sufficient demand on the grid and at sufficiently high power prices. As indicated, with fast reserves of up to 20% per minute for hot HRSG's the combined storage and CHP can attribute to frequency restoration/replacement reserves (15 minutes Program Time Unit (PTU), imbalance markets) and hourly and daily reserve power. Power generation can be stopped or ramped down during periods with e.g. high supply of renewable energy and associated low spark spread. The combination of a CHP unit with a storage facility and associated additional operational flexibility in power generation may offers flexibility and stability for regional grids (gas engine and small gas turbine CHP's) and 110 – 150 kV high voltage grids (larger CHP's, district heating CHP's). Whether this also leads to reduced or deferred investments for grid reinforcements depends on the total installed capacity relative to grid transport capacity. In case of oversupply of wind power on the high voltage grid, grid load on the 110 – 150 kV grids and regional grids may be balanced to demand and to grid transport capacity by ramping down CHP production capacity to levels tuned with grid transport capacity. In case of power deficit on the high voltage grids provision of power by CHP's may however be restricted by regional grid capacities and transformer capacities or – in case of shortage on the 220 and 380 kV grids the capacities of the 110 – 150 kV grids and the capacities of the transformer stations between both types of high voltage grids.

Figure 4-5 Map of the Dutch high voltage power grid.

The potential for implementation of these options is not precisely known yet and more insight would require a further consideration of the CHP-facilities in The Netherlands and of their operational patterns.

Value is added through reduction of fuel consumption (less start/stop cycles) and by allowing power production with the most efficient and economic unit at a certain time.

Hybrid systems including electric heat pumps and gas fired heating systems (either CHP's or gas fired boilers) have the advantage of enabling optimization on efficiency and economic use of the technology itself and optimal use of infrastructures. These systems are able to provide additional power load demand when power is oversupplied and can generate power from gas in times power consumption tends to overshoot supply. When applying this on district level, in combination with a district heating network, local grid investments that aim for facilitating the electrification of heat demand at household level can potentially be avoided.

4.4 Storage in heating infrastructures

Two storage options are known:

1. Storage of hot water in a tank for low temperature district heating and heating networks in horticulture.
2. Storage of medium temperature storage in molten salt storage facilities.

Storage facilities for hot water and steam allow for a partial decoupling of heat and power infrastructures. Hot water storage can be integrated with hot water heat distribution infrastructures such as district heating and heat supply networks in horticulture. The warm water to be stored can be supplied with heat pumps, electric boilers, CHP's and combinations. Steam storage facilities can be integrated with a steam network to which multiple users have access. The steam intended for storage can be supplied by electric boilers and CHP-plants. Both options are discussed in separate sections below.

4.4.1 Heat storage in district heating

Storage in the form of hot water in a buffer tank is part of a heating network fed by a CHP. The buffer is filled with hot water during periods with low renewable energy availability and high power prices and supplies heat during periods with high renewable energy availability and low power prices, during which period the CHP plant is shut down or operates in part load.

Typical investment costs as a function of storage capacity are given in Figure 4-6.

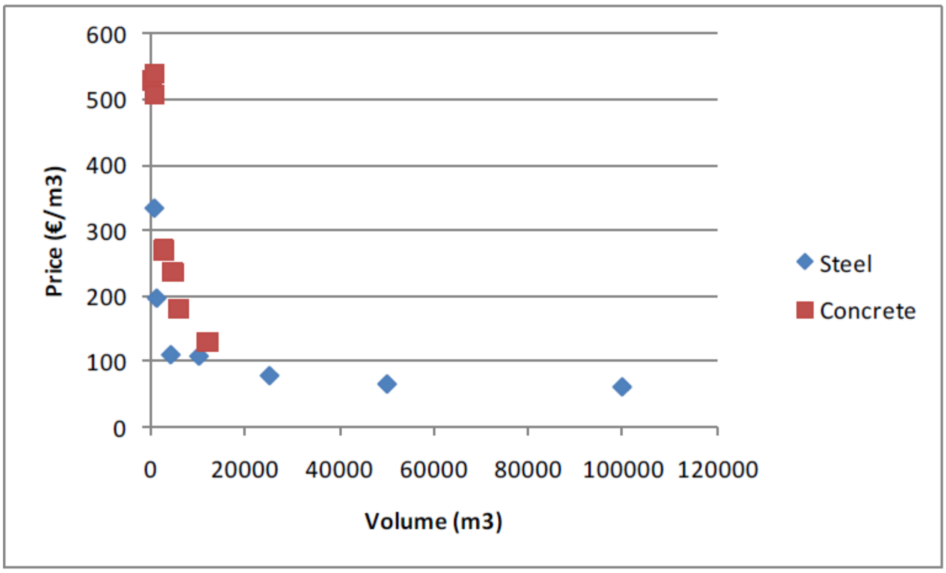


Figure 4-6 Price in €/m^3 (2011 price level) as function of storage volume in m^3

Hot water buffers have been applied in heating networks for several decades; see e.g. the district heating networks in Purmerend and The Hague. They can be considered common technology and present no technological challenges.

Though the application is quite common in The Netherlands, there is still room for additional capacity as illustrated by the construction of a new storage tank at NUON's Diemen 33 and Diemen 34 power plants.

In addition, existing storage capacity in The Netherlands may not be optimized to future market dynamics given their limited storage capacity. The storage tank constructed at Diemen has a storage capacity for supplying heat at maximum heat demand for 5 hours. In Denmark, CHP plants often have heat storage capacity to cover the heat load for a full week during the cold season. The largest tanks are above 50.000 m3. Limited storage capacity means limited time during which heat supply and power generation can be decoupled. On the other hand supply of warm water takes place mainly during wintertime, so that flexibility is mainly relevant for scenarios with large penetration of wind power.

4.4.2 Industrial high temperature heat storage

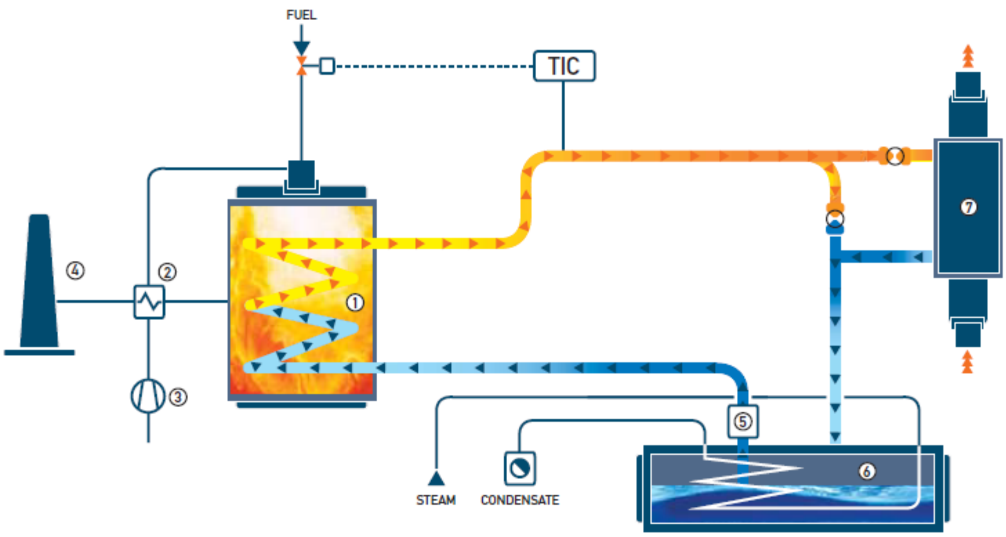
Industrial high temperature storage is generally applicable to steam networks in industrial areas. Examples of steam networks assessable to third parties include Stoompijp Rotterdam and the steam grid in the chemical industry cluster in Delfzijl.

Medium temperature storage facilities are generally based on molten salt or thermal oil as a storage medium. As with low temperature hot water based storage, medium temperature storage is based on storage of heated molten salt mixtures or thermal oil in cylindrical insulated tanks.

Molten salt based and thermal oil medium temperature storage have been applied in concentrated solar power (CSP) plants since 2008 (Andasol 1, Spain[26]). The system allows CSP's to produce power during nightly hours and clouded days. The applied system consists of two tanks, one for cooled and one for heated material. The cool salt or oil is heated by concentrated solar radiation and is subsequently stored in the second tank. The stored heat is used for generation of superheated steam, which in turn is used for driving a steam turbine and generator. Storage capacities applied range from several hours (2 – 3) up to 15 hours of full load power generation.

Molten salt and thermal oil are also applied in chemical industry and mineral processing industry in applications where high temperature heat (> 400°C) is required while preventing direct contact of the desired flammable product with a fired heater. In addition, the final product is brought uniformly to the desired process temperature of up to 600 °C without any local overheating. The technology is used for the manufacture of artificial fibres, synthetic resins (melamine), caustic soda, aluminium oxide and dyestuffs, together with applications in the textile and food industries.

[26] See: http://en.wikipedia.org/wiki/List_of_solar_thermal_power_stations



1. heater with burner, 2. air preheater, 3. combustion air fan, 4. Stack, 5. salt pump, 6. steam-heated salt tank, 7. heat user

Figure 4-7 Generalized flow sheet for heat supply with molten salt as heat transfer medium

Thermal oil can be utilized for temperature ranges from approximately 20°C to 300 – 400 °C[27], limited by thermal stability and evaporation. Thermal oils have a density of 0.9 – 1.0 mt/m^3, a specific heat of 2 kJ/kg·°K and tend to cost €2/kg - €4/kg.

As indicated above, there is no practical experience yet with such dynamic heat production from e.g. electric steam boilers etc. Additionally, for molten salts no long term there is experience with regard to corrosion and other potential operational issues.

4.4.3 Values for the power system

Heat storage facilities enable decoupling of the power or gas demand for heating and the heat demand, by buffering the heat. Hence, heat storage facilities enhance the flexibility of heat networks and heat demand as part of an integrated energy system. Heat can be supplied while the heat generating CHP is shut down during periods with low power prices or while the heat pump or electric boiler are shut down during periods with high power prices. The other way around, heat can be stored in periods in which there is no heat demand, but in which it is economically attractive to produce heat because of low (heat pump, electric boiler) or high (CHP) power prices.

4.5 Power-to-Gas

Power-to-gas entails the conversion of electrical power into a gaseous energy carrier (hydrogen and/or methane). Power-to-gas is seen as an important enabler for the energy transition as it facilitates in the integration of renewable energy by accommodation of (volatile) power in the gas infrastructure and thereby offers flexibility to the power sector and potential for decarbonisation of the gas sector.

[27] http://www.dow.com/heattrans/products/synthetic/dowtherm.htm

Figure 4-8 provides a schematic overview of the conversion pathways of power into gas and optional sequential conversion possibilities. The figure clearly shows that electrolysis is the first step in the power-to-gas process. Hydrogen application in hydrogen infrastructures, direct blending of hydrogen with natural gas and further conversion to methane are of primary focus in this study (this is infrastructure related). The actual industrial application of hydrogen is left out of scope (based on the 'third party access' criterion).

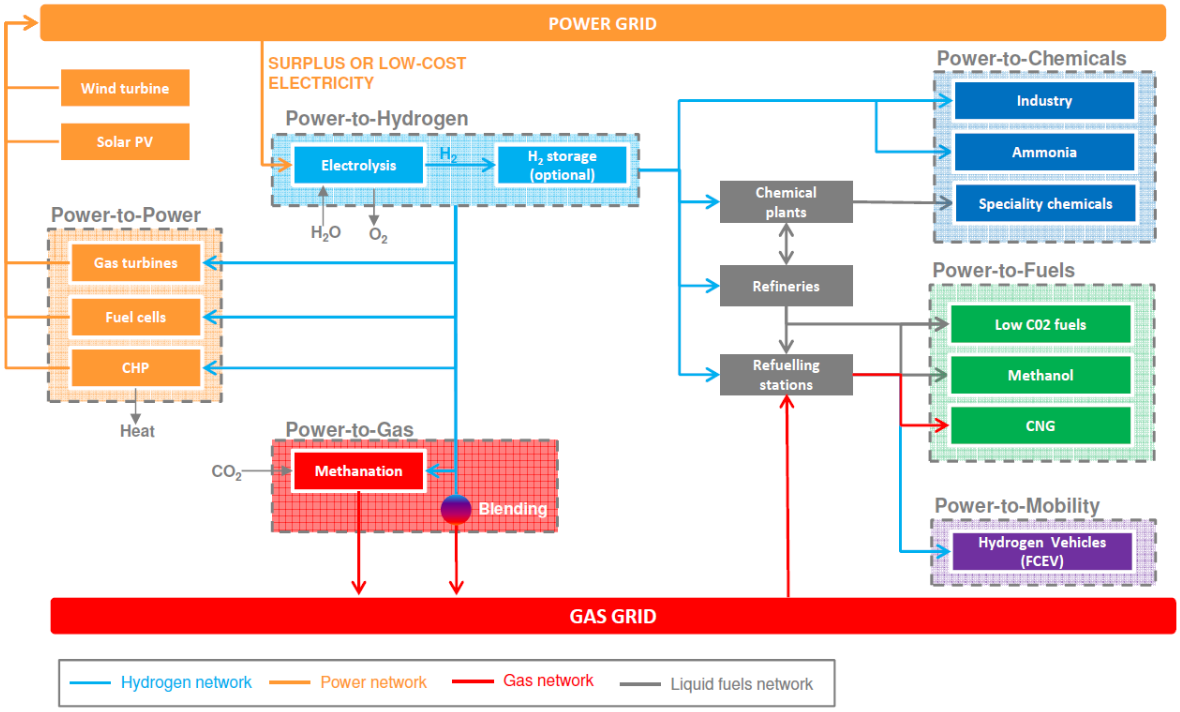


Figure 4-8 Schematic overview of power-to-gas conversion pathways[28]

In 2014, the TKI supported project report "Exploring the role for power-to-gas in the future Dutch energy system" (by ECN & DNV GL) was published. It concluded that power-to-gas can be regarded as a robust part of the mix of energy technology options required to achieve deep CO_2 emission reduction targets in the energy system (-80% to 95% in 2050) at the lowest possible cost to society. It was found that its role is of primary value for decarbonization services (as natural gas substitute) and that flexibility services in the form of demand response are of secondary importance. However, the flexibility services are essential to realize the technological, managerial and market development that enables its robust role for decarbonization in 2050.

4.5.1 Power-to-Hydrogen

Within the domain of power-to-gas the production of hydrogen by means of water electrolysis is the first step in the chain. Electrolysis describes the splitting of water into hydrogen and oxygen, driven by an electrochemical reaction: $2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$. Besides hydrogen, the process produces oxygen.

[28] Hydrogenics, Commercialisation of Energy Storage in Europe, Fuel Cells and Hydrogen Joint Undertaking, presented by Denis Thomas at the North Sea Power-to-Gas Platform meeting, February 2015.

Different techniques for water electrolysis can be identified: alkaline water electrolysis (commercially available) and proton exchange membrane electrolysis (PEM; pre-commercial) are the most common and available techniques. Related to the demand response function of power-to-gas PEM technology is preferred over alkaline, as its performance capabilities allow for dynamic operation and fast start-up and shut-down. PEM is capable of responding within seconds to fluctuations in the electricity grid and in minutes from cold start to full capacity. Also the total cost of ownership of PEM technology is foreseen to be better than that of alkaline. Solid oxide electrolysis (SOE) is still in a research phase and currently not commercially available. Besides that, SOE is a technology that (by its chemical principle) needs to be operated in steady state, not allowing for dynamic operation[29].

Centralized vs decentralized

Conceptually the technology can be applied in transmission grids and distribution grids and is relevant for industrial application as well as regional and local application. Considering the demand for hydrogen and the market value of hydrogen, the obvious locations for power-to-hydrogen plants would be either at fuel stations (small scale, few MW's; decentralized) or at hydrogen demanding industry (large scale, tens to hundreds of MW's, centralized in industrial area). Injection in gas grids is interesting because of the availability gas grids throughout the Netherlands, but it is economically less favourable than direct hydrogen application. Additionally the existing gas infrastructure does not allow for blending of (large) quantities of hydrogen into natural gas. This is because addition of H_2 lowers the Wobbe and thus the thermal input of gas. Thereby, the addition of hydrogen changes the primary air ratio on end-user appliances. The high calorific gas H-gas infrastructure offers a wider Wobbe band than the low calorific L-gas and G-gas (Groningen gas) infrastructure and thereby offers more possibilities for injection of hydrogen. As can be distilled from Figure 4-9, hydrogen admixing possibilities in L- and G-gas are significantly smaller than the possibilities for admixing with H-gas. The graph shows that the hydrogen admissibility is strongly dependant on the Wobbe-index of the gas that is in the pipe, possibly ranging between 0%-40% H_2 admixing in H-gas and 0%-10% in L-gas networks (low calorific gas networks). In case the natural gas is very low in Wobbe, no hydrogen can be injected, whereas in case the natural gas is very high in Wobbe, significant amounts of hydrogen could be injected. It should be noted that this graph and related percentages are based on the effects of hydrogen on Wobbe only, neglecting the effects of hydrogen on burning velocity (potential risk for 'flash-back') and other effects.

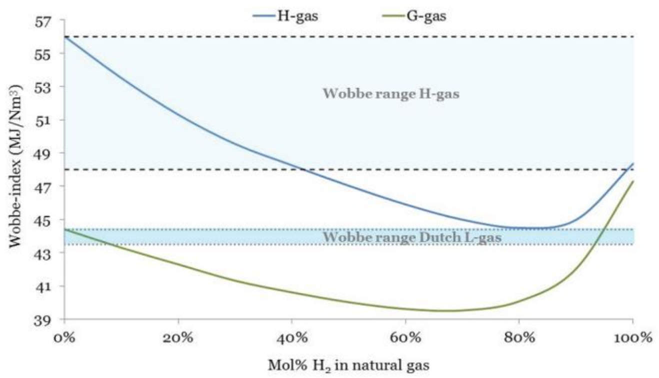


Figure 4-9 Effects of hydrogen admixing on wobbe-index of natural gas[30].

[29] Grond, L. J.; Holstein, J. and Schulze, P.: DNV KEMA (2013) Systems analysis power-to-gas; Technology Review.

[30] Gersen, S. (2014) What are the challenges of hydrogen addition to natural gas? Towards a successful introduction of hydrogen. Presentation at North Sea Power to Gas Platform, September 2014 Dusseldorf Germany.

Small scale power-to-hydrogen plants involve medium or low voltage power infrastructure and medium or low pressure gas infrastructure. For this purpose hydrogen injection is limited by the G-gas quality standards for injection. Large scale power-to-hydrogen plants most likely involve high voltage power grids and medium-high pressure gas infrastructure or dedicated hydrogen networks (in industrial areas).

Concluding
The power-to-hydrogen configuration enables coupling of the power infrastructure with the gas infrastructure. System integration complexity relates to the limited tolerance of the existing gas infrastructure to accommodate (large quantities of) hydrogen, because of its effects on combustion behaviour of natural gas and potential integrity loss of natural gas assets. Hydrogen admixing possibilities in H-gas systems are larger than in L-gas/G-gas systems. Direct application of hydrogen in e.g. industry, fuel cells, and hydrogen mobility seems preferable over admixing to natural gas (although case specific), primarily because of the economic industrial value of hydrogen and the secondary because of the hydrogen injection limitations in natural gas grids.

4.5.2 Power-to-Methane

The possible second step in the power-to-gas chain, sequential to electrolysis, entails the conversion of hydrogen into methane, using methanation. This is a catalytic synthesis process of hydrogen and carbon dioxide into methane. The process is based on the Sabatier reaction ($CO_2(g) + 4H_2(g) \rightleftarrows CH_4(g) + 2H_2O(l)$) and has become a well know process for the production of synthetic natural gas from coal, which became popular during the 70s. The opposite reaction (methane steam reforming) is widely applied for the production of hydrogen from methane.[31] The Sabatier process is highly exothermic, which offers opportunities for re-use of heat for e.g. steam production.

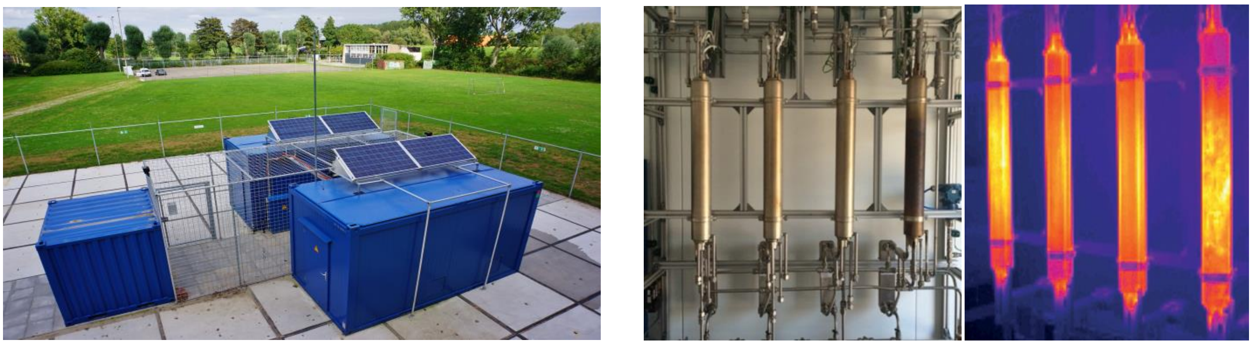


Figure 4-10 Power-to-Gas installation (left) and IR photos of the methanation process (right) of the Rozenburg power-to-methane project in the Netherlands, a project of Stedin, Ressort Wonen, Agentschap NL, Gemeente Rotterdam and DNV GL[32].

Methanation can be done with a chemical or with a biological catalyst. The technology based on a chemical catalyst is a well-known, commercially available process and is widely applied in industry, but is generally applied in large scale plants (MW to GW scale). A big disadvantage of the chemical methanation technology with regard to system flexibility is that the catalytic methanation process requires stable process conditions, precluding fast dynamic operation (ramping up and down) from its operational capabilities. For smaller capacities biological methanation can be considered. This technology is currently being commercialized; it has been proven under operational conditions but needs performance verification in real life environments. The demonstration projects that have been running

[31] Kopyscinski, J. (2010). Production of synthetic natural gas in a fluidized bed reactor – Understanding the hydronamics, mass transfer and kinetic effects. Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zürich. Diss. No 18800
[32] Stedin & DNV GL (2014) Power-to-Gas demonstration plant Rotterdam (NL).

recently show promising results related to operational flexibility in terms of ramping up and down, going in standby modus and costs.

Centralized vs decentralized

Conceptually the technology can be applied in transmission grids and distribution grids and is relevant for industrial application as well as regional and local application. Considering the availability of CO_2 as a feedstock for the methanation process, the obvious locations for power-to-methane would be either at biogas upgrading plants or wastewater treatment plants, where CO_2 is abundant (small scale, few MW's; decentralized), or at CO_2 producing industry (large scale, tens to hundreds of MW's, centralized in industrial area). Small scale power-to-methane plants involve medium or low voltage power infrastructure and medium or low pressure gas infrastructure. The gas G-gas gas network is most relevant for the small scale application of power-to-methane, which implies that the synthetic methane for the power-to-methane plant must be admixed with nitrogen or CO_2 to comply with the gas quality standards of G-gas networks. Large scale power-to-methane plants most likely involve high voltage power grids and medium-high pressure gas infrastructure (RTL/HTL). The high calorific gas HTL infrastructure offers a wider Wobbe band than the G-gas (Groningen gas) infrastructure and thereby offers more possibilities for injection of synthetic methane.

Concluding

The power-to-methane configuration integrates the power infrastructure with the natural gas infrastructure, enabling accommodation or storage of (originally electrical) energy in the gas system and carbon recycling. Additional infrastructure which could be relevant is a heat infrastructure to accommodate the high temperature process heat (steam). System integration complexity relates to the availability of CO_2, the simultaneity of sources (intermittent power vs continuous CO_2) and the incapability of the chemical methanation process for dynamic operation. Biological methanation is promising in terms of dynamic operation and costs and is currently being commercialized. Further performance verification is required to prove its value for energy system flexibility enhancement[33].

4.5.3 Values for the power system

The capabilities of the power-to-gas concept in terms of services to the power grid are based on the capabilities of electrolysis mainly. PEM electrolysis is the preferred technology for dynamic operation of the installation. Although the technology facilitates very rapid absorption of power, its role is more relevant for the 'longer term' services to the power infrastructure, as the gas infrastructure offers huge flexibility and energy containment possibilities. In combination with gas-to-power technology, power-to-gas enables long term and large scale electricity storage.

4.6 Key findings

4.6.1 Hybrid energy infrastructure concepts and system flexibility

The concepts described interact with different types of networks and enable coupling between different infrastructures. However, they all offer services to the electricity infrastructure, by providing flexibility available in infrastructures other than the electricity infrastructure. In order to determine the value of the different concepts in terms of their respective potentials to offer flexibility, one will need to

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[33] Grond, L. & Holstein, H. (2014) Power-to-gas: Climbing the technology readiness ladder - Qualification of integrated power-to-gas systems in real-life environments is the next step. Gas for Energy issue 2/2014.

distinguish between differing types of flexibility. Here both the demand for flexibility as well as the supply of flexibility will differ from one type to another. Hence, in this section a brief description of the taxonomy of flexibility in the electricity system is proposed as a framework for the valuation of concepts in terms of flexibility provision.

The taxonomy proposed primarily relates to the differing planning stages involved with electricity production. These planning stages are in part addressed in the existing short-term electricity market segments, the day-ahead market, the intraday market and the balancing mechanism. Figure 4-11 shows the mapping of the groups of concepts discussed in this chapter to the planning stages in electricity infrastructure.

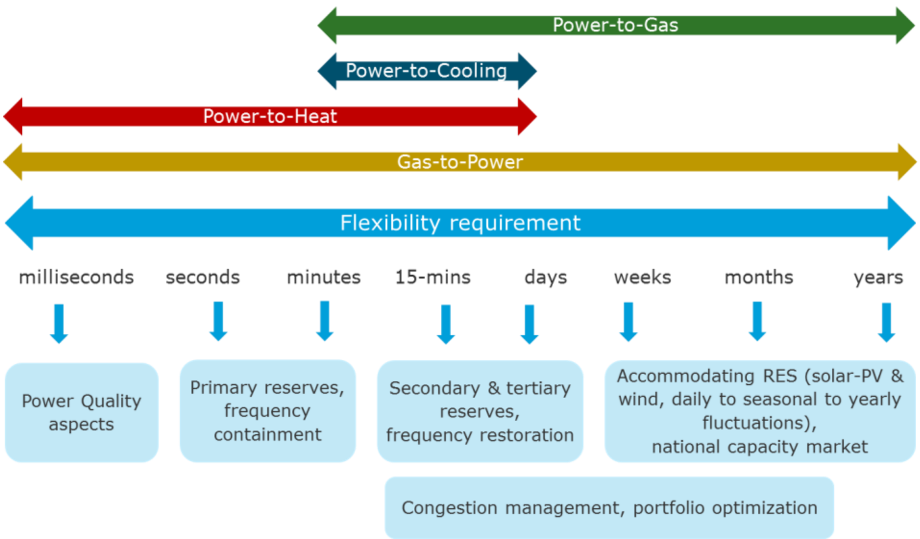

Figure 4-11 The role of concepts in the planning stages of the electricity grid

Long-term trading takes place in the forward market and Over-The-Counter (OTC) market and are not structured on the basis of system planning. Yet, one may note that flexibility needs on differing time horizons beyond day-ahead may differ substantially. Here one may think of flexibility needs relating to the periodicity in demand primarily driven by economic activity and day light resulting in day/night cycles, weekly cycles marked by business days and weekends and finally seasonal cycles, in NW EU typically showing higher demand during wintertime than in summer. As notably wind and solar-PV have low operating costs and often volume as the basis for supporting tariffs or premia these technologies show limited price responsiveness and may be taken as fully deployed and effectively weather-driven. The remainder of price responsive supply and demand options will need to match the sum of demand and contributions of solar-PV and wind, also called residual demand in long-term markets down to the day-ahead market.

The flexibility needs in the short-term market segments from day-ahead planning down to the real time market (the balancing market) are mainly driven by unplanned generator - and network outages and forecast errors in day ahead planning. Since wind and solar-PV show relatively high forecast errors in comparison to demand forecasting, increasing levels of wind and solar-PV typically increase the flexibility needs between day-ahead scheduling and real time.

Table 4-1 below presents a more detailed rating on the flexibility provision for each of the hybrid energy infrastructure concepts discussed here, reflecting the overall conclusions per category. One may note however, that the electric industrial boiler and flexible CHP options offer a broad range of flexibility services, justifying the highest overall rating.

Table 4-1 Overview of flexibility provision capabilities of the hybrid energy infrastructure concepts

	Frequency containment	Frequency restoration & replacement reserves	Accommodation of hourly fluctuations	Accommodation of daily-weekly fluctuations	Accommodation of seasonal fluctuations	Overall rating
Electric heat pump in heating network	0	++	+	-	--	+
Electric industrial boiler	++	++	++	++	++	++
Flexible CHP unit	++	++	++	++	++	++
Hybrid district heating	++	++	+	-	--	+
Power-to-Hydrogen	--	-	0	++	++	+
Power-to-Methane (chemical)	--	-	0	++	++	+
Power-to-Methane (biological)	--	-	0	++	++	+

As indicated in Figure 4-11 and Table 4-1, the gas-to-power concepts are important for (reserve) power generation and frequency restoration. These options are indispensable for service delivery along the entire range of services. The power-to-heat concepts are relevant for the 'short-term' services, both in terms of reaction time as well as in 'containment period' (the period that the infrastructure combination is able to maintain the energy). The power-to-heat options are so called 'sink-concepts', meaning that there is no way of converting the heat energy back to power again. Technical challenges of the power-to-heat concepts entail the necessity for a (efficient) heat distribution system. For heat pump systems the technological efficiency performance is in practice disappointing. The investment costs for heat pump systems are still high. Industrial electric steam boilers are low cost systems that are very well capable of responding to power supply fluctuations. No substantial technological challenges exist at the moment.

The power-to-gas options are primarily relevant for the right segment of the figure, i.e. longer 'containment' periods and thus the services that entail secondary/tertiary reserves and long term storage. In combination with conventional (CHP, gas turbine, etc) or new (fuel cells) gas-to-power technology, the power-to-gas concepts are typically 'source-concepts', enabling re-electrification if required. Technical challenges of the power-to-gas options relate to the system complexity and the efficiency. For the power-to-methane concept the availability of CO_2 and the simultaneity with power supply to the system can be challenging, because most CO_2 sources are base load whereas intermittent power supply from RES can strongly fluctuate. Currently the amount of references of dynamic power-to-gas plants is very limited, meaning that its real value to the system is to be demonstrated. Investment costs for both electrolysis and methanation are still high at this moment; a strong business case is not foreseen for the short term (at current capital investment costs).

TKI study 'Exploring the role of power-to-gas in the future Dutch energy system' [ECN & DNV GL 2014] concludes that short term flexibility in terms of absorptive power is most cost effectively offered by (industrial) electric boilers rather than the power-to-gas concepts (mainly because of the higher lifetime costs of power-to-gas technology compared to that of electric boilers). This is in line with the observation done in this analysis, based on techno-economic considerations.

4.6.2 Overview of technical and economic barriers

This chapter includes a screening of the technical and economic barriers of the different concepts. Table 4-2 summarizes these barriers. These same barriers and the underlying analysis is also being used in chapter 6 of this report and will be included in the overall analysis of the concept viability.

Table 4-2 Summary table of technical and economic barriers of the different concepts.

Concept	Application	Technical barrier	Economic barrier
Electric heat pump in heating network	District heating network	Technological efficiency in practice disappointing. Depending at heat source (air, ground water or waste heat) the efficiency at low source temperature can be very low (near zero).	Investment costs still high and total cost of ownership can be disappointing because of lower than expected efficiency performance.
Electric industrial boiler	Industrial hot water or steam networks	Not yet clear what technical modifications are required for integrating an electric boiler in a conventional steam cycle.	No barriers; at low power prices this concept is cost competitive to gas fired alternative (base case).
Flexible CHP unit	District heating network	Technological improvement necessary to make this concept possible (change of components). Also 'internal' heat storage needed in order to enable fast dynamic operation.	Investment costs and operational costs are still high.
Hybrid district heating	District heating network	Efficient coupling and operation of heat pump in combination with CHP or gas fired boiler (challenge is the actual operations philosophy)	Investment costs of heat pumps are still high and economic performance very much dependant on actual efficiency.
Hot water network storage tank facility	Industrial or district heating	No barrier, proven technology, widely applied.	No barrier, proven to be economically viable.
Medium temperature (450 C) storage	Industrial steam networks	No barriers, but considerable potential for performance improvement.	Production costs are generally higher than production costs for steam for a reference gas fired boiler.

Concept	Application	Technical barrier	Economic barrier
Power-to-Hydrogen	Industrial	Demand must be present. Potential for efficiency improvement.	Electrolysis still high investment costs due to lack of market.
	Household	Hydrogen intolerance of existing natural gas infrastructure. Potential for efficiency improvement.	Small scale electrolysers have relatively high investment costs (unit investment)
Power-to-Methane	Regional grid	Availability of CO_2 as carbon source. Wobbe index adjustment vs gas quality. Potential for efficiency improvement.	Investment costs of components still high (no market yet). Also costs for compression to grid pressure are a relevant barrier in this configuration.
	Distribution grid	Availability of CO_2 as carbon source and the availability of CO_2 in in terms of simultaneity with power supply. Wobbe index adjustment vs gas quality. Summer production might exceed local gas demand. Potential for efficiency improvement.	Small scale units have relatively high investment costs (unit investment)

5 VALUATION

This chapter presents the valuation of the various hybrid energy infrastructure concepts discussed in Chapter 4. The valuation of the various concepts will be based on three pillars, namely:

1. The value added in terms of economic value
2. The value added in terms of employment
3. The value added in terms of sustainability

In the following sections the approach and results for each of these dimensions is presented in more detail.

5.1 Economic Value

The economic value of the various concepts introduced in previous chapters would ideally be based on a valuation of the concepts on the basis of underlying costs associated with investment and operation, revenues generated in the differing electricity market segments, and finally revenues (or cost reductions) generated in sales (avoided costs) of alternate products like heat or hydrogen. Such an assessment would however rely heavily on the assumptions regarding future development of electricity market prices in the differing market segments and the development of alternate commodity markets involved. Particularly given increasing contributions of alternate sources of flexibility in the electricity market segments for example may have a significant impact on the competitiveness and positioning of the concepts introduced in this report, as well as electricity pricing.

Instead, therefore, the economic valuation is evaluated on the basis of the impact the various concepts may have on overall system costs and benefits. In addition, the economic value may relate to additional considerations of which particularly labour market impact on employment is considered to be to be a critical driver. In the following sections, system costs and benefits and labour market impact are evaluated in more detail.

5.1.1 System Costs & Benefits

The evaluation of system costs and benefits follows the methodology of social costs-benefit analysis in the sense that overall costs and benefits for the system as a whole are accounted for. Hence, it captures the cost- and benefit components associated with the energy system as a whole, but disregards distribution of costs and benefits among the stakeholders in the national energy system. In principle, concepts that offer the lowest net costs and high benefits are expected to be of highest value to the system as a whole, while distributional effects regarding differing elements of these underlying system costs and benefits may impose a barrier upon introduction of the concept in the Dutch energy system.

Methodology

Net system costs relate to the investment costs and (fixed and variable) operating costs involved with each concept on the one hand, as well as system savings on the other. In case of the hybrid energy infrastructure concepts considered in this assessment, the latter category typically involves savings outside the electricity system. For example, power to heat applications substitute heat generation by conventional means, such as deployment of a CHP or gas-fired boiler for heat generation in industrial context. The savings on natural gas consumption in this case may be characterized as a benefit and as such should be accounted for in terms of system costs and benefits.

Here, one should note that annual deployment of the concepts is driven by flexibility demand and may vary significantly for each of the categories of flexibility provision in the previous section and depends highly on scenario assumptions. In order to offer a generalised outlook on net system costs, we turn to the classic methodology of screening curves. This methodology is a conventional high-level costs assessment methodology often applied in electricity system planning. It captures the major trade-offs between capital costs, operating costs and deployment rates of assets. Screening curves illustrate the annualized capital expenditures and operating costs as a function of deployment represented by the annual number of full load hours, either in terms of total annualized cost per kW or total annualized cost per kWh.

Limitations of the methodology relate to the fact that deployment is affected by scheduling dynamics and such are not accounted for directly. Constraints relating to production planning for example, imposed by technological characteristics like start-up time, minimum up- and downtime requirements and ramp rates, but also outages and commercial constraints may limit the annual deployment of an asset. In addition, detailed cost factors that are not captured by annual deployment rates, but relate to more detailed aspects of deployment are not accounted for. Particularly costs elements that relate to the cycling rates such as total annual start-up costs and increased maintenance costs due to frequent start/stop operations are typically not accounted for. For the purpose of this exploratory evaluation, the screening curve methodology however captures the main cost factors of each of the concept introduced in previous chapters and as such illustrates the impact on system costs involved with each.

In order to establish the value of the concepts with respect to a conventional alternative we also included conventional means to source demand for flexibility in the electricity system. This relates to conventional means of sourcing or matching the increasing size and frequency of residual demand variations on day-ahead time scales and balancing energy.

Screening curves of hybrid energy infrastructure concepts

Figure 5-1 shows the screening curves of the various hybrid energy infrastructure concepts. Next to the screening curves of the hybrid energy infrastructures also two conventional technologies are included as a comparison (gas turbines and onshore wind).

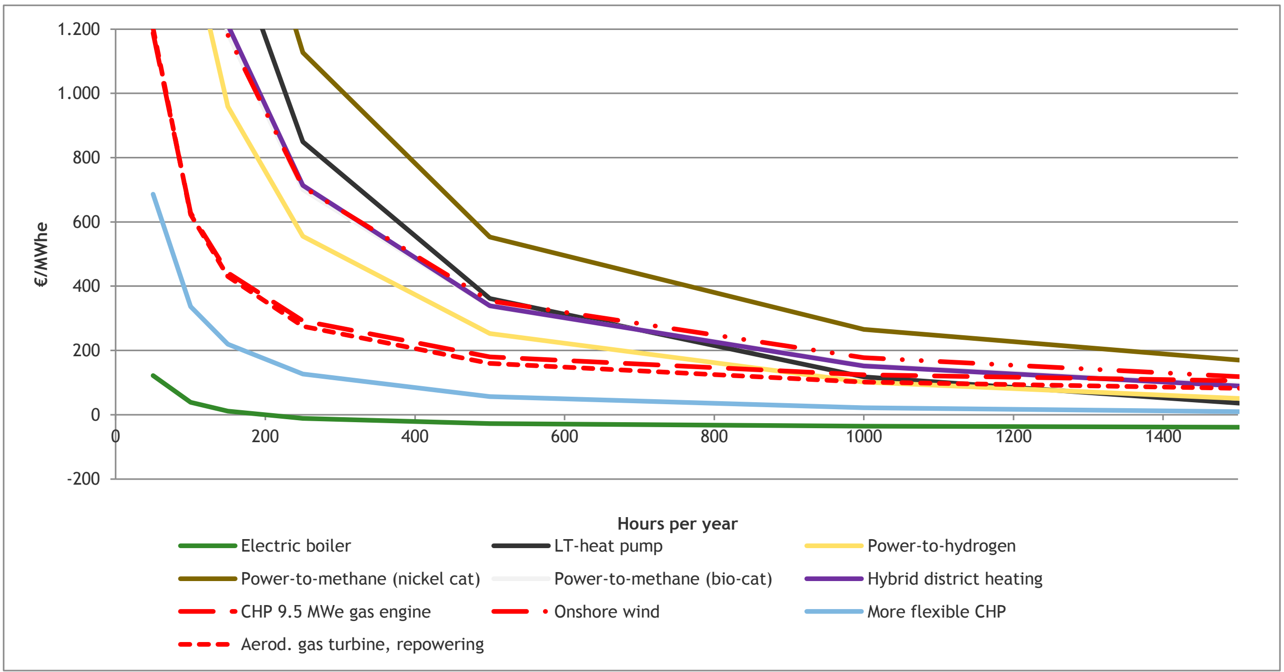

Figure 5-1 Screening curves (including savings) for each of the hybrid energy infrastructure concepts and reference technologies.

In the figure above, the screening curves for the concepts laid down in the previous chapter are presented, jointly with the reference options for matching variations in residual demand and balancing energy. The source-concepts, i.e. electricity injecting technologies and demand response options lowering demand (low temperature heat pump, hybrid district heating and flexible CHP) should be compared to the costs of conventional industrial gas turbines, aeroderivative gas turbines or the gas engines. The flexible CHP clearly performs relatively well in terms of cost-effectiveness in comparison. The low temperature heat pump shows marginal benefit over the aeroderivative gas turbines and gas engine for deployment over 1200 hours per year only, while hybrid district heating shows comparable cost-effectiveness for deployment over 1400 hours per year only.

In case of the sink-concepts, i.e. the electricity absorbing technologies and demand response options heightening demand (low temperature heat pump, the industrial electric boiler, hybrid district heating, power to hydrogen and power to methane) should be compared to curtailment of onshore wind. In this first category, the industrial electric boiler shows to be a highly cost-effective concept for the full deployment range. Power to hydrogen also shows clear benefits over the reference, be it more moderate. The low temperature heat pump shows to be more cost-effective than curtailment of onshore wind only for deployment of over some 800 hours per year. Both hybrid district heating and power to methane (bio-cat) show only marginal benefits for deployment over 1000 hours per year, while power to methane (nickel cat) clearly shows to offer no benefits in the given deployment range.

Conclusively, screening curves including savings outside the electricity system provide for an effective first/order means to evaluate the system costs and benefits associated with each of the hybrid energy infrastructure concepts. The screening curves should be compared to alternative means to match variations in residual demand and balancing energy. For conventional options for injection of electricity we turn to gas turbine technology, aero derivative gas turbines or gas engines. Hybrid energy infrastructure options for absorption of electricity may be compared to curtailment of onshore wind energy.

Conclusions based on screening curves analysis

Conclusively, from a system cost perspective the industrial electric boiler stands out and shows to be a highly cost-effective concept for absorption of electricity in comparison to the reference technology, while power to hydrogen provides an alternative with more moderate benefits in terms of net system costs. The more cost-effective concept for injection is offered by flexible CHP that clearly outperforms the benchmark as well. The low temperature heat pump, hybrid district heating and power to methane (bio-cat) show to offer marginal cost-effectiveness for deployment over some 1000 hours per year. Power to methane (nickel cat) shows relatively high costs in this timeframe, well over the reference costs of curtailment. As such, this technology does currently not provide an attractive option for limited deployment. For seasonal deployment the systems cost of the option may become comparable to alternatives.

5.1.2 Employment

In addition to the system cost perspective, impact on employment is proposed to account for in valuation of the concepts proposed. Here gross employment is evaluated, reflecting the economic activities relating to both project development as well as operation and maintenance of the systems.

Such estimates are generally based on typical rates of employment based per Euro of investment for differing sectors and industries. Secondary effects, like displacement of existing jobs, productivity increases, and considerations regarding labour market equilibrium have been disregarded.

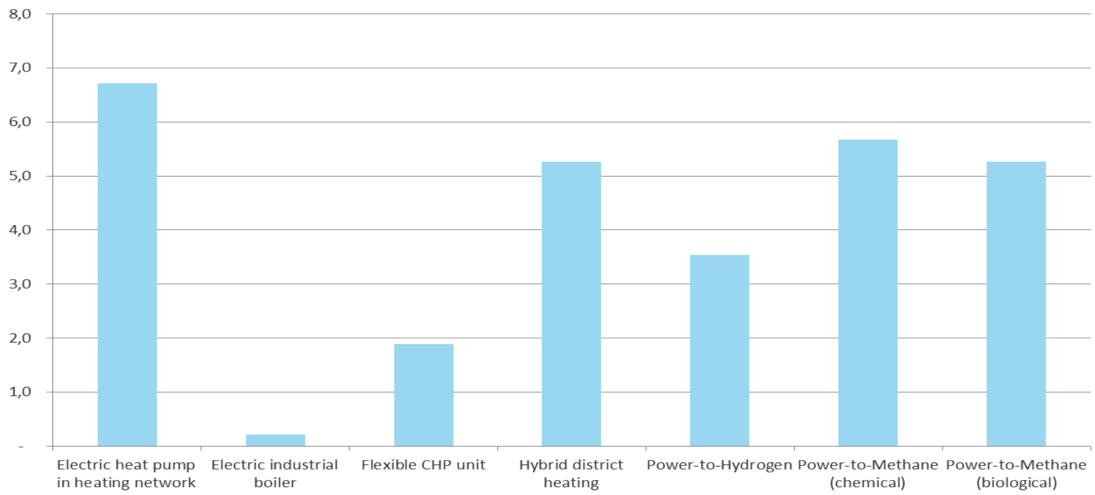

Figure 5-2 Number of FTEs per MWe of capacity for the various hybrid energy infrastructure concepts.

The figure above presents the resulting number of FTE's created per MWe of flexible capacity. Here, the more capital intensive concepts, like the low temperature heat pump show, hybrid district heating and the power to methane concepts show somewhat higher levels of FTE´s created, while the gas engine shows more moderate impact and notably the electric industrial boiler shows only a marginal impact on employment.

5.2 Sustainability

The assessment of the sustainability performance of each of the concepts is based on the potential to reduce CO_2 emissions in comparison to the reference technology for each of the concept individually. These reductions are both based on the savings with regard to alternative means in the electricity system as well as the savings in other segments of the energy system.

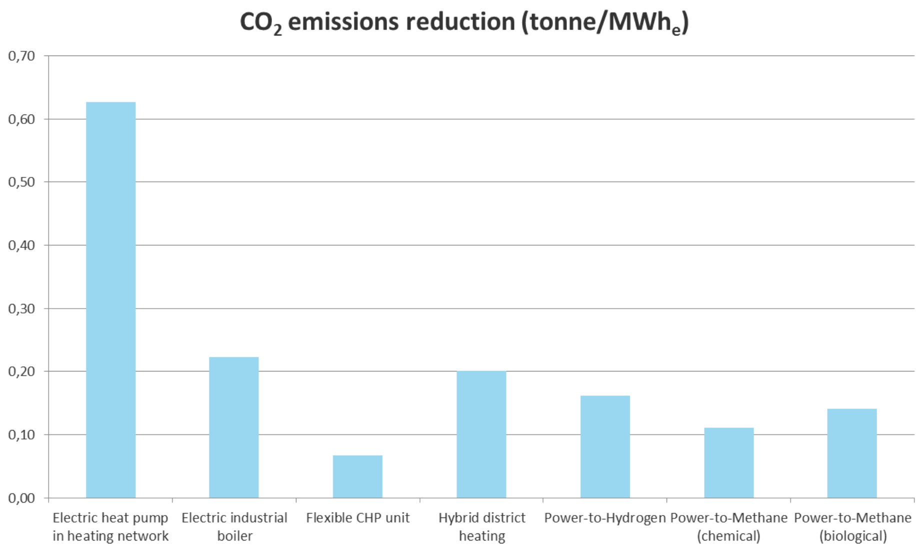

Figure 5-3 CO_2 emissions reduction per hybrid energy infrastructure concept resulting from reductions in both the electricity system as well as other segment in the energy system.

In this case most hybrid energy infrastructure concepts show savings in the range of 0.10 to 0.20 tonne/MWhe. The low temperature heat pump in heating networks stands out as an alternative that shows relatively high savings, while flexibilization of CHP shows relatively moderate performance as the candidate must-run CHPs are typically somewhat alder facilities with limited efficiency.

5.3 Conclusions

In the previous sections an evaluation of the value of each of the hybrid energy infrastructure concepts was presented with regard to three dimensions: system flexibility, economic value and sustainability. The results are presented in Table 5-1 below.

Table 5-1 Overview of the valuation of the hybrid energy infrastructure concepts

	Flexibility value	Economic value	Sustainability
Electric heat pump in heating network	+	0	++
Electric industrial boiler	++	++	+
Flexible CHP unit	++	++	0
Hybrid district heating	+	0	+
Power-to-Hydrogen	+	+	+
Power-to-Methane (chemical)	+	-	+
Power-to-Methane (biological)	+	+	+

Given the results presented, the industrial electric boiler and flexibilization of CHP can be characterized as highly flexible, highly cost-effective measures to enhance system flexibility, offering limited outlook positive impact on employment, while performing reasonable well on sustainability in terms of the potential to reduce CO_2 emissions in comparison to the reference technology.

The power-to-heat options, electric heat pump in heating network and hybrid district heating provide for options that may offer flexibility for short-term flexibility needs, from an economic perspective one may note that impact on net system cost is only marginal, but performing relatively well in terms of employment and sustainability.

The power-to-gas options all perform predominantly well in term of longer-term flexibility provision, with notably power to hydrogen and biological power to methane performing well in terms of reducing net system costs while performing well in terms of employment and sustainability. Chemical power to methane stands out among these options as a relatively costly option, unable to outperform conventional options for flexibility provision in terms of net system cost reduction.

6 BARRIERS

6.1 Introduction

In section 4.6.2 we already provided an overview of the technical and economic barriers for each concept as such. In this chapter we focus on a number of systemic barriers we see towards implementation of hybrid energy infrastructures. We focus on managerial barriers lying within the realm of corporate governance (the way business administration is typically conducted), then address barriers that arise from the typical institutional setting and ultimately also address societal factors that can hamper implementation. The main questions addressed in this chapter are given in the following table.

Table 6-1 Overview of the analysis structure of barriers

Area	Main questions typically to be addressed
Managerial and corporate governance	▪ What are the revenue streams that can be envisioned to make the concept economically viable? ▪ What are the risks of these revenue streams? o Price risks (given electricity, heat, other infrastructure modes) o Market risks o Operational risks o Regulatory risks ▪ Given the risks and rewards, who will invest? And what is the 'default route' that is the dominant alternative route?
Institutional and regulatory	- Stakeholder analysis of concepts - What are the relevant regulatory and judicial factors? Regulatory frameworks are in development; we will include an assessment of the development of STREAM, the new legislative package for the energy system supplementing the Gas and Electricity acts and technical codes governing the energy systems. Furthermore the new Heat Law is also relevant.
Societal	▪ Safety impacts ▪ Visibility ▪ 'Not in my backyard' ▪ 'Resistance costs'

We discuss these three areas separate in the next sections.

6.2 Managerial and corporate governance

The managerial barriers are very important to overcome because they deal with the business side of things. If the business case does not appear attractive because of managerial barriers, then the concepts will not see uptake in the market. We will therefore first focus on revenue streams, then identify risks to these revenue streams, and finally discuss the default routes available to the typical investor. The concepts for hybrid energy infrastructures need to be better than the default route for a company to want to invest in them.

6.2.1 Revenue streams

Before we can enter a discussion on the market and price risks, we need to describe the typical revenue streams that can be envisioned to make the concept economically viable. Revenue streams can be classified in a number of types:

A. Creating revenue from capitalising on price spreads between multiple commodity markets
B. Creating revenue from time shifting procurement in at least one commodity market
C. Extrinsic value: a certain level of insurance against future price developments (hedging). This can be seen as a revenue stream or a reduced market risk.
D. Others: reliability premiums, capacity remuneration mechanisms, balancing markets, etc.

Concepts can generate revenue streams from a number of types. In addition, some of the concepts create, due to their redundancy, a level of fault resilience. This means that costs for backup facilities are decreased, a benefit that lowers operating costs or costs of insurance.

We will follow with a discussion of the revenue streams per different concept.

A: Capitalising on price spreads between multiple commodity markets

The power-to-heat as well as the gas and hybrid concepts options provide the option to use either electricity or some other energy source to meet the heat demand. In many cases the reference will be natural gas, other gases, steam from an industrial steam network, or other fuels. The revenue streams are accrued by utilizing cost- or price differentials between electricity (be it on day ahead - , intra-day – or balancing market) on the one hand and these different commodities on the other. In the natural gas reference case combined with electric boilers, when there is a 'negative spread', i.e. the momentary (spot) electricity price is lower than the value of natural gas, then a power-to-heat boiler can be switched on and the concept is generating income. Therefore we see that revenue streams are intertwined with price developments on a number of markets: e.g. purchasing gas contracts and electricity.

The power-to-gas concepts also accrue revenue due to utilizing electricity when it's relatively cheap, and creating a product that, at the time of operation, has a higher value than electricity. Hydrogen created by the power-to-hydrogen concept creates a product that has higher value compared to natural gas, as long as there is demand for it. Currently a number of industrial clusters have a stable and strong hydrogen demand. The revenue stream will be the differential between the price of pipeline H_2 (made by steam reforming of natural gas) compared to the electricity price.

At locations where there is no demand for hydrogen, power-to-methane allows for injection in the gas grid. So the basis of valuation is the price differential between electricity and demand, however due to the low conversion efficiency, electricity prices must be significantly lower to generate revenue, and a CO_2 source of sufficient quality must also be available. Cost for CO_2 must be factored in.

Gas and hybrid concepts are similar in valuation to the concepts described above.

B: Time shifting participation in at least one commodity market

Storage systems integrated in a heating network can be operated in a number of modes which will influence the revenue streams. When combined with a flexible CHP plant, they allow the CHP plant to only operate at times of high electricity prices, which will realize a higher spark spread (e.g. differential between the cost of electricity + cost of CHP heat and gas boiler heat) for the CHP operator. When network storage systems are combined with power-to-heat options, the revenue stems from opposite price development: procure electricity when it's cheap, convert it to heat, and sell the heat later.

C: Extrinsic value: insurance against future price developments

The intrinsic value of concepts can generally be given by an expectation value of the price differential on the commodity markets multiplied by a number of hours per year that this price differential occurs (multiplied by conversion efficiencies, when applicable). As such, the concepts effectively represent a series of spread options with the price differential on the commodity markets between which the option allows to arbitrate. Next to this, options also give extrinsic value or time value, representing the value that the price differential may diverge from current expectation of the intrinsic value upon expiry. This extrinsic value can in some cases be larger than the 'intrinsic value'.

The extrinsic value is particularly high for at-the-money options (strike price near the expectation value of the underlying), while it is lower for in-the-money options (call option with strike price well below the expectation value and probability distribution of the underlying) and out-of-the-money (call option with strike price well above the expectation value and probability distribution of the underlying).
Increases in volatility of the underlying market prices imply a broadening of the probability distribution around the expectation value of the underlying commodities. Hence, extrinsic value for options currently well in-the-money or out-of-the-money may increase, while it may decline for options that are currently at-the-money.

Price volatility is typically expected to increase on both the electricity markets (due to the expected increase in variable renewables, mothballing of base load and mid-merit plants, phase-out of nuclear) as well as the gas market (due to the declining role of Groningen as a relatively cheap provider of seasonal flexibility), resulting in an increasing volatility of the spread.

The consequence of the increasing volatility of the spread is that the extrinsic value is set to increase for hybrid energy infrastructure concepts in which one energy commodity is currently expected to serve the bulk of the volume.

D: Others revenue streams: reliability premiums, capacity remuneration mechanisms, etc.

For the different concepts for hybrid energy infrastructures, it is important to note that additional revenue streams can be envisioned. These are for example (non-exhaustive list):

- Applicable to a number of options are *reliability premiums*. Presence of the concept will generally increase reliability of the infrastructure(s). For example the industrial electric boilers and heat storage systems will generate value for because it increases the reliability of the steam infrastructure of the industrial site. This is, however, very dependent on the specific site and infrastructure already present. In some specific cases reliability premiums can be significant whereas in other cases they may not materialise at all.
- Options can also generate revenue from *capacity remuneration mechanisms.* An example in the electricity context is the TSO's market for primary frequency control. It is not clear to what extent it will be possible for the hybrid energy infrastructures to generate additional value on these markets.

Because the revenue streams A-C are uniformly applicable to most (if not all) concepts for hybrid energy infrastructures, in the remainder of this chapter we will focus on these revenue streams and not go into more detail on the other revenue streams. But it is important to note that these are present.

6.2.2 Risks

Having identified the revenue streams, we can discuss the typical risks, from a managerial perspective. These risks fall apart in the main categories market risks, price risks, operational risks and regulatory risks. Risks can manifest themselves differently for the different concepts, depending on the configurations, infrastructures and markets involved. Given the number of possible configurations a full treatment all the risks is beyond the scope that we aim for in this chapter, but we will highlight the most relevant ones that can be identified.

Price risks

The main price risks are related to the possible price developments of natural gas, electricity, CO_2 and, where applicable, other markets.

We will focus on the electricity price because it is central to all concepts and poses a very real risk: many of the revenue streams identified in the preceding section depend on the sufficient occurrence of low electricity prices. Typically such risks may be quantified for the near term on the basis of price volatility in recent years. An outlook on the longer term may involve structural breaks in pricing due to changing structure of the underlying system (i.e. the cost structure of supply, demand growth and demand response options). Currently, the penetration of variable renewable generation is foreseen to depress electricity prices (at times even to zero or below). However, when the concepts see significant market uptake, this will contribute to electricity demand at such instances. This will ultimately have the effect of stabilizing the electricity price up to the strike price of these concepts (i.e. the marginal cost of operation).

Though such risks are not easily quantified, the concepts can be ranked qualitatively on the basis of the typical 'negative spread' between the electricity price vs. natural gas price they require to generate income. The larger this negative spread is, the more real the price risk for the concept becomes.
In the following table the price risk for electricity has been operationalised to the sensitivity for sufficient occurrence of low/high electricity prices, with qualitative scores.

Table 6-2 Assessment of the price risks for electricity

Group	Concept	Price risk category:	
		Low electricity prices	High electricity prices
Power-to-Heat	Electric heat pump in heating network	Medium	Limited
	Electric industrial boiler	Medium-high	Limited
Gas concepts/hybrids	Flexible CHP	Limited	High
	Hybrid district heating	Medium	Limited
Power-to-Gas	Power-to-hydrogen	Medium-high	Limited
	Power-to-methane	Very high	Limited

Storage in heating infra	Depends: when operated to maximize the use of power-to-heat, cf. electric heat pump or electric industrial boiler; when operated to make the operation of CHP flexible, cf. 'flexible CHP'

Overall assessment of price risks leads to the conclusion that the electric heat pump systems have lower price risks than electric industrial boilers. Power-to-methane has the highest price risk as the incurred efficiency penalty means it requires even lower electricity prices to start generating revenue. For the concept with heat pumps, depending on temperature regime, the significantly higher efficiency will mean a reduced risk that the concept is not generating revenue.

Regarding natural gas prices, these also endanger future revenue streams, for example if the price of natural gas were to declines very strongly due to a sudden weakening of demand and strong supply. This will endanger the revenue stream of almost all of the hybrid energy infrastructures discussed in this study: hybrid, power-to-heat and power-to-gas concepts.

In future decarbonisation scenario's (IEA 450ppm for example) the natural gas demand and – consequently - price levels are low, but the CO_2 price will be high. In these cases the gas price risk is compensated for by the CO_2 price. However this may be true in a scenario-context of in a macroeconomic perspective, corporate risk desks will treat CO_2 and natural gas price risks separately.

Price risks can be reduced or eliminated by purchasing long-term. The hedging strategies can differ between commodity markets: e.g. purchasing natural gas long term, purchasing electricity more short term. Price risk becomes more important the more CAPEX-intensive the concept becomes, given the needed return on the investment.

Market risks

Market risks entail an uninsurable risk that an entire market fails to develop as expected. This may be the case if electricity demand shrinks instead of growths, depressing the value of all assets serving the energy consumers and markets. Because this is a real risk that is largely not insurable, it will be weighed in when a decision to implement a concept is taken.

Operational risks

The different concepts have different technological aspects that are relevant in the operation.
A number of the more pronounced risks:

- Heat pumps: the efficiency of (air heat source) heat pump systems fluctuates with ambient temperature. When ambient temperature drops significantly, they may cease to operate.
- Electric industrial boilers: whilst integration into hot water and industrial steam systems is well established in an number of Scandinavian markets, integration in the wider industrial steam cycle in Dutch context is still unknown. Specifically, how well steam production by a gas fired boiler or CHP can be tuned to each other. In addition, it is not clear how an electric steam boiler fits into a network for superheated steam.
- Making CHP flexible is proven technology in a number of sectors such as agriculture, and some industrial sites. For industrial sites this will require specific attention from plant facility operators, who need to make changes to their facilities and need to assess the technological risks.
- Hybrid district heating: no specific operational risks (Reliability advantages due to combinations of conventional gas boiler or CHP with an electric heat source,)

- Heat storage tank facilities: Owner might have to allow others to control his installation. Especially in horticulture sector control of the heat buffers is a sensitive issue, heat is mission critical for crop growth and e.g. to prevent mould. Medium temperature storage is not very well established, so needs to prove itself in an industrial context in the Netherlands
- Power-to-gas options face a number of technological challenges: hydrogen tolerance, methanation process conditions shift depending on operation. Power to methane faces higher risks in this regard.

Generally, operational efficiency and risks are dependent on a number of installation and concept/technology specific aspects. Proper maintenance and inspections are usually employed to mitigate operational risks.

Regulatory risks

There are a number of regulatory risks around the concepts.

- District heating networks are governed by the Heat Law (warmtewet) which imposes limits on the tariffs imposable and other administrative duties.
- Power-to-heat and power-to-gas concepts require a high capacity connection to the electricity grid, in that case capacity payments are due. There is currently both a fixed monthly tariff for the nominal capacity, and a monthly tariff for the peak use in a month’s time. Reduced tariffs are applicable for facilities that operate less than 600 hours per year. These tariffs are a genuine risk, because changes of any aspect of this can endanger the revenue streams.

Regulatory developments are discussed in more detail in Section 6.3.2 as part of the institutional factors.

6.2.3 Investors in assets and ‘default routes’

Following the discussion of revenue streams and different dimensions of risks, we can now move on to the typical actors and default options are. Typically, what types of actors will want to invest in the assets that make up the concepts discussed? And, if these actors do not invest, what is then the ‘default route’ that will be the dominant alternative route? These questions are addressed in the following table.

Table 6-3 Assessment of the natural owner and the default route of the concepts

Group	Concept	Investor in asset	Default route
Power-to-heat	Electric heat pump in heating network	Owner of heating network, or (collective) energy supply company	District heating from gas –, biomass – or coal fired CHP plants or boilers, generally without fuel flexibility.
	Electric industrial boiler	Owner of industrial heat assets (e.g. owner of existing cogeneration plant or boiler)	Heat creation in boilers or CHP facilities using primary energy sources, most often natural gas.
Gas concepts/hybrids	Flexible CHP	Owner of CHP plant	Short term: must-run CHP plant, where the owner has no flexibility to shut down during ours of ‘negative spark spread’. Long term: phase-out of CHP, separate generation of heat

			(boilers) and electricity (flexible plants).
	Hybrid district heating	Owner of heating network, or (collective) energy supply company	District heating from gas –, biomass – or coal fired CHP plants or boilers, generally without fuel flexibility.
Power-to-gas	Power to hydrogen	Industrial company with hydrogen demand, or Industrial company with expertise and business in the manufacture of industrial gases (*)	Hydrogen is created from methane, with resulting energy and exergy losses and CO_2 emissions.
	Power to methane		Natural gas is produced from domestic or foreign fossil resources, with depletion of fossil resources and environmental burdens.
Storage in heating infra	Hot water network storage tank facility	Owner of heating network, or (collective) energy supply company, or user of heating network	No storage: creating heat from primary energy source the moment it is required, requiring a balance at all times and offering no flexibility.
	Medium temperature storage	Owner of industrial heat assets (e.g. owner of existing cogeneration plant or boiler)	

(*) Note: these actors seem a best fit given their expertise, but especially power-to-methane will be difficult to get off the ground because a natural 'problem owner' lacks, and it is not clear which stakeholder shall take responsibility for investing in and operating these installations.

6.3 Institutional factors

The institutional context of the proposed concepts for hybrid energy infrastructures can possibly result in a number of barriers to implementation of the concepts. In this section we will identify the major relevant institutional aspects and focus on recent and future developments that can either pose new barriers or aim to alleviate existing barriers.

Institutional aspects encompass both the actor-network (stakeholders) relevant for the concepts as well as social/regulatory and judicial aspects. We will first do a stakeholder inventory with analysis of the main perceptions of the stakeholders on hybrid energy infrastructures that achieve the goal of "system integration", draw conclusions from this, and then focus on the regulatory and judicial aspects and developments.

6.3.1 Stakeholders to hybrid energy infrastructures

Table 6-4 maps the relevant actors, the result of a limited stakeholder analysis. The list is non-exhaustive. The table also contains a first assessment of the stakeholders' core interests, and a sketch of their general perception on the issue of hybrid energy infrastructures and the underlying objectives of "system integration". For reasons of brevity, we will not discuss what stakeholders' perceptions on individual hybrid energy infrastructure concepts are.

Table 6-4 Stakeholders to hybrid energy infrastructures, their primary interest and an assessment of their perception on hybrid energy infrastructures

Stakeholder	Primary interest	Perception on hybrid energy infrastructures
Oil and Gas industry	Stable revenue streams from producing and trading oil and gas	**Positive** if HEIs are strengthening the role of gas as a complement to renewable energy in the future energy mix. **Negative** if HEIs develop to pose a threat to the existing business model
Operator of wind farm or solar PV facilities	Revenue model of wind/solar generation	**Positive** if it helps to preserve the market price for electricity and therefore its revenue model, **(slightly) negative** if there is a large exergetic loss (use of electricity for production of low temperature heat)
(Conventional) electricity producer	Revenue model of generation	**Negative** since this stakeholder is the current supplier of flexibility. The hybrid infrastructure will be considered a flexibility competitor
Energy supply company	Maintaining balance; revenue from additional services; customer of flexibility services	**Positive**, if it is investor in HEI, or benefits it by procuring offered flexibility **Neutral**, it can be perceived as a threat but can also offer rewards
Transmission system operator	Maintaining balance; stable investment outlook; predictable flows	**Positive** if it reduces unbalance risk
Distribution system operator	Maintaining balance; stable investment outlook; predictable flows	**Positive** if it values the different infrastructures and preserves the role and function and use of the existing asset, provided grid consequences of HEIs are manageable. If the HEI lead to higher capacity requirements and grid reinforcement, then it must be manageable.
Owner of heating network	Maintaining balance; revenue from additional services	**Positive** if it creates more value to the heating network
Owner of industrial heat assets	Cost optimisation	**Positive** if cost optimisation, neutral otherwise
Industrial company with hydrogen demand or industrial gases business	Cost optimisation	**Positive** if cost optimisation, **neutral** otherwise
Energy trading company	Revenue from trading commodities and providing services	**Positive/neutral** if it creates liquidity, **slightly negative** if it decreases volatility and bypasses traders
End user of electricity	Cost optimisation	**Positive** if cost optimisation, **neutral** otherwise
End user of heat	Cost optimisation	**Positive** if cost optimisation, **neutral**

		otherwise
End user of gas	Cost optimisation	**Positive** if cost optimisation, **neutral** otherwise
Regulator	Proper working of liberalised energy market	**Positive** if it increases the liquidity in markets and the number of buyers and sellers
Government	Keeping RES subsidies within bounds; achieving RES-targets; affordability / reliability / sustainability; proper working of liberalised energy market.	**Positive** if it contributes to its long list of goals

From the results in the table above it becomes clear that for most stakeholders their primary interests is not at stake when hybrid energy infrastructures are implemented. The exception is the conventional electricity producer since they are the current supplier of flexibility. The hybrid infrastructure will be considered a flexibility competitor. From the other stakeholder analysis overall, it would not be expected that the concepts would face serious opposition or face resistance from certain groups that warrant special attention. However, it should be noted that stakeholder groups are heterogeneous, the above assessments and conclusions are the general average. Further, it may be concluded that HEI concepts generally require involvement of a relatively high number of actors often lacking clear governance models and hampered by a relatively high risk of split incentives.

6.3.2 Regulatory developments

Regarding regulatory developments two current come to mind: the development of STROOM, the new legislative package expected to replace the electricity and gas acts. And furthermore from the European Commission the Energy Efficiency Directive (EED).

STREAM

Since 2011 the Ministry of Economic Affairs works on the legislative agenda trajectory STREAM, which stands for STREamline, Optimise, Modernise. This legislation implements the agenda set by the Energy Report of 2011 and the Coalition Government Agreement Rutte II and will also incorporate the agreements made in the SER Energy Agreemend for Sustainable Growth. Important part of STREAM is the general review of current separate electricity and gas laws, with supplementary measures of government (AMvB) and technical codes by the regulator, and combine this to a new *Gas and Electricity Law*, which can take effect from 1. Jan 2016, with only one general measure of government and one technical code that is compatible with EU requirements.

The new Gas- and Electricity Law provides a future-proof framework to further facilitate move towards proper market working and demand driven energy system. The reasons for the modernization have to do with changes to support the energy transition. The 'Memorandum of Understanding' on the new law (31-7-2014) note the following drivers:

- The share of renewable energy (electricity, gas, heat and cold) increases, leading to a different energy system, in which intermittent sources have a significant role.
- Electricity (wind, solar), heat and (bio)gas are increasingly produced locally. This means that the roles of consumers, energy companies and the larger system change.

- Electrification increases. As a result of a larger share of heat pumps and the expected market penetration of electric cars, electricity will eventually become increasingly important in the energy supply. This will affect the load on the power system. Concepts like demand response, storage and dispatchable generation will play a major role.
- More exchange between different energy systems, different conversion routes, more mutually interwoven energy infrastructures. The development and operation of individual energy infrastructures becomes more complex and interoperability becomes key.
- More demand for flexibility in the energy system, culminating from the above. Besides the flexibility conventional power plants can offer, it is expected that demand response (by consumers, businesses and industry) should be utilized and that energy storage will be needed.

The memorandum goes on to explain that it is currently unclear to what extent and at what rate each of these developments will assert itself in future energy supply, which means that the new Gas and Electricity Law will (more than the previous Electricity Law 1998 and Gas Law) be drafted as a framework that captures key principles but less deeply address details. This makes it possible to adapt the law and the working of it relatively simply, depending on future developments and policy requirements.

The chapters of the new law with relevant aspects are given in Figure 6-1.

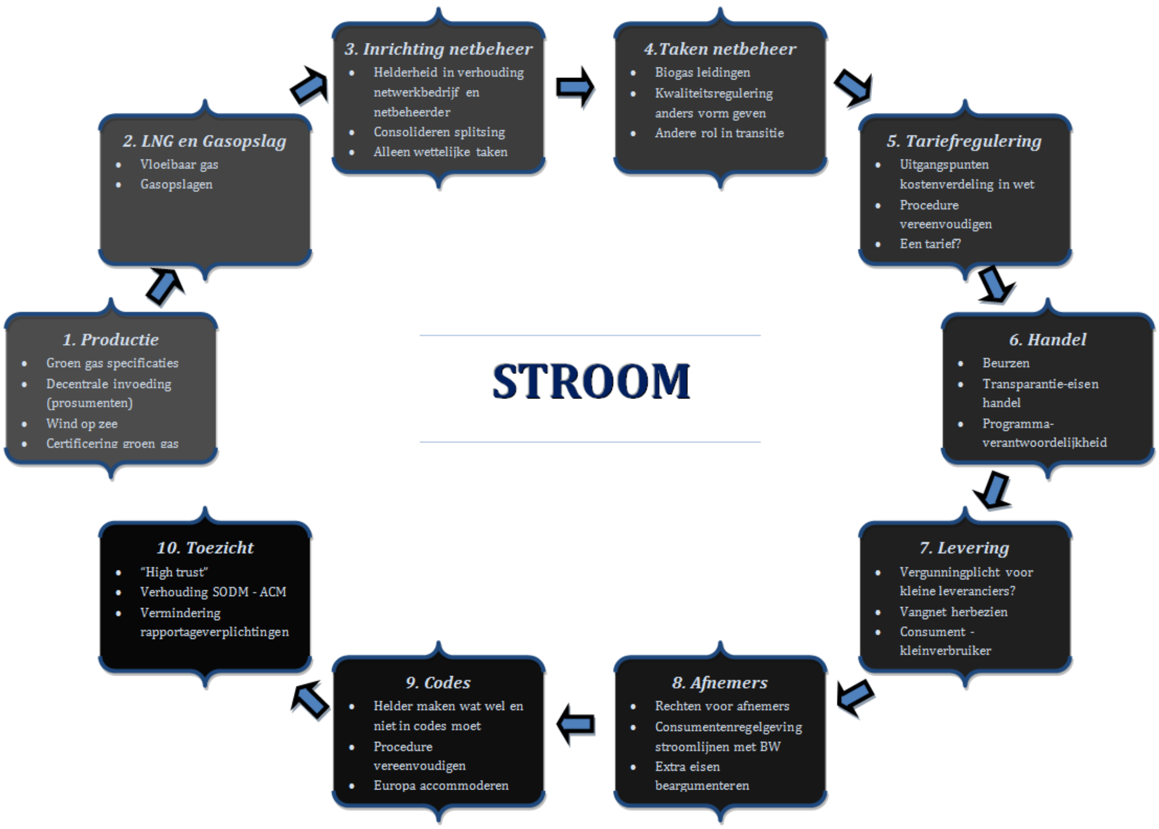

Figure 6-1 Chapters with aspects and goals of new Gas and Electricity Law (from Stroom en het Energieakkoord, April 2013)

While the text of the law isn't finished, from the Letter to the Parliament on the legislative agenda STREAM (June 18, 2014 - DGETM-EM / 14059743) as well as the Explanatory Memorandum, we can note a number of relevant aspects that influence the uptake of Hybrid Energy Infrastructures:

1. Organisation and tasks for system operators (TSO/DSO)
    a. Continuation of the strict judicial split between tasks derived from law and side-activities
        i. Tasks derived by law are done by the transmission/distribution system operator ('netwerkbeheerder'). The system operator is not allowed to perform any activities that are not explicit part of its regulated activities derived from the law.
        ii. Side activities are possible by an entity that will be called infrastructure group (in the present law 'netwerkbedrijf' cf. 'netwerkbeheerder').
    b. Continuation of the limitations imposed upon side activities by the infrastructure group. Side activities are allowed by the infrastructure group, but only under the following conditions:
        i. Strict managerial accounting rules, separate bookkeeping, no cross-financing from regulated activities, etc.
        ii. Side activities only up to a limit, the system operator work must be dominant in the infrastructure group, otherwise the holding will take on too much commercial risk.
        iii. Side activities should relate to energy infrastructures. E.g. electric charging stations, biogas grids. Exception for Gasunie which is allowed to undertake a number of specific additional activities e.g. LNG storage systems, participate in LNG terminals, build new gas grids such as e.g. CO_2 pipelines.
    c. The activities above are more clearly stated but not very different from the present status. The memorandum explicitly notes the conflict of interest between market parties who are opposed to elaborate side activities by the infrastructure group, and the values for the energy system; the energy transition, synergies and making use of knowledge that is already present. Especially when the market will not produce a sufficient quantity of services in the category of the side-activities of the infrastructure group.
2. Improvement in the way net (capacity) planning is conducted
3. Measures due to the SER Energy Agreement for Sustainable Growth
    a. Experiments General Measure of Government, to allow temporary experiments with new organisational structures
    b. Temporary expansion of activities of system operators given the needs of the transition to renewable energy.
    c. The fiscal upper limit of 5000 kWh for feed-in of electricity with 'netting' provisions for the regulatory energy tax is removed (expansion of 'salderen')
    d. Offshore grid

From these main points of STREAM and the new Gas and Electricity Law follow a number of barriers to implementing hybrid energy infrastructures, relevant for the role of the TSO/DSO/infrastructure group:

- Network operators cannot construct HEI solutions as part of their regulated activities.
- The infrastructure group around a network operator can construct and own HEI solutions, but they should be demonstrably compatible with the system tasks such as enabling a better infrastructure, etc. If this cannot be demonstrated then the activities are not allowed.

This barrier will work out different for the different concepts. If concepts for HEIs serve mostly a financial objective and there is only a limited or indirect added value to the energy system as a whole, it can be difficult for a DSO/infrastructure group to invest in these concepts. In that case, all investment should come from market parties. But one can argue if it would make sense at all to invest if the added value of the concept for the energy system is limited.

Heat law

Another relevant development is the Heat Law ('Warmtewet'), in place since 1 January 2014. It covers the following heating networks under the act:

- District heating networks.
- Heating networks through which heat is supplied in building complexes, for example, flats, with a common installation, e.g. block heating
- Heating networks supplying both heat (and cold), such as heating networks with ground source heat and cold storage

The Heat Law is only applicable to those customers that have a heat load of more than 100kW. The main focus of the Heat Law is the small consumers, which means that heat distribution to commercial and industrial customers with a large heat load is not subject to the Law. The Law is very relevant for district heating, local/decentral solutions, multi-tenant office buildings and so on. The Law is only applicable on the heating demand for space heating and cooling, hot water and *domestic* use. *Industrial* or *process* heat is not subjected to the Heat Law. Because there are so many challenges with the implementation of the Heat Law, in the course of 2015 an update will follow.

There are a number of reasons why the Heat Law can act as a barrier to energy-efficient heating / cooling technologies:

- The heat law imposes requirements on the maximum prices that may be charged for connections and energy commodity, based on a calculation by the regulator (<u>only</u> for customers with a heat load less than 100kW). Any amount that is higher is forbidden and can be challenged by the Authority for Consumers and Markets (ACM).
- There are (high) compensation fees payable by the operator of a heat grid in case of malfunctions.
- The heat law causes uncertainty because the definitions of what is covered by the law are not clear in practice and there has not been much experience with how the law is interpreted in practice. (e.g. the capacity limit of 100 kW – many utility buildings do not clearly define the capacity of connections to tenants). The current law covers heat is exclusively for space heating and hot tap water, but not space cooling, although this was in a draft version of the law.

Specific other regulatory barriers

More flexible CHP - The criterion for exemption on energy taxes may be compromised. At least 50% of the heat should be supplied by the CHP, penalizing annual downtimes below. Accordingly, profitability of CHP operations may come to depend on the annual duration of high power prices and thus the annual duration of low wind and solar-PV production, typically up to only 2500 hours yearly or some 30% of the time.

Power-to-gas - Balancing markets must allow aggregation of loads to apply for this market. Furthermore, the current regulatory/legal segmentation of the power and gas production and transmission/distribution operations hampers the implementation of power-to-gas (e.g. a gas TSO is currently not allowed to operate a power-to-gas installation because the production of gas is outside TSO's responsibilities).

Power-to-heat - In the current tariff regime, transport costs for offtake are incurred based on the capacity of the power connection. The current tariffs are payable:

I. Capacity fee regardless of use (kW contract - € per kW per year)

II. Capacity fee based on maximum quarter per month (€/kW_{max}/month or €/kW_{max}/week)

For medium voltage connections, tariff I is about 18.3 €/(kW*year) and tariff II is about 2.06 €/(kW_{max}*month). Total capacity payments for an installation with operational time of 1500 hours per year amount to 28 €/MWh_e which currently is an insurmountable barrier to power-to-heat concepts such as electric industrial boilers.

6.4 Societal factors

Societal factors are factors resulting from the activities that are 'external' to the economic activities. On first instance, societal factors are not incorporated in the business case decisions. However, if they adversely impact others, it can be important to address them, otherwise strong opposition to a project can arise that negatively affects the realisation.

Classical examples when societal factors strongly influence a project's realisation are:

- (perceived) safety impacts (e.g. nuclear power stations, gas/CO2 storage etc.),
- environmental pollution (and then especially if it is observed to affect communities),
- visibility impacts (e.g. building of power lines, landscape impacts of wind farms.)
- 'Not in my backyard' (NIMBY) (e.g. around the construction of highways)
- 'Resistance costs' (observed around energy savings measures)

Hurdles on individual concepts:

- Hot water network storage tank facility. The volume required can be large: too big to be acceptable in built environment. (space/visual quality aspects)
- Power-to-hydrogen: if hydrogen will be fed in the (L-)gas grid and the volume of it passes a certain volume% threshold, then burners will need to be adjusted. This would cause large societal resistance. However, application of power-to-hydrogen in industry is high-value and will be well accepted just fine, from a societal perspective.

With exception to the individual hurdles, which may or may not be overcome, we can expect that overall concepts for hybrid energy infrastructures will not face major societal hurdles, as the concepts are typically realised 'out of sight', generate no pollution, do not cause significant safety impacts and so on.

6.5 Key findings of barriers

In this chapter, barriers to the underlying business models, institutional and regulatory barriers and finally social barriers were covered. This section summarizes the most main findings this chapter to select the concepts that have the least expected barriers to implementation.

Managerial and corporate governance barriers

Barriers relating to the business models for each of the concepts were evaluated and several typical revenue streams to hybrid energy infrastructures were identified:

First of all, three typical revenue streams to hybrid energy infrastructures were identified:

1. capitalising on simultaneous price developments on two (or more) commodity markets
2. time shifting procurement in at least one commodity market
3. extrinsic value: insurance against future price developments and monetizing this.

For these revenue streams the price, market, operational and regulatory risks were mapped, to investigate the managerial barriers. Price risks were found to be very large because the revenue streams depend on the frequent incidence of both high and low electricity prices. There is a clear difference on how sensitive the concepts are to this risk, which was mapped in Table 6-2. Power-to-methane faces very high price risks, and increased CHP flexibility faces high price risks. Market risks are comparable for all concepts. Operational risks are highest for power-to-methane (and less so for power-to-hydrogen) due to a number of technological process condition challenges that do not exist in the other concepts.

Institutional and regulatory barriers

An assessment of institutional barriers on the basis of a stakeholder analysis suggests that the concepts do not face resistance from certain stakeholder groups that warrant special attention. However, it should be noted that stakeholder groups are heterogeneous and hybrid energy infrastructure concepts generally require involvement of a relatively high number of actors often lacking clear governance models and hampered by a relatively high risk of split incentives.

High-level evaluation of STREAM and the new Gas and Electricity Law indicate several barriers to the development of hybrid energy infrastructures, particularly regarding the role of the DSO /infrastructure group:

- DSO’s cannot construct hybrid energy infrastructure solutions as part of their regulated activities
- The infrastructure group around a DSO can construct and own HEI solutions, but they should be demonstrably compatible with the system tasks

There are a number of reasons why the Heat Law can act as a barrier to energy-efficient heating / cooling technologies:

- Maximum pricing regulation for connections and energy commodity for customers with a heat load less than 100kW
- Compensation fees payable by the operator of a heat grid in case of malfunctions.
- Uncertainty with regard to scope of the current heat law particularly with respect to the capacity limit of 100 kW and inclusion of space cooling

Further, there are a number of specific regulatory barriers which will hamper investment. Flexible CHP, power-to-gas and power-to-heat applications may face regulatory barriers in the Dutch framework. The flexibilization of CHP, and particularly the flexible deployment may hamper the requirement that at least 50% of the heat should be supplied by the CHP in order to remain exempt from energy taxes. Furthermore, the current regulatory/legal segmentation of the power and gas production and transmission/distribution operations hampers the implementation of power-to-gas (e.g. a gas TSO is not allowed to operate a power-to-gas installation because gas is being 'produced'). Finally, under the existing tariff regime power to heat is faced with transport tariffs that are based on the capacity of the connection. Hence, infrequent high-capacity offtake is burdened with relatively high transport charges that may range from some 20-30 €/MWh_e of offtake severely compromising the business case that is based on low-cost electricity.

Social barriers

Regarding social barriers, the hybrid energy infrastructure concepts are not typically confronted with significant societal hurdles, as the concepts are generally realised ‘out of sight’, generate no pollution, and do not cause significant safety impacts.

Conclusions

From the assessment of barriers to business models, the institutional - and regulatory - and finally social barriers, we can conclude the following.

Concepts that give the lowest risks to their revenue stream are:

- Electric heat pumps in district heating
- Hybrid district heating
- Heat storage options
- Power-to-hydrogen

These concepts face the least barriers to their business case.

None of the stakeholders seems to directly oppose aspects of hybrid energy infrastructures, but the concepts generally require involvement of a relatively high number of actors often lacking clear governance models and hampered by a relatively high risk of split incentives.

Regulation regarding the role of DNOs as laid down in STREAM and the new Gas and Electricity Law limits the DNOs room of manoeuvring in support of hybrid energy infrastructure concept development, while the Heat Law may impose a barrier to hybrid energy infrastructure concepts involving energy-efficient heating / cooling technologies. Further, mainly the flexibilization of CHP, power-to-gas and application of the electric industrial boiler face case-specific hurdles in today´s regulation.

No social barriers seem to impose particular hurdles to the hybrid infrastructure concepts.

7 HIGH-POTENTIAL CONCEPTS

In the previous chapters, the long list of hybrid concepts was reduced to a short list of selected concepts. The valuation of the selected concepts and an analysis of possible barriers for these concepts shows the potential of the concepts in general. In this chapter, an analysis of the concepts is carried out, to determine the most likely concepts to be successful for the Dutch economy.

First, several criteria are explained, in light of which the high-potential concepts are identified followed by the actual selection of the high-potential concepts. Finally, the barriers for each of these high-potential concepts that may be relieved through short-term measures are identified. These will lead up to recommendations for the research agenda in the next chapter.

7.1 Criteria for high-potential concepts

To determine if a concept has high-potential, two criteria are applied:

1. National market potential
2. Development potential

These two criteria are explained below.

National market potential

The concepts are analysed to determine if they have a good potential for implementation in the Dutch market. Good implementation into a market can be reached by favourable market conditions that match the characteristics of the concept.

The analysis is executed by mapping the potential product-market-combinations in both The Netherlands and NW Europe. The product-market-combinations (PMC's) are compared and assessed in order to develop a ranking of the concepts. A PMC gets a high score if the PMC has a large potential in terms of turn-over.

Development potential

If a concept has a high potential for successful product or concept development in The Netherlands, the concept potentially has a high contribution to the Dutch economy. To analyse this contribution, a SWOT-analysis of the concept in the Dutch context is performed. Is the concept developed by a Dutch company? Can the products be fabricated in The Netherlands? Are there Dutch IP's? Is there sufficient Dutch technical know-how? Can the concept easily be copied by foreign companies?

The SWOT-analysis will qualitatively show the potential of the concepts. Equal to the national market potential, the outcomes of the SWOT-analysis is compared and assessed in order to develop a ranking of the concepts.

By combining the two criteria and rankings, an overall assessment is made of the concepts and the high-potential concepts are identified. The highest ranking concepts are considered the high-potential concepts. Besides the ranking, the analysis will also show the barriers of the concepts.

7.2 Short list of high-potential concepts

Table 7-1 shows the concepts as selected in Chapter 4. In the following sections, these concepts will be analysed for their national market and development potential. The final section presents the ranking of the concepts and selection of the high-potential concepts.

Table 7-1 Overview of shortlisted hybrid energy infrastructure concepts

Category	**Concept**
Power-to-heat	Electric heat pump in heating network
	Electric industrial boiler
Gas concepts and hybrids	Flexible CHP
	Hybrid district heating
Storage in heating infrastructures	Hot water network storage facility
	Medium temperature (450 °C) storage
Power-to-gas	Power-to-hydrogen
	Power-to-methane

7.2.1 National market potential

All concepts from Table 7-1 are analysed for their market potential by mapping the PMC's of each concept, assessing the compatibility of the characteristics of the PMC to the market conditions and assessing the financial volume of the PMC. The results of the analysis are provided in a structured fashion in the tables below.

The following tables show the analysis of the national market potential of all selected concepts. These tables show:

- PMC: the Product-Market-Combination is the relevant market in which the specific concept can be introduced (or developed).
- Compatibility: based on a qualitative analysis of the concept and the PMC, a judgement on the compatibility of the concept is made. An *excellent* compatibility means that the PMC is almost 'plug-and-play', there are no real technical or market challenges for introducing the concept. A *limited* compatibility means either the market or the concept has to change significantly before functioning well.
- Market volume: indication of the size of the market, expressed in physical values that are relevant for defining the market.
- Estimate turnover: very rough estimate of the financial size of the market, e.g. sold GJ multiplied by average price per GJ. PM if estimates are not possible or unkown.

Electric heat pump in heating network

Electric heat pumps as heat suppliers to district heating networks			
PMC	**Compatibility**	**Market volume** *(NW Europe = italic)*	**Estimate turnover**
District heating networks	Good	Substantial (~20 large district heating networks, 100s smaller heating networks) *Multiple times the Dutch volume*	200-500M€

Electric industrial boiler

An electric boiler is used for producing hot water directly from electricity.			
PMC	**Compatibility**	**Market volume** *(NW Europe = italic)*	**Estimate turnover**
Industrial heat consumption	Good	Substantial (industrial heat consumption <500 °C is 250PJ/yr) *Multiple times the Dutch volume*	2,500M€ (energy related)

Flexible CHP

A more flexible operational profile of the CHP-plant requires application of several specific technological components that allow rapid ramping up and down of production or a complete standstill for several hours.			
PMC	**Compatibility**	**Market volume** *(NW Europe = italic)*	**Estimate turnover**
CHP-Utilities	Good	~20 CSGT/steam/gas turbines, and ~80 smaller CHPs *Multiple times the Dutch volume*	PM
CHP-Industry	Limited	~1,500 CHPs *Multiple times the Dutch volume*	PM
CHP-Horticulture	Good	Substantial (~2,800 CHPs) *Equal to Dutch volume*	500-1,000M€ (energy related)

Hybrid district heating

This concept entails the implementation of a centralized combined district heating system based on an electrical heat pump and a gas fired heating system, i.e. CHP system or a gas fired boiler, to be operated hybrid. This concept is well suited for application with low temperature waste heat from industry or electricity production.			
PMC	**Compatibility**	**Market volume** *(NW Europe = italic)*	**Estimate turnover**
District heating networks	Excellent	Substantial (~20 large district heating networks, 100s smaller heating networks; large supply of low temperature waste heat) *Multiple times the Dutch volume*	200-500M€
Horticulture heating networks	Excellent	Substantial (currently ~2,800 CHPs in horticulture; large supply of low temperature waste heat) *Equal to Dutch volume*	500-1,000M€ (energy related)

Hot water network storage facility

The hot water tank is part of a heating network supplied by a CHP. The buffer is filled with hot water during periods with low renewable energy availability and high power prices and supplies heat during periods with high renewable energy availability and low power prices, during which period the CHP plant is shut down or operates in part load.			
PMC	**Compatibility**	**Market volume** *(NW Europe = italic)*	**Estimate turnover**
CHP-District heating networks	Excellent	Substantial (~20 large district heating networks, 100s smaller heating networks) *Multiple times the Dutch volume*	200-500M€
CHP-Horticulture heating networks	Excellent	Substantial (currently ~2,800 CHPs in horticulture) *Equal to Dutch volume*	500-1,000M€ (energy related)

Medium temperature (450 °C) storage

Medium temperature storage could be applied in the same way in public steam networks as a hot water storage in district heating networks and similar low temperature networks. Examples of steam networks assessable to third parties include Stoompijp Rotterdam and the steam grid in the chemical industry cluster in Delfzijl.			
PMC	**Compatibility**	**Market volume** *(NW Europe = italic)*	**Estimate turnover**
Industrial steam consumption	Good	Substantial (industrial heat demand (250-500 °C) is approx. 100 PJ/yr) *Multiple times the Dutch volume*	1,000M€ (energy related)

Power-to-hydrogen

Within the domain of power-to-gas the production of hydrogen by means of water electrolysis is the first step in the chain. Electrolysis describes the splitting of water into hydrogen and oxygen, driven by an electrochemical reaction: $2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$. Besides hydrogen, the process produces oxygen.			
PMC	**Compatibility**	**Market volume** *(NW Europe = cursive)*	**Estimate turnover**
Fuel stations	Good	Small (currently small number of hydrogen vehicles) *Equal to Dutch volume*	PM
Industrial hydrogen demand	Good	PM	PM
Gas network blend-in	Good	Substantial (limited in %, but substantial in volume) *Multiple times the Dutch volume*	PM

Power-to-methane

The possible second step in the power-to-gas chain, sequential to electrolysis, entails the conversion of hydrogen into methane, using methanation. This is a catalytic synthesis process of hydrogen and carbon dioxide into methane. The process is based on the Sabatier reaction ($CO_2(g) + 4H_2(g) \rightleftarrows CH_4(g) + 2H_2O(l)$) and has become a well know process for the production of synthetic natural gas from coal, which became popular during the 70s.			
PMC	**Compatibility**	**Market volume** *(NW Europe = cursive)*	**Estimate turnover**
Synthetic/biologic methane production	Good	PM *Multiple times the Dutch volume*	PM
Waste water treatment plants	Good	Small (~200 biological waste water treatment plants; total 0.8Mton CO_2 emission) *Several times the Dutch volume*	PM
CO_2 producing industry	Good	Substantial (refineries, chemical industry and other industries combined emit 45Mton CO_2)	PM

A ranking can be made of the concepts, on the basis of a qualitative review of the analyses of the market potential. The following table shows the results of this ranking. The concepts are scored, based on this relative ranking, in which the highest ranking concept receives the highest points[34]. For the concepts of which little information is available, assumptions are made to give them a relative position to concepts that are more qualitatively founded.

[34] A 5-point scale is used to emphasise that the scoring is relative, with a high degree of uncertainty. A 8-point scale would suggest an accuracy that is not present.

Table 7-2 Ranking of hybrid energy infrastructure concepts based on national market potential

Rank	**Concept**	**Points**
1	Electric industrial boiler	5
2	Hot water network storage facility	4
3	Hybrid district heating	4
4	Power-to-hydrogen	3
5	Power-to-methane	3
6	Medium temperature (450 °C) storage	3
7	More flexible CHP	2
8	Electric heat pump in heating network	1

7.2.2 Development potential

In the following tables, for each concept a broad SWOT-analysis is carried out. Because most concepts have multiple PMC's, the analysis will be focussed on the concept itself, not at the PMC. The analysis will address development aspects, specifically innovation aspects like potential Dutch IP's and know-how.

Electric heat pump in heating network

Strengths	**Weaknesses**
- Substantial amount of heating networks - Large thermal buffering capacity - Sufficient Dutch know-how on developing and installing the concept	- Mismatch in temperature regime of heating network - No Dutch manufacturers of large heat pumps - No unique position for Dutch companies
Opportunities	**Threats**
- Availability of large volumes of low-cost electricity - Future development of heating network for reducing CO_2 emission	- Alternative heating techniques, making concept obsolete - Energy saving, making the concept less profitable

Electric industrial boiler

Strengths	**Weaknesses**
- Proven technology - Cost-effective - Highly flexible - High potential in volume and capacity	- Unknown for a large part of the potential market - Due to maturity of the concept, very limited development potential
Opportunities	**Threats**
- Excellent match for flexibility demand - Large numbers of installations can provide many jobs	- High electricity prices when heat is necessary - Limited skill necessary for installation, so job opportunities might be filled from outside The Netherlands

Flexible CHP

Strengths	**Weaknesses**
- Large number of CHPs - High capacity	- Current CHPs are very limited in their profitability, so many might be decommissioned soon - Limited additional capacity (many CHPs are already flexible) - Limited additional flexibility

Opportunities	Threats
- Dutch know-how already available	- No heat (flexible) demand or storage capacity - Limited innovation potential

Hybrid district heating

Strengths	Weaknesses
- Large potential (demand) - High availability of low temperature waste heat - Dutch know-how available	- Currently no application in The Netherlands - Limited technical innovation potential
Opportunities	**Threats**
- Future development of the built environment might lead to low temperature heating networks, in which this concept might be better suited - Limited experience outside The Netherlands, opportunities for innovation of concept/service	- Stagnation of the development of heating networks

Hot water network storage facility

Strengths	Weaknesses
- Low tech concept - High capacity	- Relative physically large - Limited innovation potential
Opportunities	**Threats**
- Additional capacity if heating networks are developed further - Especially interesting for a large share of wind power	- Large experience base outside The Netherland (Germany, Denmark)

Medium temperature (450 °C) storage

Strengths	Weaknesses
- Can be used for both electricity production	- Limited storage capacity

and industrial heat production	
Opportunities	**Threats**
- Large potential for specific heat demand	- No proven technology in combination with CHP

Power-to-hydrogen

Strengths	**Weaknesses**
- Multiple technical solutions	- Limited full scale experience with integration of hydrogen in natural gas infrastructure - Limited system compatibility with the existing gas infrastructure
Opportunities	**Threats**
- Direct use of hydrogen as feedstock (high economic value) - Much Dutch know-how and relevant innovation capacity - Blending of hydrogen with natural gas might facilitate large volumes of hydrogen (especially in H-gas networks as the admissible percentage of hydrogen mixing is higher than in G-gas networks)	- Limited capacity for distribution of hydrogen and possible end-user effects - System integration complexity of admixing hydrogen is high - Possible social resistance to large scale integration of hydrogen in natural gas grids.

Power-to-methane

Strengths	**Weaknesses**
- High capacity - Excellent system compatibility with the existing gas infrastructure	- Low efficiency - Limited flexibility in operation - High system costs due to investment in methanation technology and dependence on (high-purity) CO_2
Opportunities	**Threats**
- Indirect storage method for electricity - Carbon recycling	- Low availability of CO_2

On the basis of a qualitative review of the SWOT-analyses a ranking can be made of the concepts, regarding their development and innovation potential. The following table shows the results of this ranking. The concepts are scored, based on this relative ranking, in which the highest ranking concept receives the highest points.

Table 7-3 Ranking of hybrid energy infrastructure concepts based on development potential

Rank	**Concept**	**Points**
1	Hybrid district heating	5
2	Power-to-hydrogen	4
3	Medium temperature (450 °C) storage	4
4	Flexible CHP	3
5	Electric heat pump in heating network	3
6	Power-to-methane	2
7	Hot water network storage facility	2
8	Electric industrial boiler	1

7.2.3 Selected high-potential concepts

The analyses in the previous paragraphs are used to make a selection of three high-potential concepts for hybrid energy infrastructures. This is done by ranking the concepts on the basis of the received points in the previous analyses and giving them a weight. Because the focus of the study is to develop a research agenda, the points for the development potential will receive a weight of two. The points for market potential will have a weight of one. The table below shows the results for this ranking.

Table 7-4 Combined ranking of hybrid energy infrastructure concepts

Concept	**Market potential**	**Development potential**	**Total**	**Rank**
Electric heat pump in heating network	1	3	7	6
Electric industrial boiler	5	1	7	6
Flexible CHP	2	3	8	4
Hybrid district heating	4	5	14	1
Hot water network storage facility	4	2	8	4
Medium temperature (450 °C) storage	2	4	10	3
Power-to-hydrogen	3	4	11	2

Power-to-methane	3	2	7	6

All of the mentioned concepts are basically high potential concepts, but all have different accents. The electric industrial boiler for instance, has a high market potential and the power-to-hydrogen a high development potential. Eventually, the focus of this study is to investigate those options that have the highest value and highest potential for the future innovation agenda of the Netherlands. This is why the development potential is weighted extra, in comparison with the market potential. Straight from the shelf concepts, which are already implemented in The Netherlands, have limited or no development potential and no real value for the innovation agenda. This is why the analysis concludes the following three concepts are the high-potential concepts:

- Hybrid district heating
- Power-to-gas options (in particular power-to-hydrogen for industrial application or grid injection and to a limited extend power-to-methane (biological) for regional application and injection)
- Flexible CHP units (or upgrading existing CHP units to enhance their flexibility)

All the heat options can be supplemented in flexibility by integration of heat storage (district heat storage or industrial heat storage), this is why the heat buffer concepts are not specifically listed as high potential options, as they are rather to be considered in all power-to-heat concepts to enhance flexibility.

Noteworthy, the above short-listed high potential concepts are the concepts that offer potential for development and improvement. Electric industrial boilers are found to be of key importance to cost-effectively offer flexibility to the electricity system (see screening curves above), but are found to be mature and off-the shelf with limited barriers and are therefore not of primary focus to the innovation agenda recommendations.

8 RECOMMENDATIONS INNOVATION AGENDA

The recommendations for the innovation agenda are based on the analysis described in this report. The assessment respectively covered an economic valuation, an evaluation of the barriers and finally a selection of the high potential concepts for the Dutch context.

Based on our analysis and assumptions we identified and shortlisted the following high potential concepts which have the highest value and the highest potential. The future innovation agenda should put emphasis on these concepts:

- Hybrid district heating
- Power-to-gas options (in particular power-to-hydrogen for industrial application or grid injection and to a limited extend power-to-methane (biological) for regional application and injection)
- Flexible CHP units (or upgrading existing CHP units to enhance their flexibility)

For these concepts we have identified a number of technical barriers which can be addressed by innovation projects, e.g. aspects like developing operating philosophies of hybrid district heating or continuous efficiency improvements and gas network quality issues related to power-to-gas options and redesigning technical components in CHP allowing for ramping up and down flexibly.

But overall we would like to advise RVO to consider in particular the following recommendations in the establishment of the innovation agenda:

1. **Reconsidering the roles and responsibilities of network operators in relation to hybrid energy infrastructure concepts.**

The current regulatory framework limits network operators and potential operators of hybrid concepts to actively pursue opportunities towards implementing concepts of infrastructural system integration. To give an example, grid operators are currently not allowed to operate power-to-gas installations. In order to do so, they have to apply for several regulatory exemptions in order to obtain their permits. It should be noted that the development of such concepts is not solely the responsibility of regulated parties; also other market players can take the initiative to develop hybrid energy infrastructure concepts. Irrespective of who takes initiative, regulatory uncertainty can form a business risk. At this moment the potential stakeholders in hybrid energy infrastructures experience regulatory resistance or uncertainty to their potential pro-activity. We therefore recommend putting effort in evaluation and possibly revision of the roles and responsibilities of network operators in relation to their potential value in order to unlock energy system flexibility by coupling of energy infrastructures.

2. **Explore the potential impact of RES providing flexibility to the electricity market in relation to the value of hybrid energy infrastructure concepts.**

On the one hand increased shares of renewable energy sources have an impact on residual system load and trigger the need for flexibility. On the other hand, generators based on renewable energy sources can potentially also offer renewable reactive power. This will impact the value of hybrid infrastructures concepts which are especially suitable for frequency restoration since these solutions might compete. We advise to explore this potential impact in order to gain understanding on the robustness of the value of hybrid infrastructures.

3. Validate high-potential concepts through demonstration in operational environments

The macro level role and value of high potential concepts has been analysed and identified. In order to validate and understand their value in real life environments, we advise to gain operational experience through demonstration and validation projects. Validation of these concepts in operational environments will bridge the gap between R&D knowledge and actual implementation of the concepts. Operational experience offers to identify barriers and explore practical solutions for regulatory, contractual and operational issues as well as to validate its technological performance and to identify additional infrastructural requirements (like e.g. ICT requirements).

4. Development of alternative tariff structures for hybrid energy infrastructure concepts

Concepts like power-to-heat and power-to-gas require (large) capacity connections to the electricity grid. In the current set-up of the tariff system, the costs of the electricity networks are being paid by the consumers via the network tariffs. Grid connection costs for consumers are determined by the capacity of the power connection. There is currently both a fixed monthly tariff for the nominal capacity and a monthly tariff for the peak use in a month’s time. At the moment conventional electricity producers do not pay a network tariff. Hybrid energy infrastructure concepts can be seen as both a producer and a consumer. In some cases they are net consumers, whereas in other cases they help balancing the network. A mismatch between the tariff set-up and new system roles creates a significant risk in the business of these concepts, preventing stakeholders and investors taking initiative. Therefore we recommend exploring alternative tariff structures for hybrid energy infrastructure concepts and assess the regulatory options and limitations.

5. Explore the value of feedstock infrastructures in providing flexibility to the electricity grid.

Flexibility captured within (industrial) feedstock networks could be germinated and offered to the electricity infrastructure. For instance, the hydrogen network present in the Botlek area offers great energy capacity, both in terms of supply to as demand from the network. We advise to explore the technical, regulatory and organizational possibilities to make this flexibility available to the energy system in a structured fashion. The potential role of industry in this matter seems to be very significant and should further be exploited. A large scale pilot with industrial stakeholders could be one of the possibilities to rapidly gain insight in the viability of fully integrating feedstock networks in the energy system.

6. Impact assessment of the differences in regulatory set-ups of heat networks and other networks, regarding the impact on hybrid energy infrastructures.

Providing flexibility using hybrid energy infrastructures requires the involvement of three actors: the operator of the electricity network, the operator of the energy conversion concept at the connection point between networks and the operator of the network of the other energy carrier (gas, heat, cold). Currently the regulatory arrangements in these networks are different. The regulation of heat networks is particularly different from the regulation in electricity and gas networks. There is also the issue of privately owned networks which are not regulated. In order to facilitate the development of hybrid energy infrastructure concepts we recommend mobilizing innovative power towards reassessing the existing regulatory frameworks with a view on the future infrastructure combinations/interactions. Key is to take an holistic approach seeking alternative, fair and optimal solutions from an overall integrated energy system perspective.

7. Risk assessment of electricity system stability in relation to the current trend of electrification of heat demand in extreme meteorological scenarios.

The current trend of electrification of the heat demand is driven by cost, efficiency and emission considerations. This trend will only be proven to be successful whenever the robustness of a full-electric heat demand sector is similar or better than the current levels of security of supply (currently delivered by the gas infrastructure). Additionally, in extreme cold or hot periods (taking into account cooling by air-conditioners) flexibility by the power-to-heat (or cold) options can be limited or even eliminated by the fact that the equipment is running on full power. We strongly advise to assess the risks of infrastructural energy system integration in relation to energy systems' robustness and security of supply. Such risk assessments to be based on extreme weather scenarios and potential increased extremeness of weather changes and temperature outliers resulting from climate change (as robustness will become increasingly important).

APPENDICES

Appendix 1. Concepts out of scope

The TKI Systeemintegratie project entails 4 topics (see paragraph 1.1). This particular report focusses on one of these topics, i.e. 'the role of infrastructures'. To distinguish between the topics thus to set clear system boundaries for the analysis presented in this report, we use the following criterion in the selection of concepts that enable infrastructural system integration:
"The concept is a physical asset that realizes a physical connection between the electricity network and another network (part of an infrastructure) that offer a form of access to multiple users (regulated/negotiated)".

Based on this definition and the criteria listed in chapter 3 a selection of concepts is done, which will be further analyzed to identify their role for infrastructural system integration. The concepts that were found to be out of scope of the analysis in this report are listed below. These are concepts that are identified as relevant concepts/technologies to contribute to the energy transition and to play an important role in future energy systems, but should do not meet the criteria set in this project. In order to avoid that concepts remain undiscussed, they have been listed in **Error! Reference source not found.**. We expect these concepts to be further analyzed in one of the other topics of the TKI Systeemintegratie project.

Concepts excluded from the analysis

Concept	**Reason for exclusion**
Power-to-fuels (methanol, DME, etc)	Industrial end-use of hydrogen; no third party access to network
Power-to-Compression (underground gas storage)	Demand response; No third party access
Power-to-liquefaction (refrigeration of natural gas to LNG)	Industrial end-use; No third party access
Industrial freezers	Demand response; No third party access
Electric cooling of office buildings	Demand response; No third party access
Refrigerators and freezers in households	Demand response; No third party access
Electric heat pumps (at the end-user)	Demand response; No third party access
Micro-CHP (at the end-user)	Demand response; No third party access
Hybrid neighbourhoods: 50% of houses equipped with heat pumps and 50% with micro-CHP's	No third party access (because concept describes measures within households)
Reversible fuel cell (electrolysis) system with hydrogen network	No commercial technology yet (not foreseen te be so on the short term)

Appendix 2. Factsheets of concepts

	Electric heat pump in heating network		
Application of an electric heat pump for hot water production for horticulture or heating network. The electric heat pump is added to an existing system of an individual horticultural enterprise or a heating network in built up area's in addition to a conventional heat source/steam generator - either a gas fired boiler or a gas fired CHP. During periods with high power prices the heat pump is in hot standby and hot water is generated by the conventional gas fired heat source. During periods with low power prices the heat pump takes over hot water generation and steam production by the conventional gas fired heat source is ramped down.			
	Description	**Sources/comments**	**Valuation**
Type of Concept	Power to Heat		
Region	Regional/decentralized		
Application area	Domestic/dwellings	But also "Utility buildings" and "Greenhouse	
Type of grids involved	Electricity grid, gas grid, regional heating network		
Source of flexibility	CHP can be shut down or ramped down during periods with low power prices - when CHP power generation is uneconomical. During these periods heat for network is temporarily supplied by heat pump.		
Typical capacity	A large scale electric heat pump has a typical capacity of 1 - 10 MW generated heat (200 - 3,000 kW_e).		
Characterization of flexibility	Flexibility is dependent on season and time. Typical reaction time of one minute or less (depending on control system). Typical duration a few hours. Suitable for imbalance markets.		
Typical costs	According to DEA, 2012 an electric heat pump with send out capacity of 1 - 10 MWth utilizing a heat source of 35°C and CO_2 as refrigerant (COP 3,6) requires an investment of 500 euro/kW_{th} - 900 euro/kW_{th} installed. RVO gives much lower specific investments of only 250 euro/kW_e (COP 4.7, 500 kW_e).Typical CAPEX would amount to 30 - 300 euro/MWhe. OPEX (ex power purchase costs) are given in (DEA, 2012) as amounting to 2.4 - 4.9 euro/kWe		
Scenario dependency	Applicable in scenario's where electricity price are low or might even become negative. Only wintertime flexibility so typically scenarios with large penetration of wind. Solar flex is mainly needed in summer time and then this flexibility is not available.		
Value	Qualitative value is primarily in decarbonizing heat supply in built up area's and in providing flexibility services to the power grids. These application areas provide a modest capacity, given the limited amount of heat supplied to built up area's by means of a heating grid annually (approximately 20 PJ). Also limited flexibility value because only relevant in winter scenario's and not in summer scenario.		
Challenges			
Technological	Proven technology, applied in Denmark and Germany. Indications for improvements are given the tableto the right:	http://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP%20Tech%20Brief%20E12%20Heat%20Pumps.pdf	++
Economical	Compared with typical investments in low temperature boilers, the specific investments for electrical heat pumps are very high - 5 - 10 times higher. A high COP-value may make the heat pump economical viable for situations with low power prices.	(see table below)	+
Managerial	Management of heat pump integration into heating network has been elaborated in applications in Germany and Denmark		+
Institutional/regulatory	Need for research into the grid fee consequences of implementation of a heat pump		++
Societal	No issues		+

	2030		2050	
	Heating	Cooling	Heating	Cooling
Cost reduction, %	20-30	5-15	30-40	5-20
COP increase, %	30-50	20-40	40-60	30-50
Delivered energy cost reduction, %	20-30	10-20	30-40	15-25

Valuation is based on expected	
--	Considerable challenge, difficult to solve, no solution yet
-	Challenge exists but probably solvable, solution in development
o	No challenges, neutral or unkown, existing solution
+	Favourable environment, easliy solvable, existing solutions
++	Very favourable environment, very easily solvable, common practice
	No entry = unrated

	Electric industrial boiler		
Application of an electric boiler for medium pressure or low pressure steam generation for industrial purposes. The electric boiler is added to an existing steam system of an individual industrial company in addition to a conventional heat source/steam generator - either a gas fired boiler or a gas fired CHP. During periods with high power prices the electric boiler is in hot standby and steam is generated by the conventional gas fired heat source. During periods with low power prices the electric boiler takes over steam generation and steam production by the conventional gas fired heat source is ramped down.			
	Description	**Sources/comments**	**Valuation**
Type of Concept	Power to Heat		
Region	Local/building specific		
Application area	Industry		
Type of grids involved	Electricity grid, steam network of industrial company		
Source of flexibility	CHP or gas fired boiler can be shut down or ramped down during periods with low power prices. Steam is temporarily supplied by		
Typical capacity	A typical electric boiler has a capacity in the range of 1 - 70 MWe. It can produce steam of temperatures up to 250 - 300°C		
Characterization of flexibility	The electric boiler can ramp up from about two per cent of full load up to 100 percent within 3 - 10 minutes. No seasonal limitations. The boiler needs to be in hot standby to allow rapid ramp up in steam		
Typical costs	According to DEA, 2012 an electric boiler of 20 MW_{th} with an efficiency of 99% requires an investment of 50 - 70 euro/kW_{th}. Fixed O&M costs amount to 1,100 euro/MW_{th} and variable O&M costs to 0.5 euro/MWh_{th}. Not taken into account yet are changes in grid fee of		
Scenario dependency	There is no seasonal limitation as the heat is supplied to a contineous		
Value	Qualitative value is primarily in decarbonizing heat supply in industrial applications and in providing flexibility services to the power grids. Assuming a maximum temperature for generated steam, maximum capacity can amount to approximately 6,000 MW_{th} and a		
Challenges			
Technological	Proven technology, applied commercially in Sweden and Norway. Not yet clear what technical modifications are required for integrating an electric boiler in a conventional steam cycle.	Already applied as standard technology in heating grid in Scandinavia and Germany	++
Economical	Investment costs for the boiler sec are comparable to those of a conventional gas fired boiler. How much investments are concerned with integration into an existing steam cycle has not been explored	Specific investment costs are comparable with reference	++
Managerial	There is still need for research into the integration of an electric water heater in an industrial steam cycle. It is still unclear how well steam production by a gas fired boiler or CHP can be tuned to eachother. In addition, it is not clear how an electric steam boiler fits	Already applied as standard technology in industrial processes in Scandinavia	+
Institutional/regulatory	Need for research into the grid fee consequences of implementation of an electric boiler	Unknown yet	0
Societal	This might be a conveniant solution from a socialal perspective because no need for new infrastructure, decarbonization of industry and products and operated in industrial environment (safety).		+

Valuation is based on expected challenges in this field	
--	Considerable challenge, difficult to solve, no solution yet
-	Challenge exists but probably solvable, solution in development
o	No challenges, neutral or unkown, existing solution
+	Favourable environment, easliy solvable, existing solutions
++	Very favourable environment, very easily solvable, common practice
	No entry = unrated

	Flexible CHP unit		
Application of a combined heat and power (CHP) system to provide flexibility to both the electricity network and gas network by enabling to ramp up or down power production whenever demanded. Heat storage is needed in order to store the produced heat in times of power production need and lack of heat demand.			
	Description	**Sources/comments**	**Valuation**
Type of Concept	Gas to Power	Flexible CHP enables to provide power load whenever intermittency of RES results in a generation dip. Flexible operation also offers the possibility to ramp up or down according to the demand for heat or electricity.	
Region	National and Regional/Decentral (industrial or district heating)	This concept entails CHP installations for feeding into district heating networks for domestic or office building heating. Application for feeding industrial heating networks is also included.	
Application area	Grid/Market Support		
Type of grids involved	Electricity grid; natural gas grid, heating network		
Source of flexibility	Ramping up & down; reserve power load	Flexible CHP enables to ramp up when power prices are high and ramp down when power prices are low. Furthermore, flexibility to the energy system in delevered through power generation capacity to back up RES fluctuation	
Typical scale	Commercially available in a wide range of power & heating capacity	Small as well as large scale installations available	
Characterization of flexibility	Cold start to full load: <5 min. Deployment from standby to full load: 1 min.		
Typical costs	Investment costs: 350 euro/kWe at 9,5 MWe. Operational costs: 5 euro/MWhe at 9 Mwe.		
Scenario dependency	Applicable in scenario's where electricity price are high, to provide flexible power load. Dependency is on the instantaneous heat demand and the simultaneity with low power prices. This depenence can be eliminated by applying a heat storage facility.		
Value	Its value is in possibility to create reserve power to back up RES, while feeding heat to district heating. Additional operational flexibility offers dynamic ramping when needed.		
Challenges			
Technological	CHP units are common technology and widely applied. The technical challenge is the coupling of the CHP in dynamic mode with the heating network and or storage tank.	Coupling of the networks with the installation in a way that dynamic/flexible operation is enabled is a technological challenge.	+
Economical	Economic challenge is the additional investments that are needed to enable dynamic operation of the CHP, for fast ramping.	Current commercially available CHP systems are not engineered for dynamic operation. However, relatively small technological changes need to be done in order to add this capability. So solutions are there but just need to be implemented and the benefits have to outway the costs	+
Managerial	CHP installations need to be controlled based on external (real-time) signals: power price, imbalance markets, heat demand and heat storage capacity (availability).	Coupling of the networks with the installation in a way that dynamic/flexible operation is enabled is a technological challenge.	+
Institutional/regulatory	No specific challenges identified. Balancing markets must allow aggregation of loads to apply for this market.		o
Societal	No specific challenges identified		+

Valuation is based on expected challenges in this field	
--	Considerable challenge, difficult to solve, no solution yet
-	Challenge exists but probably solvable, solution in development
o	No challenges, neutral or unkown, existing solution
+	Favourable environment, easliy solvable, existing solutions
++	Very favourable environment, very easily solvable, common practice
	No entry = unrated

	Hybrid district heating		
This concept entails the implementation of a centralized combined district heating system based on an electrical heat pump and a gas fired heating system, i.e. CHP system or a gas fired boiler, to be operated hybrid.			
	Description	Sources/comments	Valuation
Type of Concept	Gas-to-Power & Power-to-Heat [combined]		
Region	National and Regional/Decentral (district heating)		
Application area	Grid/Market Support		
Type of grids involved	Electricity grid; natural gas grid, heating network		
Source of flexibility	Fuel switch; ramping up & down; reserve power load		
Typical scale	Heat pump systems are commercially available < 1 Mwe, CHP systems are commercially available in small scale and large scale systems.		
Characterization of flexibility	Cold start to full load: <5 min. Deployment from standby to full load: 1 min.		
Typical costs	Investment costs: 1477 - 2000 euro/kWe at 9,5 MWe. Operational costs: 5 euro/MWhe & 10 €/kWe at 9 Mwe.		
Scenario dependency	Applicable in scenario's where electricity price are high, to provide flexible power load, and when power prices are low. Shifting balance between power use and power production. Dependency is on the instantaneous heat demand and the simultaneity with prices. This depenence can be eliminated by applying a heat storage facility.		
Value	Its value is in possibility to create reserve power to back up RES, while feeding heat to district heating. Additional operational flexibility offers dynamic ramping when needed and by consuming electricity to avoid grid imbalance resulting from surplus power. High efficiency concept.		
Challenges			
Technological	CHP units are common technology and widely applied. The technical challenge is the coupling of the CHP in dynamic mode with theheat pump system and the heating network and or storage tank. Heat pump systems often do not meet their technological performance in terms of efficiency. Technical challenge is to realize the coupling and operating philosophy	Coupling of the networks with the hybrid system in a way that dynamic/flexible operation is enabled, is a technological challenge. Also the subsequent dynamic operation based on price or supply/demand signals is a challenge.	-
Economical	Economic challenge is the additional investments that are needed to enable dynamic operation of the CHP, for fast ramping. Also the investment costs of heat pump systems are high and return on investment can be challenging.	Current commercially available CHP systems are not engineered for dynamic operation. However, relatively small technological changes need to be done in order to add this capability. So solutions are there but just need to be implemented and the benefits have to outway the costs. Additionally the total investment of the hybrid system must be covered by the benefits.	-
Managerial	Hybrid sistrict heating needs to be controlled based on external (real-time) signals: power price, imbalance markets, heat demand and heat storage capacity (availability).		-
Institutional/regulatory	No specific challenges identified. Balancing markets must allow aggregation of loads to apply for this market.		o
Societal	'No specific challenges identified		+

Valuation is based on expected challenges in this field	
--	Considerable challenge, difficult to solve, no solution yet
-	Challenge exists but probably solvable, solution in development
o	No challenges, neutral or unkown, existing solution
+	Favourable environment, easliy solvable, existing solutions
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	No entry = unrated

	Heat storage in district heating		
A hot water tank is integrated in a hot water heating network providing heat to built environment or horticultural area. Heat is produced by a CHP - e.g. a gas engine. Part of the produced heat is stored in the hot water tank. In periods of low power prices the CHP can be shut down and hot water is temporarily supplied by the storage tank.			
	Description	Sources/comments	Valuation
Type of Concept	Gas to Power		
Region	Regional/decentralized		
Application area	Domestic/dwellings	But also "Utility buildings" and "Greenhouse cultivation"	
Type of grids involved	Electricity grid, regional heating network		
Source of flexibility	CHP can be shut down during periods with low power prices. Heat for network is temporarily supplied from storage tank.		
Typical capacity	Varying from smaller units of several hundreds of MWhth to large scale units of several thousands of MWh_{th} for district heating. Ratio between storage capacity and power generation capacity of the CHP is approximately 10 MWh_{th} to 1 MW_e.	Assumption: storage capacity 10 hours at maximum capacity. Heat/power ratio of the CHP heat source is approximately 1 : 1.	
Characterization of flexibility	Flexibility is dependent on season and time. Typical reaction time of one minute or less (depending on control system) for supply of hot water from tank, for CHP 3% - 5% per minute rap down, 1/2 - 1 hour for ramp up from cold start to fullload. Typical duration a few hours. Suitable for imbalance markets.		
Typical costs	Investment for a hot water buffer of 22,000 m3 at a pressure of 7 barg (energy content is 1,800 MWh) is roughly estimated at 5 million €. For 90/70 ° C systems behind for instance a gas engine for horticulture, utility buildings or district heating this is a very cost-effective measure		
Scenario dependency	Applicable in scenario's where electricity price are low. Mainly wintertime flexibility so typically scenarios with large penetration of wind but also imblance market which is year round.		
Value	Qualitative value is primarily in providing flexibility services to power generation associated with low temperature heating grids and horticulture. As most of these systems have already been fitted with such a storage facility, potential will be limited.	But there still is potential, as illustrated by http://www.nuon.com/activiteiten/producten-en-diensten/stadswarmte/stadswarmteprojecten/warmtebuffer-diemen/	
Challenges			
Technological	Proven technology, no challenges. Adjustments only concern the integration of the hot water tank in the heating network, No adjustments are required in the buildings or greenhouses receiving the distributed hot water.	Possibly adjustments for exisitng buildings. Space is an issue.	++
Economical	Intermediate storage of heat in hot water tanks is common technology, having been applied for decades proving economic viablitiy.		++
Managerial	Owner might have to allow others to control his installation. Especially in horticultural environment sensitive issue, due to importance of heat (e.g. to prevent mold).	In netherlands years of experience with this issue. For built environmet newer issue	+
Institutional/regulatory	No issues known		
Societal	No issues known		

Valuation is based on expected challenges in this field	
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-	Challenge exists but probably solvable, solution in development
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	No entry = unrated

	Industrial heat storage		
A molten salt storage tank is integrated in a steam system of an industrial production site for storage of medium temperature heat. Heat is produced by a CHP - e.g. a gas turbine with HRSG. Part of the produced heat is stored in the storage tank. In periods of low power prices the CHP can be shut down and steam is temporarily supplied by			
	Description	Sources/comments	Valuation
Type of Concept	Gas to Power		
Region	Local/building specific		
Application area	Industry		
Type of grids involved	Electricity grid, industrial steam network		
Source of flexibility	CHP can be shut down during periods with low power prices. Steam is temporarily supplied from storage tank.		
Typical capacity	Typical storage capacity amounts to hundreds of MWh_{th}. Ratio between storage capacity and power generation capacity of the CHP is approximately 20 MWh_{th} to 1 MWe.	Assumption: storage capacity 10 hours at maximum capacity. Heat/power ratio of the CHP heat source is approximately 1 : 1.	
Characterization of flexibility	Typical reaction time of one minute or less (depending on control system) for supply of hot water from tank, for CHP 3% - 5% per minute rap down, 1/2 - 1 hour for ramp up from cold start to fullload. Typical duration a few hours. Suitable for imbalance markets.		
Typical costs	A 850 MWh steam storage facility requires an investment of M€ 125. Assuming the storage facility is utilized on a daily base - storing 850 MWhth every day - storage costs amount to €13 - €14 per GJ of steam.		
Scenario dependency	Applicable in scenario's where electricity price are low.		
Value	'Qualitative value is primarily in providing flexibility services to power generation associated with process steam generation (CHP plant)		
Challenges			
Technological	Commercally applied technology, but still considerable potential for innovation. Adjustments only concern the integration of the molten salt storage tank in the steam network, No adjustments are required in the processes receiving and consuming steam.	Required space for storage tank is an issue.	+
Economical	Investment costs are higher than production costs for steam for a reference gas fired boiler.		-
Managerial	Reliability might be an issue. Industrial managers are not fond of changes in their production installation. Need for proven technology and examples of succesful implementation.		o
Institutional/regulatory	No issues known		
Societal	No issues known		

Valuation is based on expected challenges in this field	
--	Considerable challenge, difficult to solve, no solution yet
-	Challenge exists but probably solvable, solution in development
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	No entry = unrated

	Power-to-Hydrogen		
Application of power-to-gas technology (electrolysis) to convert electricity into a gaseous energy carrier (hydrogen) for the purpose of producing industrial feedstock, fuel, energy storage, de-bottlenecking or capacity transfer.			
	Description	**Sources/comments**	**Valuation**
Type of Concept	Power to Gas	PEM Electrolysis **Important note:** for electrolysis , different technologies (principles) are available. We chose PEM electrolysis because of its technical capabilities and market perspective. However, alkaline electrolysis can be considered as well (mature technology but not very well able to follow fluctuating loads).	
Region	National and Regional/Decentral	Hydrogen application in gas grids is limited by gas grid specifications (and possible end-user intolerance to H2) or by hydrogen demand of industrial processes. In terms of accommodation of excess power the regional level is most relevant since power capacity issues are expected to be more likely in regional then in transmission grids.	
Application area	Grid/Market Support & Industrial or mobility application	Hydrogen application in mobility (fuel stations) and industry is economically most obvious. Also injection in gas transmission or distribution grids is to be considered.	
Type of grids involved	Electricity grid; natural gas grid; industrial H2 grids (e.g. NH3 production industry), fuel stations		
Source of flexibility	Industrial demand for hydrogen, gas grid energy capacity		
Typical scale	Commercially available in a range: 500kW - 10 MW (realistically)	PEM electrolysis is about commercially available from several kW's up to 2 MW per stack. PEM's can be stacked up to 100's of MW's. In the near future PEM systems of 50 - 100 MW per stack are expected.	
Characterization of flexibility	Cold start: <10 min. Deployment from standby: seconds. 1 - hundreds of MW's.	Minimum run time per start-stop: >few hours to days to prevent from material degradation and integrity loss. Source: *DNV GL & ECN (2013) Technology Review Power to Gas.*	
Typical costs	Investment costs: 1500 euro/kWe at 100 kWe. Investment costs: 700 euro/kWe at 5 MWe. Operational costs: 1,8 euro/MWhe at 100 kWe and 100 hours. Operational costs: 0,022 euro/MWhe at 5MWe and 4000 hours. At this momentelectrolysis hydrogen can be produced at about 5 - 8 euro/kg whereas SMR hydrogen (conventional steam methane reforming) is produced at 2 - 3 euro/kg.	MW and MWh's mentioned is 'absorption' capacity / installed capacity, not production. Investment costs are 'balancing of plant' but could be with margin of + or - 30% depending on site specific issues. Electrolysers have a lifetime of about 50,000 operating hours, however, the lifetime will decrease a a function of cycles (dynamic and start/stop operations) as the catalyst will degrade.	
Scenario dependency	Applicable in scenario's where electricity price are low or might even become negative (renewable or non-renewable) or locations that (will) experience physical overload of power: grid bottlenecks.		
Value	Qualitative value is primarily in decarbonizing energy system, industry and mobility, and secondary in providing flexibility services to the power grids. These application areas provide a huge accommodation capacity (orders of magnitude bigger than alternatives)	Source: *ECN/DNVGL 2014 - Exploring role for PtG in Dutch Energy System* . Please note that flexibility service is an essential value to enable establishment of a power-to-gas market. However, its role seems to be more robust as decorbonazation technology to realize far-going emission reduction targets.	
Challenges			
Technological	Demonstration phase (market launch preperation). PEM electrolysis an emerging technology and is applied in fuel cells as well (PEM) Design and operating requirements for PtG, aplied for providing flexibility to the energy system, demand for qualification and verification of the technology for that specific purpose. [please note that alkaline electrolysis is mature technology and widely applied for industrial hydrogen production, already for decades. But Alkaline electrolysis does not meet the dynamic performance capabilities of PEM].	As hydrogen is currently very limited accepted for injection in the existing natural gas grid, household application of electrylosis for flexibility enhancement does not seem to be obvious. Rather to be foreseen for locations where hydrogen demand exists (fuel stations, industry, etc). Water supply is required but electrolysis includes water desalination (reversed osmosis) so tapwater is sufficient. Graded a '+' because the technology (chemical principles) is known. But new application requires technological adaptions and improvements. In terms of efficiency and operational capabilities, there is potential for improvement. Making the technology an interesting enabler.	+
Economical	High investment costs for electrolysis , however, strong investment cost decreases possible. Economics can also be optimized by increasing the utilization; by combining flexibility services with producing industrial feedstock/products (hydrogen or derivatives).	Graded a 'o' because the investment costs are currently high, but expected to drop significantly (up to 60% decrease) when market develops. At the moment a robust business case is still limitedely possible.	o
Managerial	PtG installations need to be controlled based on external (real-time) signals: power price, imbalance markets, hydrogen tolerance, process conditions.	Technically possible but developments required	+
Institutional/regulatory	**1.** Balancing markets must allow aggregation of loads to apply for this market. **2.** The current regulatory/legal segmentation of the power and gas production and transmission/distribution operations hampers the implementation of power-to-gas (e.g. gas TSO is not allowed to operate PtG installation because gas is 'produced'). **3.** Since PtG is a cross sectoral solution it remains unclear whcih stakeholder should take responsibility for investing in and operating PtG installations. **4.** Current TSO/DSO gas quility standards limit the injection of hydrogen into the gas infrastructure.	On a institutional and regulatory level there is lots to develop and improve in order to make PtG reality and adopted by market parties	-
Societal	Hydrogen application in industry and mobility is a high value application, because renewable products/derivatives can be produced. This system might not optimize on CO2-emissions; because of relatively low efficiency at this moment. Furthermore, the physical properties of hydrogen are distinctive from those of natural gas, thereby causing social resistance to admixing hydrogen into natural gas and possibly the need to replace burners (both industrial and domestic) in order to guarantee safe end-use of hydrogen.	Injection of hydrogen in natural gas grids is not a typically 'accepted' option at the moment. Hydrogen application in fuell station is an interesting configuration (from business case and applicability perspective). But hydrogen mobility needs te be established, which means that there is a dependency of developments in the mobility sectore for this specific configuration to be useful. 'Graded a '-' for injection of hydrgen in the gas grid. It would get a '++' for application in industry. A logic first step for implementation of electrolysis for 'demand side management' purposes would be the industrial application (high value and infrastructure available). Power-to-hydrogen can than be further exploited when hydrogen mobility emerges and natural gas grids are prepared for unconventional gases as hydrogen.	+

Valuation is based on expected challenges in this field	
--	Considerable challenge, difficult to solve, no solution yet
-	Challenge exists but probably solvable, solution in development
o	No challenges, neutral or unkown, existing solution
+	Favourable environment, easliy solvable, existing solutions
++	Very favourable environment, very easily solvable, common practice
	No entry = unrated

	Power-to-Methane		
Application of power-to-gas technology (electrolysis and methanation) to convert electricity into a gaseous energy carrier (methane) for the purpose of energy storage, de-bottlenecking or capacity transfer.			
	Description	**Sources/comments**	**Valuation**
Type of Concept	Power to Gas	PEM Electrolysis and methanation (nickel based). Efficiency of PEM electrolysis is 75% - 80% and methanation is approx. 85%. Total power-to-gas efficiency is 60% - 70%. Nickel based methanation is exothermic and produces heat (approx 300 C) which can be applied in industry. **Important note:** for both electrolysis and methanation, different technologies (principles) are available. We chose PEM electrolysis because of its technical capabilities and market perspective. We chose nickel based methanation because of its applicability and state of development. However, alkaline electrolysis can be considered as well (mature technology but not very well able to follow fluctuating loads) and biological methanation (in R&D phase and not much or none industry references)	
Region	National and Regional/Decentral	Availability of CO2 for methanation induces limitation in locations. CO2 sources relevant for PtG are industrial CO2 and CO2 from biogas. In terms of accommodation of excess power the regional level is most relevant since power capacity issues are expected to be more likely in regional then in transmission grids.	
Application area	Grid/Market Support & Gas (commodity) production	Injection in gas transmission or distribution grids is obvious. Also CNG storage/supply can be considered. High temperature heat from methanation can be applied in industry (putting constraints to location though).	
Type of grids involved	Electricity grid; natural gas grid	Regional and transmission grids	
Source of flexibility	Capacity and volume in gas infrastructure to accommodate electricity (surplus/excess) to prevent power curtailment and decarbonize gas sector		
Typical scale	Commercially available in a range: 500kW - 10 MW (realistically)	Methanation commercially available: >3MW (up to GW scale). However, biological methanation can be done at smaller capacities (> 200 kW). PEM electrolysis is about commercially available from several kW's up to 2 MW per stack. PEM's can be stacked up to 100's of MW's. In the near future PEM systems of 50 - 100 MW per stack are expected.	
Characterization of flexibility	Cold start: <10 min. Deployment from standby: seconds. 1 - hundreds of MW's.	These numbers hold for electrolysis, methanation is a less flexible technology (ramp-up/down in 5-10 minutes; cold start <hours). Hydrogen buffer can be applied. Minimum run time per start-stop: >few hours to days to prevent from material degredation and integrity loss. Source: *DNV GL & ECN (2013) Technology Review Power to Gas.*	
Typical costs	Investment costs: 3500 €/kWe at 100 kWe. Investment costs: 1500 €/kWe at 5 MWe. Operational costs: 4 €/MWhe at 100 kW and 100 hours. Operational costs: 0,042 €/MWh at 5MW and 4000 hours.	MW and MWh's mentioned is 'absorption' capacity / installed capacity, not production. Investment costs are 'balancing of plant' but could be with margin of + or - 30% depending on site specific issues. Operational costs exclude costs for electricity and for CO2 (as it is assumed that CO2 is otherwise emitted) which can be substracted from biogas upgrading. In case carbon capture is foreseen additional costs for CO2 (a 10 - 15 €/ton) needs to be considered.	
Scenario dependency	Applicable in scenario's where electricity price are low or might even become negative (renewable or non-renewable) or locations that (will) experience physical overload of power: grid bottlenecks. Or where a demand is for renewable hydrogen as a feedstock or fuel.		
Value	Qualitative value is primarily in decarbonizing energy system and industry (renewable hydrogen in industry and mobility), secondary in providing flexibility services to the power grids.	Source: *ECN/DNVGL 2014 - Exploring role for PtG in Dutch Energy System* . Please note that flexibility service is an essential value to enable establishment of a power-to-gas market. However, its role seems to be more robust as decorbonazation technology to realize far-going emission reduction targets.	
Challenges			
Technological	Demonstration phase (market launch preperation). PEM Electrolysis is an emerging technology and is in reversed process used in fuel cells. Design and operating requirements for PtG, aplied for providing flexibility to the energy system, demand for qualification and verification of the technology for that specific purpose. The CO2 source might be an issue; CO2 needs to have high purity.	Because of the infrastructure and sources required it seems to be an applicable solution for industry or biogas production plants. Methane injection in natural gas grid can be done. Injection in L-gas/G-gas networks wobbe adjustment is required (done with nitrogen or CO2), in H-gas networks methane can purely be injected. Graded a 'o' because a combination of considerations: the technology (chemical principles) is known and has been applied. But new application requires technological adaptions and improvements. In terms of efficiency and operational capabilities, there is potential for improvement. On the resource site, CO2 (quality and quantity) is important and puts constraints on its applicability. This system configuration requires lots of infrastructure in cae of efficient operation (power, CO2, water, heat, gas and possibly oxygen).	**o**
Economical	High investment costs for electrolysis and methanation, however, strong investment cost decreases possible. Economics can also be optimized by increasing the utilization; by combining flexibility services with producing industrial feedstock/products (hydrogen or derivatives).	Graded a '0' because the investment costs are currently high, but expected to drop significantly (up to 60% decrease) when market develops. At this moment there is not yet a robust business case for PtG.	**o**
Managerial	PtG installations need to be controlled based on external (real-time) signals: power price, imbalance markets, hydrogen tolerance, methanation process conditions.	Technically possible but developments required	**+**
Institutional/regulatory	**1.** Balancing markets must allow aggregation of loads to apply for this market. **2.** The current regulatory/legal segmentation of the power and gas production and transmission/distribution operations hampers the implementation of power-to-gas (e.g. gas TSO is not allowed to operate PtG installation because gas is 'produced'). **3.** Since PtG is a cross sectoral solution it remains unclear which stakeholder should take responsibility for investing in and operating PtG installations.	On a institutional and regulatory level there is lots to develop and improve in order to make PtG reality and adopted by market parties	**-**
Societal	Methane is an accepted gas and all infrastructure is present. This system might not optimize on CO2-emissions; because of relatively low efficiency and end-use emission of CO2 (renewable or non-renewable).	Gas quality adjustment before injection might be needed, but is common practice. CO2 recycling is an important feature of power-to-methane. Also methane as a product is a known and accepted substance. This technology is easy to implement from a societal side because all infrastructure is available and known.	**+**

Valuation is based on expected challenges in this field	
--	Considerable challenge, difficult to solve, no solution yet
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	No entry = unrated

Appendix 3. Overview of valuation of concepts

Electric heat pump in heating network

Quantification and monetarization of value of concepts	Type	Qualitative contribution	Motivation of qualitative ranking	Quantification of value	Monetization of value
Frequency containment reserves'(30 seconds)	System stability	+/++	Based on the fact that time required from cold start to full load is only several minutes.	Does this concept has the opportunity to provide this service. How much kW of primary reserve can be supplied.	Expected price level for delivering primary reserves (EUR/kW)
Frequency restoration/replacement reserves (15 minutes TPU, imbalance markets)	System stability	+/++	Based on the fact that time required from cold start to full load is only several minutes.	Amount of kWh available to supply on 15-minutes base	Value per kWh, bases on current markets and projection to future. Use ECN-study?
Reserve power (hour)	System stability	0/+	not relevant as a direct power generation technology, the technology consumes electricity and is applied for utilization of surplus power. However, as the technology can be ramped down or shut down very quickly, it could be regarded as interruptible capacity or 'negative' reserve power.	Amount of kW available to supply on daily basis	Price per kW, reference alternative (GT)
Reserve power (day)	System stability			Amount of kW available to supply on daily basis	Cost per kW, reference alternative (GT)
Reserve power (week)	System stability			Amount of kW available to supply on weekly basis	Cost per kW, reference alternative (GT)
Reserve power (year)	System stability			Amount of kW available to supply on yearly basis	Cost per kW, reference alternative (GT)
Reduced or deferred investments HV-grid	Grids	0	A heat pump is typically too small in scale to have a real impact on HV-grid imbalances and is connected to low or medium voltage grids	Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year)
Reduced or deferred investments MV-grid	Grids	0/+	In town quarters with both high penetration level of PV and heat distribution grid implementing electric heat pumps may provide an outlet for surplus electricity during colder periods during the year	Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year)
Reduced or deferred investmens LV-grid	Grids	0/+	In town quarters with both high penetration level of PV and heat distribution grid implementing electric heat pumps may provide an outlet for surplus electricity during colder periods during the year	Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year). Cost of alternative (volt/var control
Jobs created	Economic value	0/+	There is probably some employment related to installation and production. As it concerns centralized units employment creation potential will be limited.	Number of jobs	Value per job
Value added	Economic value	+	Assuming the businesscase is sufficiently favourable for implementation, there will obviously be additional added value compared to the reference situation with gas fired heat generation and surplus power that has to be disposed of.		
Export value	Economic value	0/+	Not very many heat pump producers in The Netherlands, certainly not of large heat pumps.	Number of units/hours of services	Value per unit/service
CO2-reduction	Sustainability	0	See discussion concerning coal based power production in scenario's with high renewable energy contributions	Total reduction per concept (ton CO2)	Value of CO2, based on expected market cost for CO2.

Qualitative contribution	
--	No contribution at all now or in future, far better alternatives/competition
-	Possible contribution now or in future, some better alternatives/competition
o	Realistic contribution now or in near future, competitive with regard to alternatives/competition
+	Significant contribution now, far better than or few alternatives/competition
++	Very significant contribution now, hardly any alternatives/competition
no entry	unrated

Electric industrial boiler

Quantification and monetarization of value of concepts	Type	Qualitative contribution	Motivation of qualitative ranking	Quantification of value	Monetization of value
Frequency containment reserves'(30 seconds)	System stability	+/++	Based on the fact that time required from cold start to full load is only several minutes and from hot standby (at 1% - 10% load) to full load within 30 seconds.	Does this concept has the opportunity to provide this service. How much kW of primary reserve can be supplied.	Expected price level for delivering primary reserves (EUR/kW)
Frequency restoration/replacement reserves (15 minutes TPU, imbalance markets)	System stability	+/++	Based on the fact that time required from cold start to full load is only several minutes.	Amount of kWh available to supply on 15-minutes base	Value per kWh, bases on current markets and projection to future. Use ECN-study?
Reserve power (hour)	System stability	0/+	not relevant as a direct power generation technology, the technology consumes electricity and is applied for utilization of surplus power. However, as the technology can be ramped down or shut down very quickly, it could be regarded as interruptible capacity or 'negative' reserve power.	Amount of kW available to supply on daily basis	Price per kW, reference alternative (GT)
Reserve power (day)	System stability			Amount of kW available to supply on daily basis	Cost per kW, reference alternative (GT)
Reserve power (week)	System stability			Amount of kW available to supply on weekly basis	Cost per kW, reference alternative (GT)
Reserve power (year)	System stability			Amount of kW available to supply on yearly basis	Cost per kW, reference alternative (GT)
Reduced or deferred investments HV-grid	Grids	0	An electrode boiler is typically too small in scale to have a real impact on HV-grid imbalances and is connected to the medium voltage grids	Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year)
Reduced or deferred investments MV-grid	Grids	0/+	In town quarters or regions with both high penetration level of PV and wind and industrial heat demand or heat distribution grids electrode boilers may provide an outlet for surplus electricity year round, respectively in winter period.	Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year)
Reduced or deferred investmens LV-grid	Grids	0	An electrode boiler is typically connected to medium voltage grid.	Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year). Cost of alternative (volt/var control
Jobs created	Economic value	0/+	There is probably some employment related to installation and production. As it concerns centralized units employment creation potential will be limited.	Number of jobs	Value per job
Value added	Economic value	+	Assuming the businesscase is sufficiently favourable for implementation, there will obviously be additional added value compared to the reference situation with gas fired heat generation and surplus power that has to be disposed of.		
Export value	Economic value	0	No electrode boiler producers are known to be based in The Netherlands	Number of units/hours of services	Value per unit/service
CO2-reduction	Sustainability	0	See discussion concerning coal based power production in scenario's with high renewable energy contributions	Total reduction per concept (ton CO2)	Value of CO2, based on expected market cost for CO2.

Qualitative contribution	
--	No contribution at all now or in future, far better alternatives/competition
-	Possible contribution now or in future, some better alternatives/competition
o	Realistic contribution now or in near future, competitive with regard to alternatives/competition
+	Significant contribution now, far better than or few alternatives/competition
++	Very significant contribution now, hardly any alternatives/competition
no entry	unrated

Flexible CHP unit

Quantification and monetarization of value of concepts	Type	Qualitative contribution	Motivation of qualitative ranking	Quantification of value	Monetization of value
Frequency containment reserves'(30 seconds)	System stability	0	Based on the fact that time required from cold start to full load is only several minutes and from hot standby (at 1% - 10% load) to full load within 30 seconds.	Does this concept has the opportunity to provide this service. How much kW of primary reserve can be supplied.	Expected price level for delivering primary reserves (EUR/kW)
Frequency restoration/replacement reserves (15 minutes TPU, imbalance markets)	System stability	++	From stand by modus this concept offers good opportinity to provide frequency restauration.	Amount of kWh available to supply on 15-minutes base	Value per kWh, bases on current markets and projection to future. Use ECN-study?
Reserve power (hour)	System stability	++	All applicible since flexible CHP can act as short term restoration as well as long term power and heat generation	Amount of kW available to supply on daily basis	Price per kW, reference alternative (GT)
Reserve power (day)	System stability			Amount of kW available to supply on daily basis	Cost per kW, reference alternative (GT)
Reserve power (week)	System stability			Amount of kW available to supply on weekly basis	Cost per kW, reference alternative (GT)
Reserve power (year)	System stability			Amount of kW available to supply on yearly basis	Cost per kW, reference alternative (GT)
Reduced or deferred investments HV-grid	Grids	--	Not connected to HV	Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year)
Reduced or deferred investments MV-grid	Grids		Not relevant for grid investment avoidence.	Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year)
Reduced or deferred investmens LV-grid	Grids		Not relevant for grid investment avoidence.	Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year). Cost of alternative (volt/var control
Jobs created	Economic value	++	Since flkexible CHP units are not widely applied yet, there is a good perspective related to the employment contribution. It is expected that the manufatcurers industry as well as operational workforce can be developed.	Number of jobs	Value per job
Value added	Economic value				
Export value	Economic value	++	The Dutch knowledge on gas fired heaters is important in international context. This concept contributes to maintaining and further developing the knowledge on gas fired heating systems. Potential additional knowledge creation on the developments for making the technology highly flexible and also the potential application of 'new gases' in flexible CHP's (and the technical adaptions to be done to realize efficient and effective operation).	Number of units/hours of services	Value per unit/service
CO2-reduction	Sustainability	0	High efficient concept for power generation as heat is utilized. However, there will be alternatives with similar or better CO2 reduction potential. The score on this parameter is also dependent of the source of gas utilized. In case of biogas the CO2 reduction potentail is great.	Total reduction per concept (ton CO2)	Value of CO2, based on expected market cost for CO2.

Qualitative contribution	
--	No contribution at all now or in future, far better alternatives/competition
-	Possible contribution now or in future, some better alternatives/competition
o	Realistic contribution now or in near future, competitive with regard to alternatives/competition
+	Significant contribution now, far better than or few alternatives/competition
++	Very significant contribution now, hardly any alternatives/competition
no entry	unrated

Hybrid district heating

Quantification and monetarization of value of concepts	Type	Qualitative contribution	Motivation of qualitative ranking	Quantification of value	Monetization of value
Frequency containment reserves'(30 seconds)	System stability	--	This concept focusses on the more long term heat delivery to a district heating network. The CHP part of this concept can be a flexible one, however, it is still very unlikely that this concept contributes to frequency reserve, as it is a more base load concept.	Does this concept has the opportunity to provide this service. How much kW of primary reserve can be supplied.	Expected price level for delivering primary reserves (EUR/kW)
Frequency restoration/replacement reserves (15 minutes TPU, imbalance markets)	System stability	--	More relevant than frequency reserve power but still not very likely because of the more baseload character of the concept	Amount of kWh available to supply on 15-minutes base	Value per kWh, bases on current markets and projection to future. Use ECN-study?
Reserve power (hour)	System stability	-	Not likely, see above reasons. In case of flexible CHP combination, than possible service	Amount of kW available to supply on daily basis	Price per kW, reference alternative (GT)
Reserve power (day)	System stability	++	Very likely service to be provided efficiently by this concept. Both for power conception by heat pump as well as power generation by CHP	Amount of kW available to supply on daily basis	Cost per kW, reference alternative (GT)
Reserve power (week)	System stability	++	Very likely service to be provided efficiently by this concept. Both for power conception by heat pump as well as power generation by CHP	Amount of kW available to supply on weekly basis	Cost per kW, reference alternative (GT)
Reserve power (year)	System stability	++	Very likely service to be provided efficiently by this concept. Both for power conception by heat pump as well as power generation by CHP	Amount of kW available to supply on yearly basis	Cost per kW, reference alternative (GT)
Reduced or deferred investments HV-grid	Grids		Not relevant for grid investment avoidence.	Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year)
Reduced or deferred investments MV-grid	Grids		Not relevant for grid investment avoidence.	Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year)
Reduced or deferred investmens LV-grid	Grids	++	Because of the combination of CHP with heat pump, the heat pump on district level provides a 'relieve' to the distribution power grid. This concept especially can contribute to avoiding grid reinforcement in LV grids.	Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year). Cost of alternative (volt/var control
Jobs created	Economic value	++	Since flexible CHP units are not widely applied yet, there is a good perspective related to the employment contribution. It is expected that the manufatcurers industry as well as operational workforce can be developed. For heat pumps the market is already established, so less to be developed. However, in the operation and maintenance of systems workforce is needed.	Number of jobs	Value per job
Value added	Economic value				
Export value	Economic value	++	The Dutch knowledge on gas firedand heat pumps heaters is important in international context. There a several manufacturs of these subsystems. This concept contributes to maintaining and further developing the knowledge on gas fired heating systems. Potential additional knowledge creation on the developments for making the technology highly flexible and also the potential application of 'new gases' in flexible CHP's (and the technical adaptions to be done to realize efficient and effective operation).	Number of units/hours of services	Value per unit/service
CO2-reduction	Sustainability	++	The combination of heat pump (with high COP) and a CHP for ancillary services makes the concept highly efficient and enables optimal power and heat production.	Total reduction per concept (ton CO2)	Value of CO2, based on expected market cost for CO2.

Qualitative contribution	
--	No contribution at all now or in future, far better alternatives/competition
-	Possible contribution now or in future, some better alternatives/competition
o	Realistic contribution now or in near future, competitive with regard to alternatives/competition
+	Significant contribution now, far better than or few alternatives/competition
++	Very significant contribution now, hardly any alternatives/competition
no entry	unrated

Heat storage district heating

Quantification and monetarization of value of concepts	Type	Qualitative contribution	Motivation of qualitative ranking	Quantification of value	Monetization of value
Frequency containment reserves'(30 seconds)	System stability	0	Not relevant, gas engine or gas turbine fast reserve is not fast enough to follow changes within the containment reserves range	n.r.	Expected price level for delivering primary reserves (EUR/kW)
Frequency restoration/replacement reserves (15 minutes TPU, imbalance markets)	System stability	+	Addition of a storage tank may provide flexibility in terms of reserve power generation availability, while produced heat is temporarily stored. In theory the whole generation capacity is available for full hours or a full day. In practice reserve capacity may only be available in summer, when heat demand is low and the CHP-plant does not have to produce heat full time based. Ramp rate or fast reserve is high enough for significant load changes within minutes.	Amount of kWh available to supply on 15-minutes base	Value per kWh, bases on current markets and projection to future. Use ECN-study?
Reserve power (hour)	System stability			Amount of kW available to supply on daily basis	Price per kW, reference alternative (GT)
Reserve power (day)	System stability			Amount of kW available to supply on daily basis	Cost per kW, reference alternative (GT)
Reserve power (week)	System stability	0	Not relevant, storage capacity is not sufficient for periods longer than approximately a day and is not intended for seasonal storage or periodic storage	Amount of kW available to supply on weekly basis	Cost per kW, reference alternative (GT)
Reserve power (year)	System stability			Amount of kW available to supply on yearly basis	Cost per kW, reference alternative (GT)
Reduced or deferred investments HV-grid	Grids	0/+	By balancing oversupply of renewable wind power, requirements for investments for oversupply situations can be reduced or deferred. However, investments may be required to allow sufficient use of CHP power supply in periods with unforeseen shortages in renewable power.	Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year)
Reduced or deferred investments MV-grid	Grids			Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year)
Reduced or deferred investmens LV-grid	Grids	0	Not relevant, power generation equipment utilizing storage facilities considered in this fact sheet is not connected to low voltage grid.	Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year). Cost of alternative (volt/var control
Jobs created	Economic value	0	Not relevant	Number of jobs	Value per job
Value added	Economic value	+	Added value cnsists of costs reduction by reduction of fuel consumption and by allowing power production with the most efficient and economic unit at a certain time. Added value is mainly limited to summer in which the CHP-plant does not have to produce full load continiously.		
Export value	Economic value	0	As utilization of a storage tank is standard technology, no technological innovation is involved and no export value is to be expected.	Number of units/hours of services	Value per unit/service
CO2-reduction	Sustainability	+	By allowing optimized operation of the CHP-plant, fuel consuming start/stop and part load operations during which the plant operates less efficient can be minimized	Total reduction per concept (ton CO2)	Value of CO2, based on expected market cost for CO2.

Qualitative contribution	
--	No contribution at all now or in future, far better alternatives/competition
-	Possible contribution now or in future, some better alternatives/competition
o	Realistic contribution now or in near future, competitive with regard to alternatives/competition
+	Significant contribution now, far better than or few alternatives/competition
++	Very significant contribution now, hardly any alternatives/competition
no entry	unrated

Industrial heat storage

Quantification and monetarization of value of concepts	Type	Qualitative contribution	Motivation of qualitative ranking	Quantification of value	Monetization of value
Frequency containment reserves'(30 seconds)	System stability	0	Not relevant, gas engine or gas turbine fast reserve is not fast enough to follow changes within the containment reserves range	n.r.	Expected price level for delivering primary reserves (EUR/kW)
Frequency restoration/replacement reserves (15 minutes TPU, imbalance markets)	System stability	+	Addition of a storage tank may provide flexibility in terms of reserve power generation availability, while produced heat is temporarily stored. In theory the whole generation capacity is available for full hours or a full day. In practice	Amount of kWh available to supply on 15-minutes base	Value per kWh, bases on current markets and projection to future. Use ECN-study?
Reserve power (hour)	System stability			Amount of kW available to supply on daily basis	Price per kW, reference alternative (GT)
Reserve power (day)	System stability			Amount of kW available to supply on daily basis	Cost per kW, reference alternative (GT)
Reserve power (week)	System stability	0	Not relevant, storage capacity is not sufficient for periods longer than approximately a day and is not intended for	Amount of kW available to supply on weekly basis	Cost per kW, reference alternative (GT)
Reserve power (year)	System stability			Amount of kW available to supply on yearly basis	Cost per kW, reference alternative (GT)
Reduced or deferred investments HV-grid	Grids	0/+	By balancing oversupply of renewable wind power, requirements for investments for oversupply situations can be reduced or deferred. However, investments may be required to allow sufficient use of CHP power supply in	Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year)
Reduced or deferred investments MV-grid	Grids			Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year)
Reduced or deferred investmens LV-grid	Grids	0	Not relevant, power generation equipment utilizing storage facilities considered in this fact sheet is not connected to low voltage grid.	Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year). Cost of alternative (volt/var control
Jobs created	Economic value	0	Not relevant	Number of jobs	Value per job
Value added	Economic value	+	Added value cnsists of costs reduction by reduction of fuel consumption and by allowing power production with the most efficient and economic unit at a certain time.		
Export value	Economic value	0	The technology has been and is being further developed in countries with relevant solar power potential.	Number of units/hours of services	Value per unit/service
CO2-reduction	Sustainability	+	By allowing optimized operation of the CHP-plant, fuel consuming start/stop and part load operations during which the plant operates less efficient can be minimized	Total reduction per concept (ton CO2)	Value of CO2, based on expected market cost for CO2.

Qualitative contribution	
--	No contribution at all now or in future, far better alternatives/competition
-	Possible contribution now or in future, some better alternatives/competition
o	Realistic contribution now or in near future, competitive with regard to alternatives/competition
+	Significant contribution now, far better than or few alternatives/competition
++	Very significant contribution now, hardly any alternatives/competition
no entry	unrated

Power-to-hydrogen

Quantification and monetarization of value of concepts	Type	Qualitative contribution	Motivation of qualitative ranking	Quantification of value	Monetization of value
Frequency containment reserves'(30 seconds)	System stability	--	Technically this service can be delivered by the power-to-methane concept whenever it is in stand-by modus or operated below maximum capacity (operating to serve other portfolio). On the electricity site of the concept there is sufficient ramping capacity. The gas side of this concept is more restrictive, as gas conditioning in the electrolyser and the gas chromatograph measuring take time (up to 15 min.) to adapt. During this period the concept efficiency is close to zero because the produced gas does not comply with quality standards and cannot be injected in the gas grid. **Concluding: technically possible but inconvenient in terms of effeciency, durability and economic revenue; conventional units more suitable.**	Does this concept has the opportunity to provide this service. How much kW of primary reserve can be supplied.	Expected price level for delivering primary reserves (EUR/kW)
Frequency restoration/replacement reserves (15 minutes TPU, imbalance markets)	System stability	-	Technically possible, whenever it is in stand-by modus or operated below maximum capacity. When the concept is operating to serve another portfolio, this service is an interesting ancillary service additional to its basic operation. Economic considerations dinally define the optimal opration strategy of the concept. A high number of operational hours per year is preferred over low utilization (so number of ISP's (Imbalance Settlement Periods)/PTU's (program time unit) to be determined in operational strategy).	Amount of kWh available to supply on 15-minutes base	Value per kWh, bases on current markets and projection to future. Use ECN-study?
Reserve power (hour)	System stability	0	Technically possible, whenever it is in stand-by modus or operated below maximum capacity. When the concept is operating to serve another portfolio, this service is an interesting ancillary service additional to its basic operation. Economic considerations dinally define the optimal opration strategy of the concept. A high number of operational hours per year is preferred over low utilization (so number of ISP's (Imbalance Settlement Periods)/PTU's (program time unit) to be determined in operational strategy).	Amount of kW available to supply on daily basis	Price per kW, reference alternative (GT)
Reserve power (day)	System stability	0	See motivation in "Reserve power (hour)"	Amount of kW available to supply on daily basis	Cost per kW, reference alternative (GT)
Reserve power (week)	System stability	+	Power-to-hydrogen dedicated for reserve power accommodation over a week time period is technically possible and (depending on the business case) could be economically promissing. The volume and capacity of the gas infrastructure is offered through this concept and makes perfect sense on the week to week flexibility. Although the hydrogen injection limits of the existing gas infrastructure should be considered. A high number of operational hours per year is preferred over low utilization. **Concluding: in particular a promising application of the power-to-hydrogen concept as an enabler for utilizing gas infrastructure's flexibility.**	Amount of kW available to supply on weekly basis	Cost per kW, reference alternative (GT)
Reserve power (year)	System stability	++	This concept is in particular relevant for seasonal 'storage' of energy as it enables to use the flexibility in the gas infrastructure (capacity, volume, storage) for accommodation of volatile (renewable) power. The capabilities of this concept-infrastructure combination is unrivalled by any other power storage concept. Condition is the availability of underground gas storages.	Amount of kW available to supply on yearly basis	Cost per kW, reference alternative (GT)
Reduced or deferred investments HV-grid	Grids	0/+	It is unlikely that the HV grids connecting to offshore wind parks offers insufficient capacity, as grid operators are obliged to install sufficient grid capacity related to the wind parks to be connected. In NL it therefor does not seem obvious to connect power-to-hydrogen concept to a HV grid (as HV transmission capacity is expected to be sufficient).	Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year)
Reduced or deferred investments MV-grid	Grids	+	Power-to-hydrogen concept is likely to play an important role to reduce MV power grid investments, as this grid accommodates wind and solar power and is more abundant. Foreseen unit scale for power-to-methane in this configuration is en few tens of MW's per installation.	Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year)
Reduced or deferred investmens LV-grid	Grids	-/0	There could be an important role for power-to-hydrogen for accommodating domestic solar power curtailment in LV-grids. However, the gas network at this level (low pressure gas distribution grid) could introduce gas injection capacity restrictions in summertime (when gas demand is very low), even more restrictive is the gas quality standard for hydrogen addition to natural gas. Therefore it is expected that power-to-hydrogen concept for this purpose only realizes a shift from the energy capacity problem in the power grid to the gas grid. R&D stimulation for bi-directional gas grids and accommodation of hydrogen could be effective to tackle this issue (multi-purpose as that would also benefit injection potential of biomethane in gas distribution grids).	Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year). Cost of alternative (volt/var control
Jobs created	Economic value	+	The power-to-hydrogen concept potentially contributes to conservation (or partly concervation) of the gas infrastructure and gas sector in the future. In that respect, this concept potentially contributes to the 70,000 jobs of the gas sector in NL today (ref. TKI Gas). So conservation of jobs in the gas installation and services market is foreseen.	Number of jobs	Value per job
Value added	Economic value	+	As the storage time required by the energy system is increases, the value added of the power-to-hydrogen option increases. For short cycle 'storage', the efficiency and costs of the concept could be a barrier, but its competetive advantage is large when enabling the use of flexibility in the gas infrastructure (including gas underground storages, etc) to offer a relief to the flexibility problems in the power grid.		
Export value	Economic value	+	NL is a country with outstanding knowledge, experience and expertise on gas markets and technology. This an importante competative advantage that can further be exploited by gas oriented concepts, like power-to-hydrogen. These concepts score relatively good on export value relative to non-gas oriented concepts.	Number of units/hours of services	Value per unit/service
CO2-reduction	Sustainability	-/0	Application of hydrogen from this concept as feedsctock for industrial processes or as fuel (hydrogen as a product) has high value in terms of carbon reduction, as it saves on the use of fossil sources for hydrogen production. Hydrogen injection in the gas grid however has some downsides in terms of end-use carbon emission: as the end-user equipment in the existing natural gas infrastructure is specifically designd and set for a specific gas quality (in a small bandwith) the addition of hydrogen to the existing natural gas infrastructure will result in efficiency loss at the end-users. There, the specific carbon and NOx emissions are likely to increase rather than decrease. That is an important meso-level consideration that must not be ignored.	Total reduction per concept (ton CO2)	Value of CO2, based on expected market cost for CO2.

Qualitative contribution	
--	No contribution at all now or in future, far better alternatives/competition
-	Possible contribution now or in future, some better alternatives/competition
o	Realistic contribution now or in near future, competitive with regard to alternatives/competition
+	Significant contribution now, far better than or few alternatives/competition
++	Very significant contribution now, hardly any alternatives/competition
no entry	unrated

Power-to-methane

Quantification and monetarization of value of concepts	Type	Qualitative contribution	Motivation of qualitative ranking	Quantification of value	Monetization of value
Frequency containment reserves'(30 seconds)	System stability	--	Technically this service can be delivered by the power-to-methane concept whenever it is in stand-by modus or operated below maximum capacity (operating to serve other portfolio). On the electricity site of the concept there is sufficient ramping capacity. The gas side of this concept is more restrictive, as gas conditioning in the electrolyser and in the methanation process and the chromatograph measurements takes time (up to 15 min.) to adapt. During this period the concept efficiency is close to zero because the produced gas does not comply with quality standards and cannot be injected in the gas grid. **Concluding: technically possible but inconvenient in terms of effeciency, durability and economic revenue; conventional units more suitable.**	Does this concept has the opportunity to provide this service. How much kW of primary reserve can be supplied.	Expected price level for delivering primary reserves (EUR/kW)
Frequency restoration/replacement reserves (15 minutes TPU, imbalance markets)	System stability	-	Technically possible, whenever it is in stand-by modus or operated below maximum capacity. When the concept is operating to serve another portfolio, this service is an interesting ancillary service additional to its basic operation. Economic considerations dinally define the optimal opration strategy of the concept. A high number of operational hours per year is preferred over low utilization (so number of ISP's (Imbalance Settlement Periods)/PTU's (program time unit) to be determined in operational strategy).	Amount of kWh available to supply on 15-minutes base	Value per kWh, bases on current markets and projection to future. Use ECN-study?
Reserve power (hour)	System stability	0	Technically possible, whenever it is in stand-by modus or operated below maximum capacity. When the concept is operating to serve another portfolio, this service is an interesting ancillary service additional to its basic operation. Economic considerations dinally define the optimal opration strategy of the concept. A high number of operational hours per year is preferred over low utilization (so number of ISP's (Imbalance Settlement Periods)/PTU's (program time unit) to be determined in operational strategy).	Amount of kW available to supply on daily basis	Price per kW, reference alternative (GT)
Reserve power (day)	System stability	0	See motivation in "Reserve power (hour)"	Amount of kW available to supply on daily basis	Cost per kW, reference alternative (GT)
Reserve power (week)	System stability	+	Power-to-methane dedicated for reserve power accommodation over a week time period is technically possible and (depending on the business case) could be economically promissing. The volume and capacity of the gas infrastructure is offered through this concept and makes perfect sense on the week to week flexibility. A high number of operational hours per year is preferred over low utilization. **Concluding: in particular a promising application of the power-to-methane concept as an enabler for utilizing gas infrastructure's flexibility.**	Amount of kW available to supply on weekly basis	Cost per kW, reference alternative (GT)
Reserve power (year)	System stability	++	This concept is in particular relevant for seasonal 'storage' of energy as it enables to use the flexibility in the gas infrastructure (capacity, volume, storage) for accommodation of volatile (renewable) power. The capabilities of this concept-infrastructure combination is unrivalled by any other power storage concept. Condition is the availability of underground gas storages.	Amount of kW available to supply on yearly basis	Cost per kW, reference alternative (GT)
Reduced or deferred investments HV-grid	Grids	0/+	It is unlikely that the HV grids connecting to offshore wind parks offers insufficient capacity, as grid operators are obliged to install sufficient grid capacity related to the wind parks to be connected. In NL it therefor does not seem obvious to connect power-to-methane technology to a HV grid (as HV transmission capacity is expected to be sufficient).	Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year)
Reduced or deferred investments MV-grid	Grids	+	Power-to-methane concept is likely to play an important role to reduce MV power grid investments, as this grid accommodates wind and solar power and is more abundant. Foreseen unit scale for power-to-methane in this configuration is en few tens of MW's per installation.	Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year)
Reduced or deferred investmens LV-grid	Grids	-/0	There could be an important role for power-to-methane for accommodating domestic solar power curtailment in LV-grids. However, the gas network at this level (low pressure gas distribution grid) could introduce gas injection capacity restrictions in summertime (when gas demand is very low). Therefore it is expected that power-to-methane concept for this purpose only realizes a shift from the energy capacity problem in the power grid to the gas grid. R&D stimulation for bi-directional gas grids could be effective to tackle this issue (multi-purpose as that would also benefit injection potential of biomethane in gas distribution grids)	Amount of kW available to supply per year	Cost per kW grid based on scenario's NB-NL (levelized cost/year). Cost of alternative (volt/var control
Jobs created	Economic value	+	The power-to-methane concept potentially contributes to conservation of the gas infrastructure and gas sector in the future. In that respect, this concept potentially contributes to the 70,000 jobs of the gas sector in NL today (ref. TKI Gas). So conservation of jobs in the gas installation and services market is foreseen.	Number of jobs	Value per job
Value added	Economic value	++	As the storage time required by the energy system increases, the value added of the power-to-methane option increases. For short cycle 'storage', the efficiency and costs of the concept could be a barrier, but its competetive advantage is large when enabling the use of flexibility in the gas infrastructure (including gas underground storages, etc) to offer a relief to the flexibility problems in the power grid. Additional to flexibility service delivery to the power infrastructure, the power-to-methane concept offers the possibility for carbon recycling, which is unique relative to alternatives and therefore adds significant sociatal value.		
Export value	Economic value	+	NL is a country with outstanding knowledge, experience and expertise on gas markets and technology. This an importante competitive advantage that can further be exploited by gas oriented concepts, like power-to-methane. These concepts score relatively good on export value relative to non-gas oriented concepts.	Number of units/hours of services	Value per unit/service
CO2-reduction	Sustainability	++	Power-to-methane enables carbon recycling, by chemically binding hydrogen to carbon dioxide. The production of a cubic meter of synthetic natural gas with this process in turn saves on the use of a cubic meter natural gas. This concept enables to decarbonize the gas sector by accommodating renewable power. Other carbon effects are assumed to be identical for all concepts facilitating the accommodation of renewables.	Total reduction per concept (ton CO2)	Value of CO2, based on expected market cost for CO2.

Qualitative contribution	
--	No contribution at all now or in future, far better alternatives/competition
-	Possible contribution now or in future, some better alternatives/competition
o	Realistic contribution now or in near future, competitive with regard to alternatives/competition
+	Significant contribution now, far better than or few alternatives/competition
++	Very significant contribution now, hardly any alternatives/competition
no entry	unrated

About CE Delft

CE Delft is an independent research and consultancy organisation specialised in developing innovative solutions to environmental problems. CE Delft is skilled across a wide range of environmental topics and also familiar with the associated policy networks: trade and industry, government and non-governmental organisations alike. The solutions CE Delft delivers are technologically robust, economically prudent, politically feasible and socially equitable. Eager to share its knowledge and understanding, CE Delft makes its research findings publicly available whenever it can.

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